1

CANADIAN THESES ON MICROFICHE

THÈSES CANADIENNES SUR MICROFICHE

National Library of Canada
Collections Development Branch

Canadian Theses on
Microfiche Service

Ottawa, Canada
K1A 0N4

Bibliothèque nationale du Canada
Direction du développement des collections

Service des thèses canadiennes
sur microfiche

NOTICE

The quality of this microfiche is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Previously copyrighted materials (journal articles, published tests, etc.) are not filmed.

Reproduction in full or in part of this film is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30. Please read the authorization forms which accompany this thesis.

AVIS

La qualité de cette microfiche dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

Les documents qui font déjà l'objet d'un droit d'auteur (articles de revue, examens publiés, etc.) ne sont pas microfilmés.

La reproduction, même partielle, de ce microfilm est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30. Veuillez prendre connaissance des formules d'autorisation qui accompagnent cette thèse.

THIS DISSERTATION
HAS BEEN MICROFILMED
EXACTLY AS RECEIVED

LA THÈSE A ÉTÉ
MICROFILMÉE TELLE QUE
NOUS L'AVONS REÇUE

Canada

0-315-19910-5

National Library
of Canada

Bibliothèque nationale
du Canada

Canadian Theses Division / Division des thèses canadiennes

Ottawa, Canada
K1A 0N4

67817

PERMISSION TO MICROFILM — AUTORISATION DE MICROFILMER

• Please print or type — Ecrire en lettres moulées ou dactylographier

Full Name of Author — Nom complet de l'auteur

GEORGE YUH-YING SHING

Date of Birth — Date de naissance

Aug 23, 1954

Country of Birth — Lieu de naissance

Taiwan, Republic of China

Permanent Address — Residence fixe

790 Springland Drive, #114, Ottawa, Ontario K1V 6L7

Title of Thesis — Titre de la thèse

Microprocessor Model for Predicting Weld
Heat-Affected Zone and Fusion Zone Hardnesses

University — Université

Carleton University

Degree for which thesis was presented — Grade pour lequel cette thèse fut présentée

M. ENG.

Year this degree conferred — Année d'obtention de ce grade

Spring, 1985

Name of Supervisor — Nom du directeur de thèse

Malcom J. Bibby

Permission is hereby granted to the NATIONAL LIBRARY OF CANADA to microfilm this thesis and to lend or sell copies of the film

The author reserves other publication rights, and neither the thesis nor extensive extracts from it may be printed or otherwise reproduced without the author's written permission

L'autorisation est, par la présente, accordée à la BIBLIOTHÈQUE NATIONALE DU CANADA de microfilmer cette thèse et de prêter ou de vendre des exemplaires du film

L'auteur se réserve les autres droits de publication, ni la thèse ni de longs extraits de celle-ci ne doivent être imprimés ou autrement reproduits sans l'autorisation écrite de l'auteur

Date

March 18, 1985

Signature

G. Shing

**Microprocessor Model for Predicting
Weld
Heat-Affected Zone and Fusion Zone Hardnesses**

George Yuh-Ying Shing

*A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the
Degree of Master of Engineering*

DEPARTMENT OF MECHANICAL AND AERONAUTICAL ENGINEERING
CARLETON UNIVERSITY
OTTAWA, ONTARIO
CANADA.

February 1985

The undersigned recommends to the Faculty of Graduate Studies and Research, acceptance of the thesis: *Microprocessor Model for Predicting Weld Heat-Affected Zone and Fusion Zone Hardnesses*, submitted by George Yuh-Ying Shing, in partial fulfillment of the requirements for the Degree of Master of Engineering.

Thesis Supervisor

Chairman
Department of Mechanical
and Aeronautical Engineering

ABSTRACT

Several independent models for predicting the fusion zone (FZ) and the heat-affected zone (HAZ) hardness of a weld have been proposed. Two of the more recent and potentially useful models are the methods suggested by Terasaki(1980) [1] and Yurioka et al(1981) [2]. In this thesis, these are compared to the Arata- α model [3] which is recommended by Chong [4] as the most accurate method of predicting weld hardness among the models available before 1980. The accuracy of these three models is evaluated by comparing some 176 measured hardness values [2,3,5,6,7,8] for a wide range of steels and welding conditions against calculated values.

The welding conditions (voltage, current, welding speed and efficiency) are used to calculate an 800 to 500°C weld cooling time. The cooling time is then combined with a hardening model to predict HAZ hardness. There are four relationships available for this purpose, the Adams-Bibby model [9,10], the Chakravarti model [11], the Adams-2.5D model [12], and the Kohira model [13]. These are evaluated by comparing some 55 measured $r_{h/s}$ values [2,10,14] for a wide range of welding conditions with calculated cooling time ($r_{h/s}$) values.

To apply the hardness models in welding engineering practice where central computing facilities may not be available, e.g. (shop practice), it has been suggested that they can be modified for hand-held pocket type microprocessor, such as the Tandy TRS-80 Model PC-2. This is expected to add flexibility and convenience, in utilizing these models in the industry. A microprocessor method composed of the Yurioka hardness predicting model and the Kohira cooling time ($r_{h/s}$) model is presented by the author. This microprocessor method is compared to a previous method proposed by Trauttmansdorff [5].

ACKNOWLEDGEMENTS

I would like to express my deepest appreciation to my thesis supervisor Dr. M. J. Bibby, for his continued interest, encouragement and guidance provided during this thesis and throughout my stay at Carleton University.

I also would like to thank Professor J. A. Goldak for his encouragement and support during this program

Thanks are expressed to all my friends for their helpful and constructive assistance

Finally, I would like to present this thesis to my beloved mother and wife.

TABLE OF CONTENTS

Abstract	i
Acknowledgements	ii
Contents	iii
List of Figures	v
List of Tables	viii
Nomenclature	x
1 INTRODUCTION	1
2 A QUALITATIVE DESCRIPTION OF THE WELD COOLING TIME AND HARDENING MODELS	5
2.1 Cooling Time Model	5
2.1.1 Heat Input Rate and Energy Input Rate	10
2.1.2 Thermal Properties	11
2.2 Predicting Microstructure	13
2.3 Hardening Model	14
3 MODELS FOR CALCULATING COOLING TIMES	17
3.1 Adams-Bibby Model	17
3.2 Chakravarti Model	18
3.3 Adams-2.5D Model	20
3.4 Kohira Model	24
3.5 A Comparison of Cooling Time Models	25
4 MODELS FOR PREDICTING HARDNESSES	31
4.1 Arata- α Model	31
4.2 Terasaki Model	37
4.3 Yurioka Model	39
4.4 Comparison of the Arata- α , Terasaki and Yurioka Hardness Models	41

5	MICROPROCESSOR APPLICATION	48
5.1	Justification for Using of Small Computer	48
5.2	Program Description and Operation	48
5.3	Accuracy Evaluation	49
5.4	Comparison of Interactive Programs for The Two Microprocessor Methods	52
6	DISCUSSION	56
7	CONCLUSIONS	66
8	FUTURE WORK	67
	References	68
	Appendix-A	70
	Appendix-B	73
	Appendix-C	76
	Appendix-D	78
	Appendix-E	85
	Appendix-F	89
	Appendix-G	91
	Appendix-H	93

LIST OF FIGURES

Figures

1.1 Schematic time-temperature representations of points in the neighborhood of a weld	4
2.1 Schematic flow chart for predicting weld HAZ hardness	8
2.2 (a) Idealised point heat source used to simulate a shallow penetration weld (b) Idealised line heat source used to simulate a deep penetration weld (c) Coordinate system for two-dimensional heat flow calculations	9
2.3 Temperature dependence of thermal conductivity and volumetric specific heat	12
2.4 Time-temperature weld curves superimposed on the continuous cooling transformation (CCT) diagram	15
2.5 Schematic representation of the characteristic hardening curve	16
3.1 Flow chart of the Adams-Bibby model for calculating cooling time between 800 and 500°C	19
3.2 Schematic diagram to show 2.5D transition zone (linear heat input (J/mm) constant)	21
3.3 Relation between plate thickness and cooling time between 800 and 500°C	22
3.4 Flow chart of Adams-2.5D model for calculating cooling time between 800 and 500°C	23
3.5 Flow chart of the Kohira model for calculating cooling time between 800 and 500°C	27
3.6 Calculated cooling time $\tau_{8/5}$ plotted against measured values (a) Adams-Bibby model (b) Chakravarti model (c) Adams-2.5D model (d) Kohira model (experimental data taken from source [2])	28

3.7 Calculated cooling time $\tau_{R/5}$ of Kohira model and Adams-2.5D model plotted against measured values from all sources [2,10,14]	29
4.1 Relationship between welding CCT diagram and hardness curve (a) welding CCT diagram (b) welding CCTSH (Continuous Cooling transformation Structure Hardness) diagram	32
4.2 The characteristic hardness curve used to approximate the welding CCTSH curve	32
4.3 Flow chart of Arata-α model for predicting HAZ hardness	36
4.4 Flow chart of the Terasaki model for predicting HAZ hardness	38
4.5 Flow chart of the Yurioka model for predicting HAZ hardness	40
4.6 Predicted characteristic hardness curves (Arata-α, Terasaki and Yurioka models) for typical steels ranging from a microalloy steel ($C=0.05\%$) through to a higher carbon machine steel ($C=0.45\%$) (a) steel I (b) steel II (c) steel III (d) steel IV (e) steel V (f) steel VI	44
4.7 Arata-α model predicted hardnesses plotted against measured values from all sources [2,3,5,6,7,8]	45
4.8 Terasaki model predicted hardnesses plotted against measured values from all sources [2,3,5,6,7,8]	46
4.9 Yurioka model predicted hardnesses plotted against measured values from all sources [2,3,5,6,7,8]	47
5.1 Flow chart of microprocessor method M2 for predicting HAZ hardness	50
6.1 Kohira model calculated cooling time $\tau_{R/5}$ using 5 sets different thermal constants plotted against measured values from source [2]	61

- 6.2 Kohira model calculated cooling time $\tau_{8/5}$ plotted against surface conductance**
- (a) low heat input weld, thin plate (0.8 KJ/mm) (b) low heat input weld, thick plate (1.1 KJ/mm) (c) high heat input weld, without preheat (4.4 KJ/mm) (d) high heat input weld, with preheat (4.5 KJ/mm, $T_0 = 200^\circ\text{C}$) **64**
- 6.3 Schematic diagram of a bead-on plate weld to show the actual heat source configuration of a weld** **65**
- 6.4 Schematic diagram to show the effect of joint configuration on heat flow**
- (a) Butt weld (b) Fillet weld **65**

LIST OF TABLES

Tables

2.1 Weld Efficiency Values	11
2.2 Thermal Properties for Calculating Cooling time between 800 and 500°C	13
3.1 Summary of C_r Values Corresponding to Relative Thickness	22
3.2 Comparison of Cooling Time Models for Calculating $\tau_{8/5}$	30
3.3 Difference between Predicted (Adams-2.5D and Kohira models) and Measured Cooling Time $\tau_{8/5}$ from all Sources	30
4.1 Limitations in Chemical Composition of Arata-α Model	35
4.2 Chemical Composition of Six Selected Steels Used in Comparison of Hardness Models	43
4.3 Difference between Predicted (Arata-α, Terasaki and Yurioka Models) and Measured Hardness from All Sources	43
5.1 Instructions for Operating Microprocessor M2 Hardness program	51
5.2 Calculated Cooling Times to Demonstrate the Reliability of Computer Cooling Time Software	53
5.3 Chemical Composition of Five Selected Steels Used in Evaluation of M2 Hardness Model Software	53
5.4 Calculated Hardness Values to Demonstrate the Reliability of Computer Hardness Model Software	54
5.5 A Comparison of Cooling Times Calculated With M1 and M2 for Several Welding Situations	54
5.6 A Comparison of HAZ Hardness Values Calculated With M1 and M2 for Several Steels	55
5.7 Thermal Properties Used in Microprocessors M1 and M2	55

6.1 A Comparison of Bessel Function $K_0(X)$ Calculated with Two Different Equations	60
6.2 Various Thermal Properties for Calculating Cooling Time between 800 and 500°C	60
6.3 A Comparison of Calculated Cooling Times between 800 and 500°C with Decreasing Surface Conductance	62

NOMENCLATURE

a, b	Constants in Arata- α model
C	Specific heat ($J/Kg \text{ } ^\circ C$)
C_{eq}	Carbon equivalent in Terasaki model
C_{eqI}, C_{eqII}	Carbon equivalent in Yurioka model
CP6	Carleton University mainframe Honeywell computer
C_p	Volumetric specific heat capacity ($J/mm^3 \text{ } ^\circ C$)
d	Heat transfer coefficient, $d = \alpha/K$, (mm^{-1})
E	Energy input rate (J/s)
EBW	Electron beam weld
FZ	Fusion zone
GMAW	Gas metal arc weld
GTAW	Gas tungsten arc weld
h	Thickness (mm)
H_c	Saturation thickness (mm)
H_r	Relative thickness
H_v	Hardness (VHN)
HAZ	Heat-affected zone
I	Current (Amperes)
K	Thermal conductivity ($J/mm \text{ } ^\circ C \text{ } s$)
K_0	Bessel function of second kind and zero order
M1	Microprocessor method 1
M2	Microprocessor method 2
MPa	Megapascal
Q	Net heat input rate (J/s)
r	Radial distance from the heat source (mm)
SAW	Submerged arc weld
SMAW	Shielded metal arc weld
t	Time (s)
T	Temperature ($^\circ C$)

T_0	Preheat temperature ($^{\circ}\text{C}$)
T_{∞}	Ambient temperature ($^{\circ}\text{C}$)
U_n	Eigenvalues
U_{wn}	Eigenvalues at weld
U_{pn}	Eigenvalues at plate
v	Welding speed (mm/s)
V	Voltage (Volts)
VHN	Vickers hardness number
x, y, z	Coordinates
α	Surface conductance ($\text{J/mm}^2 \text{ } ^{\circ}\text{C s}$)
α_w	Surface conductance at weld ($\text{J/mm}^2 \text{ } ^{\circ}\text{C s}$)
α_p	Surface conductance at plate ($\text{J/mm}^2 \text{ } ^{\circ}\text{C s}$)
η	Welding efficiency (%)
λ	Thermal diffusivity (mm^2/s)
ρ	Density (Kg/mm^3)
$\tau_{8/5}$	Cooling time between 800 and 500 $^{\circ}\text{C}$ (s)
τ_{2D}	Cooling time between 800 and 500 $^{\circ}\text{C}$ for two-dimensional heat flow (s)
$\tau_{2.5D}$	Cooling time between 800 and 500 $^{\circ}\text{C}$ for two-dimensional and half heat flow (s)
τ_{3D}	Cooling time between 800 and 500 $^{\circ}\text{C}$ for three-dimensional heat flow (s)
τ_{M0}	Cooling time between 800 and 500 $^{\circ}\text{C}$ for 0% martensite transformation (s)
τ_{M100}	Cooling time between 800 and 500 $^{\circ}\text{C}$ for 100% martensite transformation (s)
τ_{5c}	Initial trial cooling time to 500 $^{\circ}\text{C}$ (s)
τ_{8c}	Initial trial cooling time to 800 $^{\circ}\text{C}$ (s)
ξ	Distance in front of the heat source (mm)

Subscripts

2D	Two-dimensional heat flow
3D	Three-dimensional heat flow

Chapter 1

INTRODUCTION

Welding is a localized coalescence of metals. In a welding process, a temperature gradient is set up in the material, ranging from the melting point at the joint centerline to ambient temperature some distance away. In turn, three distinct regions are formed in a welded joint, i.e. fusion zone (weld metal), heat-affected zone (HAZ), and base metal (Figure 1.1)[15].

The fusion zone (FZ) and HAZ are subject to severe thermal changes. When the peak temperature exceeds the critical temperature for steels (723°C) all or part of the material in the HAZ is transformed to austenite (point 4, Figure 1.1). The transformed material subsequently decomposes to hardened microstructures as the weld cools. Martensite, a very hard and brittle phase appears if the cooling time is short.

In principle, the microstructure and hence hardness can be predicted by imposing the HAZ cooling curve on a CCT (continuous cooling transformation) diagram. However, in practice this is an awkward procedure. Therefore Japanese investigators have suggested another representation where HAZ hardness is plotted against the weld cooling time from 800 and 500°C ($\tau_{8/5}$) for given steel. This representation is called the characteristic hardening transformation curve (CHTC explained in more detail in chapter 2). The CHTC can be represented mathematically by curve fitting. At the same time, mathematical relationships are available for calculating $\tau_{8/5}$ from the welding parameters. These can then be combined as a quantitative method for predicting the hardening expected in the HAZ for a given welding situation.

Hardness is considered to be a very useful parameter for determining the quality and hence expected performance of a welded joint. It is an indirect measure of tensile strength and toughness [16]. The small size of the FZ and HAZ generally preclude the direct measurement of strength and toughness. As the hardness increases the strength increases ($TS(MPa) = 3.5VHN$ (Vickers Hardness Number)) and the toughness decreases. In addition, there is a loss of plasticity as the hardness

increases and this together with relatively high residual tensile stresses that form as a result of thermal shrinkage can lead to crack formation as the weld cools

Since the base metal is usually higher in carbon content than the weld metal, higher hardness levels are likely to appear in the HAZ. Thus, there is often more concern with hardness in this region than in the weld metal. In practice, the HAZ hardness level is usually limited to 325 VHN to minimize the possibility of cold cracking [17]. In other words, a weld where the hardness exceeds 325 VHN might contain cold cracks while a weld where the hardness is less than this value can be regarded generally speaking as satisfactory. Because of the importance of HAZ hardness, it often ends up in engineering codes. For example, a maximum HAZ hardness of 280 VHN is imposed on northern pipelines and similar limits are written into the welding specifications for offshore construction. The advantages to the engineering community of having a method of predicting HAZ hardness are therefore apparent.

In view of the importance of HAZ hardness, several investigators have researched methods of predicting it from the input cooling time $\tau_{8/5}$ and chemical composition of workpiece. There are seven semi-empirical hardness models, i.e. the Bastien model [18], the Arata- α and β models [3], the Beckert model [19], the Seyffarth model [20], the Terasaki model [1], and the Yurioka model [2], available for this purpose. Based on Chong's comparative investigation [4], the Arata- α model is shown to be the most accurate method for predicting HAZ hardness among the first three models. On the other hand, Yurioka et al [2] compared the Beckert and the Seyffarth models, with a model proposed by Yurioka himself. The predicted hardnesses of the Beckert and Seyffarth models were found to deviate considerably from the measured values for low carbon steels. To find the best hardness model, it therefore, follows that the most reliable method of predicting HAZ hardness must be either the Arata- α , the Terasaki or the Yurioka models. Calculated values from these three models are compared to measured HAZ hardnesses in this thesis. Such an evaluation is not available in the literature and is potentially very useful.

As mentioned above, the welding conditions (V , I , v , η) are submitted to the hardness model in terms of a cooling time $\tau_{8/5}$ (800-500°C). It is, therefore, necessary to have a means of determining the weld cooling time ($\tau_{8/5}$). In some cases, $\tau_{8/5}$ can be measured directly by implanting a thermocouple into the weld pool. However, a measured $\tau_{8/5}$ is often not available and must be calculated from the welding parameters. Several methods have been proposed for calculating the $\tau_{8/5}$ from the input welding parameters. Four independent relationships, i.e. the Adams-Bibby

[9,10], the Chakravarti [11], the Adams-2 5D [12] and the Kohira [13] models, are available for this purpose. These methods are evaluated by comparing calculated cooling times $\tau_{8/5}$ with experimentally measured values from the literatures in this investigation.

While the cooling time and HAZ hardness calculations are straightforward, in principle, they are lengthy in practice. Because of this the best available HAZ hardness model is combined with the best available cooling time model and modified for use in a small portable (hand held) microprocessor unit. Such units are now relatively inexpensive (<\$200) and in practice can be dedicated for this purpose. A first generation model assembled by Trauttmansdorff is already being tested in practice by the AMCA corporation and the new improved version proposed in this thesis will follow shortly.

Objectives

Specifically the objectives of this thesis are threefold:

- (1) To determine the best model among the seven available for predicting HAZ hardness from the chemical composition of the base material and the welding parameters
- (2) To determine the best method for calculating the cooling time $\tau_{8/5}$ among those available
- (3) To combine the results of objectives (1) and (2), and adapt where necessary to assemble a microprocessor unit for predicting HAZ hardness in practice

A qualitative description of the theory of weld heat flow and hardening model is contained in chapter 2. The four models for calculating cooling time ($\tau_{8/5}$) are evaluated, and calculated times are compared with measured values in chapter 3. The three hardness models (Arata- α , Terasaki, Yurioka) are evaluated, and calculated hardnesses are compared to measured values in chapter 4. The validity and accuracy of the microprocessor software for predicting the HAZ hardness of a weld is evaluated in chapter 5. In addition, predicted cooling times $\tau_{8/5}$ and hardnesses from the first generation microprocessor method of Trauttmansdorff are compared to predicted values from the microprocessor method suggested in this thesis. The performance and limitations of the microprocessor method are contained in the discussion section (in chapter 6). Chapter 7 contains the conclusions.

Figure 1.1 Schematic time-temperature representations of points in the neighborhood of a weld

Chapter 2

A QUALITATIVE DESCRIPTION OF THE WELD COOLING TIME AND HARDENING MODELS

As outlined in chapter 1, there are two independent models that must be established and combined into one system in order to predict HAZ hardness via microprocessor in the general case for a wide range of welding conditions and base material chemistries. The first is a cooling time model and the other is a hardening model. The methods available for calculating $t_{8/5}$ are based on the conventional theory of moving heat sources first presented by Rosenthal [21]. The welding parameters (voltage, current, welding speed and efficiency of the welding process) and the base material thermal properties (thermal conductivity and volumetric heat capacity) are submitted to the Rosenthal theory for this calculation. On the other hand, the HAZ hardening models are based on the chemical composition of base metal. When the chemical composition is submitted to a hardening model, a characteristic hardness curve is generated such as that shown in Figure 2.1. The $t_{8/5}$ calculated from the cooling time model is then compared to the characteristic hardening curve to predict HAZ hardness. A schematic diagram to this effect is shown in Figure 2.1 and is dealt with in detail in this chapter.

3.1 Cooling Time Model

In the Rosenthal model the heat source is approximated as either a point (shallow welding technique) or a line (deep welding technique) (Figure 2.2) moving across the workpiece at the welding speed v . The temperature field around the heat source is transient as it runs onto the workpiece but it soon reaches a state termed quasi-stationary. The quasi-stationary state can be visualized in terms of isotherm surfaces surrounding the heat source. Such surface isotherms are shown in Figure 2.2. If the workpiece is thin the isotherms extend through the plate as sort of pear shaped cylindrical surfaces. The molten zone is defined by the melting point isotherm. The width of the fusion zone corresponds to the maximum width of the melting point isotherm. At the same time, the HAZ width is defined by the maximum width of the critical temperature isotherm (723°C). The isotherm surfaces expand initially as the heat source

runs onto the workpiece. Thereafter, they grow to a size that remains constant throughout most of the welding process. At the same time, they move through the workpiece stationary with respect to the heat source. The process is known as a quasi-stationary.

The thermal history of a fixed point adjacent to the weld can be determined if the isotherm surfaces are known. Consider, for example, a point on the centerline of a weld well in front of the heat source. It is initially at ambient temperature. The temperature increases as the isotherms pass over this point. If the isotherm spacing is known and since they move with the heat source at the welding speed v the time required for each one to pass the fixed point can be calculated. In this way a time-temperature history for the point in question can be calculated from which cooling rates, cooling times, and other relevant thermal parameters can be calculated.

In fact, the isotherms can be calculated from the Rosenthal theory of moving heat sources [21]. It is assumed that there is no heat loss from the surface by radiation or convection and that the heat transfer mechanism is one only of conduction away from the heat source in the workpiece. For a shallow penetration weld (approximated by a point source) heat moves outward from the source in all directions including the through the thickness (Figure 2.2b). The heat transfer in this case is said to be three-dimensional (3D). It should, however, be noted that this is three-dimensional in semi-space since heat is not conducted above the surface of the workpiece. If the workpiece is thin (Figure 2.2a) heat from the source quickly saturates the through thickness direction and it then moves outward parallel to the plane of the workpiece. Heat flow in this case is said to be two-dimensional (2D). In addition, a deep penetration weld (Figure 2.2b) defined as a weld of $h/w > 10$, where h is the fusion zone penetration depth and w is the fusion zone width, is said to always be 2D as the area available for conduction parallel to the workpiece surface is much greater than that available for conduction perpendicular to the workpiece.

According to the Rosenthal theory the temperature distribution around the heat source is as follows

for 2D heat flow

$$T = T_a + \frac{Q}{2\pi K h} e^{-\frac{v r}{2\lambda}} K_0\left(\frac{v r}{2\lambda}\right) \quad (1)$$

for 3D heat flow

$$T = T_0 + \frac{Q}{4\pi K} e^{-\frac{u\xi}{2\lambda}} \frac{e^{-\frac{u^2 r^2}{4\lambda}}}{r} \quad (2)$$

where

ξ =the coordinate distance in front of the heat source (Figure 2 2c)-the ξ, y, z axes system moves with the heat source $\xi = x - vt$

r =the radial distance from the heat source (mm)

$$r = \sqrt{\xi^2 + y^2} \quad (2D)$$

$$r = \sqrt{\xi^2 + y^2 + z^2} \quad (3D)$$

t =time (s)

T =temperature ($^{\circ}C$)

Q =the heat input rate (J/s)

K =the thermal conductivity of the material (J/mm $^{\circ}C$ s)

h =is the weld depth (mm)

C_p =the volumetric specific heat capacity (J/mm³ $^{\circ}C$)

v =the welding speed (mm/s)

λ =the thermal diffusivity (mm²/s), $\lambda = \frac{K}{C_p}$

T_0 =preheat temperature ($^{\circ}C$)

K_0 =a Bessel function of second kind and zero order

Implicit in these relationships are several assumptions. The point and line heat sources are clearly gross assumptions since real welding arcs and other sources occupy considerable space. As mentioned above, it is assumed (at least in the most basic treatment presented here) that there is no surface transfer. The workpieces are assumed to be infinite in ξ, y (2D) and in ξ, y, z (3D). The temperature is assumed infinite at $r=0$, clearly not the case in reality. The thermal constants K, C_p, λ are assumed independent of temperature (a linear solution to the transient heat flow problem).

Figure 2.1 Schematic flow chart for predicting weld HAZ hardness

Figure 2.3 (a) Idealised point heat source used to simulate a shallow penetration weld (b) Idealised line heat source used to simulate a deep penetration weld (c) Coordinate system for two-dimensional heat flow calculations

While the assumptions give rise to considerable doubt about the accuracy of the Rosenthal solution, relationships 1 and 2 are basic and provide a good framework for discussion of the heat transfer during the welding process. In addition, under some conditions (generally areas remote from the heat source where temperatures are lower) relationships 1 and 2 provide a quite reasonable description of the isotherm positions.

2.1.1 Heat Input Rate and Energy Input Rate

The energy input supplied by a typical welding unit can be calculated according to the following:

$$E = VI \quad (3)$$

where

E =energy input rate (J/s)

V =welding voltage ($Volts$)

I =welding current ($Amperes$)

To account for heat losses in the heat source itself (i.e. not all heat supplied by the unit reaches the workpiece) the energy input must be multiplied by an efficiency term:

$$Q = \eta E \quad (4)$$

where

Q =net heat input rate (J/s)

η =efficiency of welding process (%)

In principle, the efficiency is defined as the ratio of the energy absorbed by the workpiece to the energy delivered by the welding unit. The primary loss mechanism is intense radiation from the welding arc itself although resistance (joule) losses in the workpiece does account for some of the difference. Efficiencies are measured by standard calorimetric techniques and are found to vary with the process. The most commonly accepted welding efficiencies from the work of Christensen [22] and from the investigation of Yurioka [2] are listed in Table 2.1.

Table-2.1**Weld Efficiency Values**

Process	Efficiency (%)
Shielded Metal Arc Weld (SMAW)	80
Submerged Arc Weld (SAW)	95
Gas Metal Arc Weld (GMAW)	40
Gas Tungsten Arc Weld (GTAW)	70
Electron Beam Weld (EBW)	85

2.1.2 Thermal Properties

One of the difficulties with the Rosenthal relationships is selecting mean thermal properties. In fact, the thermal properties (K , λ , and C_p) are quite temperature sensitive (Figure 2.3) [23] and yet mean values must be selected for the Rosenthal calculations. In principle, a non-linear relationship could be used that would take the variation of the thermal properties with temperature into account. However, this is complex in practice and only done when the numerical methods (finite element and finite difference schemes) are used. Several mean values for thermal conductivity and volumetric heat capacity have been suggested by various authors. In this thesis, the thermal constants are taken from the work of Yurioka [2] as shown in Table 2.2. This is justified in chapter 6.

Figure 2.3 Temperature dependence of thermal conductivity and volumetric specific heat

Table-2.2

**Thermal Properties for Calculating Cooling Time
between 800 and 500°C**

Welding process \ Thermal property	SMAW	SAW	GMAW	GTAW	EBW
Thermal conductivity, K ($J/mm \cdot ^\circ C \cdot s$)	0.025	0.025	0.025	0.025	0.041
Thermal diffusivity, λ (mm^2/s)	4.20	4.20	4.20	4.20	9.10
Surface conductance at weld, α_w ($J/mm^2 \cdot ^\circ C \cdot s$)	8.37×10^{-5}	4.18×10^{-6}	8.37×10^{-5}	8.37×10^{-5}	8.37×10^{-5}
Surface conductance at plate, α_p ($J/mm^2 \cdot ^\circ C \cdot s$)	8.37×10^{-5}	8.37×10^{-5}	8.37×10^{-5}	8.37×10^{-5}	8.37×10^{-5}

* Low α_w due to covered flux in SAW

2.2 Predicting Microstructure

In a weld, the material in the HAZ transforms to austenite and subsequently decomposes into various microstructures such as martensite, bainite, pearlite and ferrite. In principle, these microstructures can be predicted by superimposing a cooling curve calculated with the appropriate Rosenthal relationship on a CCT (continuous cooling transformation) diagram as shown in Figure 2.4. However, generating the entire cooling curve and applying it to a CCT diagram is not easy in practice. It has, therefore, become customary to deal with one single cooling parameter such as a cooling rate or cooling time. In fact, in recent years the cooling time between 800 and 500°C ($\tau_{8/5}$) has become almost universal insofar as predicting HAZ hardness is concerned. The Rosenthal

relationships can be manipulated to obtain explicit expressions for $\tau_{8/5}$ (2D) and $\tau_{8/5}$ (3D). These are outlined in chapter 3 and they are used throughout this thesis for the discussion of HAZ hardening.

Although cooling time calculations apply only to the weld centerline, it has been shown that there is little difference between this cooling time and the cooling time in the coarse grained HAZ for a wide range of welding conditions [9]. This centerline cooling rate calculation is used for both FZ and HAZ hardness calculations.

2.3 Hardening Model

Instead of applying the entire cooling curve or the cooling time $\tau_{8/5}$ to a CCT diagram to predict microstructure and hardness, Japanese researchers have suggested that hardness is a unique function of cooling time $\tau_{8/5}$. They suggest that there is a "*characteristic hardness curve*" (Figure 2.5) for each steel (VHN vs. $\tau_{8/5}$). All of the hardening models are used to generate the characteristic hardening curve. A cooling time is then calculated from the welding parameters, applied to the characteristic hardness diagram and a HAZ hardness, thereby, predicted. The hardening models are themselves generated by regression analyses from a large number of HAZ hardness measurements.

Figure 2.4 Time-temperature weld curves superimposed on the continuous cooling transformation (CCT) diagram.

Figure 2.5 Schematic representation of the characteristic hardening curve (τ is the cooling time from 800 to 500°C)

Chapter 3

MODELS FOR CALCULATING COOLING TIMES

Four conventional models are available for calculating the cooling time $\tau_{8/5}$ of a weld. They are the Adams-Bibby model, the Chakravarti model, the Adams-2.5D model and the Kohira model. In addition, numerical models could be used but are lengthy and not yet considered appropriate for a small hand-held microprocessor unit. They are, therefore, not dealt with in this investigation. The theory of each model is reviewed briefly and the accuracy is evaluated by comparing to measured values in this chapter.

3.1 Adams-Bibby Model

The Adams-Bibby model was the method used to calculate $\tau_{8/5}$ in a previous microprocessor system proposed by Trauttmansdorff. This model is a combination of Adams' relationship for calculating $\tau_{8/5}$ and Bibby's principle for identifying whether a two-dimensional or a three-dimensional heat flow model should be applied. Based on the Adams relationships, the $\tau_{8/5}$ can be calculated by following equations:

For 3D heat flow

$$\tau_{3D} = \left(\frac{1}{2\pi K}\right)\left(\frac{Q}{v}\right)\left[\left(\frac{1}{500 - T_o}\right) - \left(\frac{1}{800 - T_o}\right)\right] \quad (5)$$

For 2D heat flow

$$\tau_{2D} = \left(\frac{1}{4\pi K C_p}\right)\left(\frac{Q}{v h}\right)^2 \left[\left(\frac{1}{500 - T_o}\right)^2 - \left(\frac{1}{800 - T_o}\right)^2\right] \quad (6)$$

where

τ_{2D} = 2D cooling time from 800°C to 500°C (s)

τ_{3D} = 3D cooling time from 800°C to 500°C (s)

K = thermal conductivity ($J/s \text{ mm } ^\circ C$)

C = specific heat ($J/Kg \text{ } ^\circ C$)

ρ = density of the workpiece (Kg/mm^3)

Q = heat input rate (J/s)

v = welding speed (mm/s)

h = plate thickness (mm)

T_o = preheat temperature ($^\circ C$)

The heat input rate is calculated from the relationship

$$Q = \eta VI \quad (7)$$

Using Equations 5 and 6 to obtain a $\tau_{8/5}$, it is necessary to decide whether to apply a 2D or 3D heat flow analysis. Bibby's principle states that: "Hardness values are calculated assuming first 2D heat flow and then 3D heat flow. The appropriate hardness is the lower of the two calculated values." It implies that the cooling time $\tau_{8/5}$ used to calculate FZ or HAZ hardness should be the larger value (τ_{2D} or τ_{3D}). The Adams-Bibby model is summarized in the flow chart as shown in Figure 3.1. A computer program has been assembled to calculate the appropriate $\tau_{8/5}$ as shown in appendix A.

3.2 Chakravarti Model

An independent relationship for calculating $\tau_{8/5}$ has been proposed by Chakravarti [8]. This is shown as Equation 8:

$$\tau_{8/5} = 4.125 \times 10^{-4} \left[\frac{(VI)^{1.235}}{v^{0.765}} \right] + 0.037T_o - 1.71 \quad (8)$$

However, it is worth noting that this is an empirical relationship generated by a regression analysis from a number of measured cooling times $\tau_{8/5}$. The measured cooling times were taken from cooling curves of submerged arc bead on plate welds where the plate thickness is some 75mm. This implies that all the experiments were conducted under 3D heat flow conditions and it probably does not apply where the heat flow is two-dimensional.

In this relationship there are no thermal properties involved in the cooling time calculation. This, in turn, considerably simplifies the task of calculation. A computer program of Chakravarti relationship is contained in Appendix B.

Figure 3.1 Flow chart of the Adams-Bibby model for calculating cooling time between 800 and 500°C

3.3 Adams-2.5D Model

The Adams-2.5D model should in principle be better than the previous two since it treats the 2.5D region quantitatively rather than approximating it as either 2D or 3D (see Figure 3.2). The 2.5D cooling region is identified by calculation in this method. The traditional Rosenthal 3D relationship is then modified to obtain a more accurate $\tau_{8/5}$ in this region. A modified Adams method is described as follows [12].

For a given set of welding conditions, a relative thickness (H_r) is calculated according to

$$H_r = \frac{C\rho h^2(T - T_o)}{Q/v} \quad (9)$$

where

H_r = relative thickness (mm)

T = temperature (taken as 650°C i.e. midway between 800 and 500°C)

If the value of relative thickness is in the range of 0.3 and 1.0, i.e. $0.3 < H_r < 1.0$, then the heat flow is considered as 2.5D and $\tau_{8/5}$ is calculated by Equation 10:

$$\tau_{2.5D} = \left(\frac{1}{C_r}\right)\left(\frac{1}{2\pi K}\right)\left(\frac{Q}{v}\right)\left[\left(\frac{1}{500 - T_o}\right) - \left(\frac{1}{800 - T_o}\right)\right] \quad (10)$$

where

$\tau_{2.5D}$ = 2.5D cooling time from 800 to 500°C (s)

C_r is defined as the ratio of the cooling time on thick plate to the cooling time on finite plate and can be obtained from Figure 3.3 for a calculated relative thickness. On the other hand, Table 3.1 which is summarized from Figure 3.3 can also be used to obtain the value of C_r by interpolation. If the value of relative thickness is greater than 1.0, then it is considered to be 3D heat flow and $\tau_{8/5}$ is calculated by Equation 5. On the other hand, if H_r is lower than 0.3, $\tau_{8/5}$ is obtained by Equation 6 for 2D heat flow. This model is summarized in the flow chart as shown in Figure 3.4. A computer program of Adams-2.5D model is contained in Appendix C.

Figure 3.2 Schematic diagram to show 2.5D transition zone
(linear heat input (J/mm) constant)

Figure 3.3 Relation between plate thickness and cooling time between 800 and 500°C

Table-3.1

Summary of C_r Values Corresponding to Relative Thickness

$\frac{C_r h^3 (T - T_o)}{Q/v}$	C_r
0.3	0.30
0.4	0.43
0.5	0.63
0.6	0.76
0.7	0.85
0.8	0.91
0.9	0.94
1.0	0.97

Figure 3.4 Flow chart of the Adams-2.5D model for calculating cooling time between 800 and 500°C

3.4 Kohira Model

While the Adams model (modified here for computer implementation) is considered better than the first two described there is still some question about the calculation in the 2.5D region. The relative thickness parameter is based on empirical data and is not entirely to be trusted. In view of these difficulties, Kohira suggests a general relationship valid for all heat flow morphologies (2D, 2.5D and 3D). The "mirror image" technique is used to generate the time-temperature history of weld applied to a plate of finite thickness:

$$T = T_{\infty} + \frac{Q}{\pi K h} \exp\left(\frac{v^2 t}{2\lambda}\right) \sum_{n=0}^{\infty} A_{wn} K_0 \left[\frac{vt}{h} \sqrt{U_{wn}^2 + \left(\frac{vh}{2\lambda}\right)^2} \right] + 2(T_0 - T_{\infty}) \sum_{n=0}^{\infty} A_{pn} \left[\frac{\sin U_{pn}}{U_{pn}} - \frac{hd_p(\cos U_{pn} - 1)}{U_{pn}^2} \right] \exp\left(-\frac{\lambda U_{pn}^2 t}{h^2}\right) \quad (11)$$

where

T_{∞} = ambient temperature ($^{\circ}C$)

t = time after welding (s)

K = thermal conductivity ($J/mm \cdot ^{\circ}C \cdot s$)

λ = thermal diffusivity (mm^2/s)

α = surface conductance ($J/mm^2 \cdot ^{\circ}C \cdot s$)

d = heat transfer coefficient, $d = \alpha/K$ (mm^{-1})

d_p = heat transfer coefficient at plate (mm^{-1})

U_n = eigenvalues satisfying $\tan U_n = 2hdU_n/(U_n^2 - h^2d^2)$

U_{wn} = eigenvalues at weld

U_{pn} = eigenvalues at plate

A_n = coefficient, $A_n = U_n^2/(U_n^2 + h^2d^2 + 2hd)$

A_{wn} = coefficient at weld

A_{pn} = coefficient at plate

Although this relationship is not explicit in terms of $\tau_{8/5}$, it can be obtained by an iteration technique. However, a number of calculations are involved in this method to obtain any one $\tau_{8/5}$.

and it is not clear that it is appropriate for a small microprocessor. A computer program has been assembled as shown in Appendix D. A flow chart of this program is shown in Figure 3.5.

3.5 A Comparison of Cooling Time Models

As a preliminary means of evaluating and screening the calculation schemes, cooling time values calculated from the four models described above are compared to the experimental results of Yurioka [2]. These results are used because they include a wide range welding conditions from low heat input welds to high heat input welds with a fixed plate thickness of 20 mm. This gives rise to 2D, 2.5D and 3D heat flow conditions. The various calculated cooling times $\tau_{8/5}$ are listed in Table 3.2. It can be seen from Figure 3.6a that the calculated results of Adams-Bibby model are very close the measured data for small cooling times $\tau_{8/5}$, but seems to run into difficulty as the $\tau_{8/5}$ increases ($\tau_{8/5} > 20s$). Similarly, there seems to be a problem with the Chakravarti model (Figure 3.6b) as large deviations occur in the long cooling time $\tau_{8/5}$ regions. On the other hand, the Adams-2.5D and the Kohira models give better calculated results over a wider range of cooling times as shown in Figure 3.6c and d.

In view of the obvious difficulties with the Adams-Bibby and Chakravarti methods, the investigation centered on a comparison of the Adams-2.5D model and the Kohira model for a wide range of welding conditions and plate thicknesses. The experimental results are mainly taken from independent investigations presented by Adrichem [14] and the AMCA Corporation [10], together with some measurements from Yurioka [2]. The plate thicknesses were from 12.7 to 50.8mm which covers most of the range found in practice. In the mean time, the heat inputs varied from 0.803 to 5.11 KJ/mm which represents a wide range welding conditions. Figure 3.7 plotted as measured cooling time $\tau_{8/5}$ versus calculated cooling time $\tau_{8/5}$ shows that the results of the Kohira model are less scattered than the results of the Adams-2.5D model. In particular, the Kohira model calculated cooling times $\tau_{8/5}$ are much closer to the measured values in the long cooling time region ($\tau_{8/5} > 20s$).

The Kohira model and Adams-2.5D model can be compared on a statistical basis. It is seen in Table 3.3 that the calculated values of Kohira model are on average 11% higher than measured values together with $\pm 21\%$ standard deviation, while the calculated Adams-2.5D cooling time $\tau_{8/5}$ exceeds the measured values by $14\% \pm 34\%$. This strongly supports using the Kohira model where

computer facilities exist. There is, however, no question that the Kohira model is considerably more complex and requires several times the computer capacity required by the Adams model.

Based on the accuracy analysis of four cooling time $\tau_{8/5}$ calculation models, the Kohira model is selected for use in the hand-held pocket computer. This is described in chapter 5 in this thesis.

Figure 3.5 Flow chart of the Kohira model for calculating cooling time between 800 and 500°C

Figure 3.6 Calculated cooling time $t_{9/5}$ plotted against measured values (a) Adams-Bibby model (b) Chakravarti model (c) Adams-2.5D model (d) Kohira model (experimental data taken from source [2])

Figure 3.7 Calculated cooling time $\tau_{3/5}$ of Kohira model and Adams-2.5D model plotted against measured values from all sources [2,10,14]

Table-3.2

**Comparison of Cooling Time Models for
Calculating $t_{8/5}$**

Welding Conditions	Preheat Temperature (°C)	Cooling Time between 800 and 500°C (s)				
		Measured	Adams-Bibby	Chakravarti	Adams-2.5D	Kohira
V=24volts I=120Amps v=3.58mm/s	20	3.1	3.3	1.9	3.3	3.1
	100	4.1	4.4	4.9	4.4	4.1
	200	6.4	6.8	8.6	6.8	6.3
V=25volts I=170Amps v=2.50mm/s	20	7.0	6.9	5.2	6.9	6.9
	100	9.5	10.3	8.2	9.7	9.0
	200	14.9	20.4	11.9	15.9	14.4
V=29volts I=285Amps v=1.83mm/s	20	24.6	46.7	16.9	39.5	30.7
	100	37.9	72.9	19.9	67.3	44.7
	200	50.2	144.3	23.6	144.3	70.5

* Experiment was conducted by SMAW

Table-3.3

**Difference between Predicted (Adams-2.5D and Kohira models)
and Measured Cooling Time $t_{8/5}$ from All Sources**

Predicting model	Adams-2.5D	Kohira
Difference *	14 % ± 34%	11 % ± 21%

* Difference is average difference together with standard deviation

Chapter 4

MODELS FOR PREDICTING HARDNESSES

In view of the importance of predicting hardness in practice, several independent models have been proposed to accomplish this purpose. The Bastien model [18], the Arata- α and β models [3], the Beckert model [19], the Seyffarth model [20], as well as the recently developed Terasaki model [1] and Yurioka model [2] are all presented to predict HAZ hardness of a weld in terms of the cooling time $\tau_{8/5}$ and the chemical composition of the workpiece. As mentioned in chapter 1, the first three models were compared by Chong [4] and the Arata- α model was suggested as the best among those models proposed before 1980. In this chapter, the theory of Arata- α model, the Terasaki model and the Yurioka model are briefly described. The accuracy of these three hardness models are compared with one another and with measured values from experiments for a wide range of steels and welding conditions.

4.1 Arata- α Model

As discussed in chapter 2 the maximum hardness of the HAZ can be estimated from a welding CCT diagram. Figure 4.1(a) shows a typical welding CCT diagram and (b) is a CCTSH (continuous cooling transformation structure hardness) diagram showing the relationship between hardness and cooling time $\tau_{8/5}$ obtained from (a). In Figure 4.1(a) τ_{M100} and τ_{M0} indicate the critical cooling times (from 800 to 500°C) for transformation to 100% martensite and 0% martensite, respectively. It is clear from Figure 4.1(b) that the HAZ hardness is closely connected with the quantity of martensite in the structure. The hardness is almost a constant value in the region of 100% and 0% martensite, but drops sharply between 100% and 0% martensite.

Therefore, two assumptions were made by Arata et al [3] to obtain an approximate CCTSH curve as shown in Figure 4.2.

- (i) The hardness saturates at $\tau < \tau_{M100}$ with a hardness value at τ_{M100}
- (ii) In the region of $\tau > \tau_{M100}$ the hardness decreases exponentially passing through point B and is asymptotic with $\tau \rightarrow \infty$

The characteristic hardness curve shown in Figure 4.2 is an approximation to the CCTSH curve (actual hardness curve). A and B in the Figure represent the critical points for 100% and 0% martensite, respectively.

Figure 4.1 Relationship between welding CCT diagram and hardness curve (a) welding CCT diagram (b) welding CCTSH (Continuous Cooling Transformation Structure Hardness) diagram

Figure 4.2 The characteristic hardness curve used to approximate the welding CCTSH curve

To generate the characteristic hardness curve, it is necessary to calculate the critical points (i.e. $H_v(r_{M100}) - r_{M100}$, $H_v(r_{M0}) - r_{M0}$). Steels are classified into conventional steels (C, Si, Mn type steels) and high strength (HT) steels. Alloying elements other than C, Si and Mn are contained in amounts less than 0.1 w/o in conventional steels. There are separate relationships for each category to calculate characteristic values as follows:

(a) The characteristic values for conventional steels:

A-characteristic value:

$$H_v(r_{M100}) = 835C + 287 \quad (12)$$

$$\log(r_{M100}) = 2.55\left(C + \frac{Mn}{6.3} + \frac{Si}{3.6}\right) - 0.92 \quad (13)$$

B-characteristic value:

$$H_v(r_{M0}) = 273\left(C + \frac{Mn}{13} + \frac{Si}{9.7}\right) - 133 \quad (14)$$

$$\log(r_{M0}) = -0.37\left(C - \frac{Mn}{1.1} - \frac{Si}{0.44}\right) + 1.02 \quad (15)$$

(b) The characteristic value for HT (high strength) steels:

A-characteristic value:

$$H_v(r_{M100}) = 835C + 287 \quad (16)$$

$$\log(r_{M100}) = 5.9\left(C + \frac{Mn}{19} + \frac{Si}{14} + \frac{Ni}{37} + \frac{Cr}{19} + \frac{Mo}{9.1} - \frac{V}{49} + \frac{B}{0.31}\right) - 1.13 \quad (17)$$

B-characteristic value:

$$H_v(r_{M0}) = 500\left(C - \frac{Mn}{38} - \frac{Si}{68} - \frac{Ni}{45} + \frac{Cr}{9.0} + \frac{Mo}{9.9} + \frac{V}{2.1} + \frac{B}{0.48}\right) + 153 \quad (18)$$

$$\log(\tau_{M0}) = -0.2\left(C - \frac{Mn}{4.3} - \frac{Si}{0.4} - \frac{Ni}{0.58} + \frac{Cr}{0.45} - \frac{Mo}{0.49} + \frac{V}{240} - \frac{B}{0.0024}\right) + 1.60 \quad (19)$$

where

$H_v(\tau_{M100})$ = hardness of 100% martensite (VHN)

$H_v(\tau_{M0})$ = hardness of 0% martensite (VHN)

τ_{M100} = cooling time between 800 and 500°C for 100% martensite transformation (s)

τ_{M0} = cooling time between 800 and 500°C for 0% martensite transformation (s)

Chemical composition is in weight %

Arata et al suggested that the characteristic curve (see Figure 4.2) between the two critical points A and B can be generated by Equation 20:

$$H_v = \frac{b}{e^{\log(\tau+a)}} + N \quad (20)$$

where

τ = cooling time between 800 and 500°C for a given weld (s)

N = numerical constant

150 for conventional steels

160 for high strength steels

a, b = constants in the Arata- α relationship

If $\tau \leq \tau_{M100}$ (i.e. fully martensite)

$$H_v(\tau_{M100}) = 835C + 287 \quad (21)$$

The constants a and b in Equation 20 are calculated by:

$$a = \frac{\tau_{M100} [\log^{-1}(\ln \frac{H_1}{H_1^*})] - \tau_{M100}}{1 - [\log^{-1}(\ln \frac{H_1}{H_1^*})]} \quad (22)$$

$$b = H_1 \exp[\log(\tau_{M100} + a)] \quad (23)$$

where

$$H_1 = H_v(\tau_{M100}) - N$$

$$H_2 = H_v(\tau_{M0}) - N$$

A computer program for the Arata- α model is contained in appendix E to handle the lengthy calculations involved. The flow chart of this program is shown in Figure 4.3. This was the model selected by Trauttmansdorff for use in the original microprocessor method for predicting welding HAZ hardness. However, it is not clear that it is the most accurate model. It should also be noted that the chemical limitations for the Arata- α model are as follows (Table 4.1). Since carbon is limited to contents greater than 0.07% the Arata- α method cannot, in principle, be used for the new microalloy steels. This is, in fact, a considerable disadvantage because conventional steels have been replaced by microalloy steels in many instances. At the same time, the microalloy steels are destined to be the prime pipeline, transportation, offshore and ship plate materials, a very large market indeed.

Table—4.1
Limitations in Chemical Composition
of Arata- α Model

Chemical Composition	Weight %
C	0.07-0.53 %
Mn	0-1.50 %
Si	0-0.60 %
Ni	0-3.50 %
Cr	0-1.50 %
Mo	0-0.60 %
V	0-0.15 %
B	0-0.01 %

Figure 4.3 Flow chart of the Arata- α model for predicting HAZ hardness

4.2 Terasaki Model

Instead of calculating the critical point values A and B in Arata- α model, Terasaki proposed two simple explicit relationships for generating the characteristic hardness curve. These relationships shown as Equations 24 and 25 were derived by a stagewise multiple regression analysis from extensive experimental data.

$$\tau \leq \tau_{M100}$$

$$H_v = 812C + 293 \quad (24)$$

$$\tau > \tau_{M100}$$

$$H_v = (992C - 230C_{eq} + 250) \exp\left\{-\frac{3\tau_{8/5}}{310C_{eq}}\right\} + 188C_{eq} + 80 \quad (25)$$

where

H_v = predicted hardness (VHN)

$$\log \tau_{M100} = 2.5C_{eq} - 1.21$$

$$C_{eq} = C + \frac{Mn}{3} + \frac{Ni}{8} + \frac{Cr}{12} + \frac{Mo}{2} + \frac{Cu}{5}$$

As can be seen from Equation 25, the maximum hardness is only related to cooling time $\tau_{8/5}$ and carbon equivalent (C_{eq}). Cooling time $\tau_{8/5}$ can be submitted as a calculated or measured value. The carbon equivalent is calculated from the chemical composition. It is an indication of the effects of carbon and alloy elements on the hardness and hardenability expressed as an equivalent amount of carbon.

The amount of calculation for predicting HAZ hardness is reduced considerably when it is compared with Arata- α model. This model is summarized in the flow chart as shown in Figure 4.4. A computer program of the Terasaki method is contained in Appendix F.

Figure 4.4 Flow chart of the Terasaki model for predicting HAZ hardness

4.3 Yurioka Model

Based on Beckert's original concepts [19] and a regression analysis performed on a number of HAZ hardness measurements, Yurioka et al proposed an alternative formulation to the Terasaki relationship for predicting weld HAZ hardness shown as Equation 26:

$$H_v = 408C + 164C_{eqI} + 183 - (389C - 149C_{eqI} + 100) \tan^{-1} \left\{ \frac{\log \tau_{8/5} - 2.822C_{eqII} + 0.262}{0.526 - 0.195C_{eqII}} \right\} \quad (26)$$

Two carbon equivalents (i.e. C_{eqI} and C_{eqII}) are included in Equation 26 to generate a characteristic HAZ hardness curve for a wide variety of steels. C_{eqI} is formulated by Equation 27 and related to the hardness of long cooling time welds, while C_{eqII} is calculated by Equation 28 and corresponds to the critical cooling time for a 100% martensite structure in the HAZ.

$$C_{eqI} = C + \frac{Si}{24} + \frac{Mn}{8} + \frac{Ni}{40} + \frac{Cr}{8} + \frac{Mo}{4} + \frac{Cu}{15} + \frac{(Nb + V)}{5} + 10B \quad (27)$$

$$C_{eqII} = C - \frac{Si}{30} + \frac{Mn}{5} + \frac{Ni}{20} + \frac{Cr}{4} + \frac{Mo}{6} + \frac{Cu}{5} + 10B \quad (28)$$

When Equation 26 is compared with Equation 25, it should be noted that the Yurioka and Terasaki models are similar except that two carbon equivalents are included in the Yurioka model and only one in the Terasaki model. Presumably this is intended as a refinement. There is, however, no reference to this in the literature. In fact, Yurioka et al do not reference the Terasaki work at all and it is not clear that they were aware of it when they generated the above formulations. A flow chart of a computer program for the Yurioka model is shown in Figure 4.5. The computer code is contained in Appendix G.

Figure 4.5 Flow chart of the Yurioka model for predicting HAZ hardness

4.4 Comparison of the Arata- α , Terasaki and Yurioka Hardness models

It is known that the empirical formulas of the Arata- α model, the Terasaki model and the Yurioka model were all derived from regression analyses. It is, therefore, not clear which model is the most accurate and best model for use in a microprocessor. To clarify this, the characteristic hardness curve generated by these models are compared for a wide range of welding conditions and steels. These steels (see Table 4.2) were selected range from low carbon ($C=0.05\%$) microalloy materials through to higher carbon machine steels ($C=0.45\%$). The steel I, II, and III are plain carbon steel. The carbon content in these steels increases from 0.15 to 0.45% with the same contents of 0.3% Si and 1.2% Mn. In the mean time, steel IV and V have the same contents of C, Si, and Mn as steel I, but the alloy content increases. This, in principle, indicates that the hardenability is increasing through steels I, IV to V. Finally, steel VI is a typical microalloy material with very low carbon content, 0.05% V and 0.05% Nb.

From Figures 4.6(a) to (f), for this series of steels, hardnesses were plotted versus cooling time $t_{8/5}$ to examine the characteristic hardness curves generated by each model. By and large, the results of the Yurioka and Terasaki models have similar characteristic hardness curves. While the Arata- α model generates different characteristic hardness curves in medium carbon and microalloy steels as seen in Figures 4.6 (c) and (f). It seems that there are some difficulties with the Arata- α model in generating the proper characteristic hardness curves for the medium carbon and microalloy steels. This is possible because the chemical composition of this steel is close to the limitations in chemical composition of Arata- α model. In plain carbon steels (Figures 4.6(a,b,c)), the predicted hardness of Yurioka model are higher than those calculated by Terasaki and Arata- α models except in the low carbon steel. In low carbon, low alloy steel, the characteristic hardness curve generated by these three hardness models are, in general, very similar as seen in Figure 4.6 (d), while in high hardenability and microalloy steels, the Yurioka model predicts lower hardness values (see Figure 4.6 (e) and (f)).

In addition to comparing characteristic hardness curves generated by the Arata- α , Terasaki and Yurioka models, the accuracy is also evaluated by comparing some 176 experimentally measured values [2,3,5,6,7,8,] against calculated values. The experimental results include a wide range carbon content and a variety of alloys which covered most of the structural, pipeline, pressure vessel and ship plate materials.

Figures 4.7 to 4.9 are the predicted hardnesses by Arata- α model, Terasaki model and Yurioka model versus measured hardnesses, respectively. Predicted values are equal to measured values along the solid line in these Figures. In general, it can be seen that there are a few more symbols down below the solid line in all diagrams. This indicates that predicted hardnesses for all three models are slightly lower than the measured hardnesses. Moreover, the Yurioka model seems to be the most accurate method for predicting HAZ hardness since there is less scatter in Figure 4.9 compared with Figures 4.7 and 4.8.

To quantify the accuracy a statistical analysis of these models was carried out. The results are shown in Table 4.3. It is clearly seen that the Yurioka model predicted the best results. The average difference (calculated-measured) is -1.9% and the standard deviation is $\pm 10\%$. The results of Arata- α model and Terasaki model are $-1.4\% \pm 13.5\%$ and $-3.4\% \pm 11\%$, respectively. Although, the average difference is smaller for the Arata- α model than for the Yurioka model, the standard deviation of Arata- α model is larger, i.e. the scatter in the results is larger (see also Figure 4.7). Therefore, the Yurioka model is considered to be the most reliable method of predicting HAZ hardness.

However, the difference in the accuracy between these three models seems is less than expected. It is surprising that the average difference between the measured and calculated HAZ hardnesses is no more than 3.5% at most and only 1.4% for the Arata- α model. In addition, the standard deviation values are similar (10 to 13.5%) and this too is surprising. Without the benefit of this analysis the Yurioka model might well be perceived to be much more refined and therefore much more accurate than the other two. This does not seem to be the case. All of these models seem to be reasonably good on average. However, larger differences from steel to steel can be expected and the characteristic hardness curves in Figure 4.6 can be used as a guide.

Based on this investigation the Yurioka model is the one selected for using in the hand-held unit. Implementation of the unit is discussed in the next section.

Table-4.2

**Chemical Composition of Six Selected Steels
Used in Comparison of Hardness Models**

Steel	C	Si	Mn	Ni	Cr	Mo	Cu	V	Nb	B
I	0.15	0.3	1.2							
II	0.23	0.3	1.2							
III	0.45	0.3	1.2							
IV	0.15	0.3	1.2		0.5					
V	0.15	0.3	1.2	1.0	0.5	0.4				
VI	0.05	0.3	1.2					0.05	0.05	

Table-4.3

**Difference between Predicted (Arata- α , Terasaki and Yurioka Models)
and Measured Hardness from All Sources**

Predicting model	Arata- α	Terasaki	Yurioka
Difference *	-1.4% $\pm$ 13.5%	-3.4% $\pm$ 11%	-1.9% $\pm$ 10%

* Difference is average difference together with standard deviation

Figure 4.6 Predicted characteristic hardness curves (Arata- α , Terasaki and Yurioka models) for typical steels ranging from a microalloy steel ($C=0.05\%$) through to a higher carbon machine steel ($C=0.45\%$) (a) steel I (b) steel II (c) steel III (d) steel IV (e) steel V (f) steel VI

Figure 4.7 Arata- α model predicted hardnesses plotted against measured values from all sources

- ◆ - experimental data taken from ref. [2]
- - experimental data taken from ref. [5]
- ⊕ - experimental data taken from ref. [3]
- ▲ - experimental data taken from ref. [6,7,8]

Figure 4.8 Terasaki model predicted hardnesses plotted against measured values from all sources

- ◆ - experimental data taken from ref. [2] + - experimental data taken from ref. [3]
- - experimental data taken from ref. [5] ▲ - experimental data taken from ref. [6,7,8]

Figure 4.9 Yurioka model predicted hardnesses plotted against measured values from all sources

- ◆ - experimental data taken from ref. [2] + - experimental data taken from ref. [3]
- - experimental data taken from ref. [5] ▲ - experimental data taken from ref. [6,7,8]

Chapter 5

MICROPROCESSOR APPLICATION

Based on the conclusions of chapter 3 and chapter 4, the Kohira model seems to be the best method for calculating cooling time $t_{8/5}$ while the Yurioka model is the best method for predicting weld HAZ hardness. These two models are combined into one system for use in a hand-held microprocessor unit (M2). The system and unit are described in this chapter.

5.1 Justification for Using of Small Computer

As mentioned in chapter 3, obtaining a $t_{8/5}$ by the Kohira model involves extensive calculations. It is impossible to perform these calculations manually. Therefore, a computer system is considered necessary to carry out all the calculations. As a result of investigating available computing systems, the recently developed hand-held pocket computer (e.g. TRS80 model PC-2 with 10K memory capacity) is recommended for this purpose. This small computer has several advantages over personal minicomputers and central computing systems. Firstly, it is relatively easy to carry. Secondly, the low price (\$265, in 1983) can be afforded by most welding shops. Thirdly, the program is in higher level languages so that it is versatile and flexible.

5.2 Program Description and Operation

An interactive program for use in the small computer has been assembled as shown in Appendix H. This program contains the Kohira model for calculating cooling time $t_{8/5}$ and the Yurioka model for predicting HAZ hardness of a weld. The detailed flow chart of this program is shown as Figure 5.1. As can be seen from Figure 5.1, the user simply follows the display on the computer and enters the chemical composition of workpiece, the cooling time $t_{8/5}$. The HAZ hardness of the weld is then displayed in a few seconds. If the cooling time $t_{8/5}$ is not known, a few more steps need to be carried out as follows. Firstly, it is necessary to identify whether the weld is a "deep weld" or not. (see section 2.1). The user enters "yes" for deep weld (i.e. EB weld) or "no" for a shallow weld (i.e. conventional arc weld). Secondly, the program requests the

user to input an efficiency for the welding process (see section 2.1.1). Appropriate arc efficiency values are contained in Table 2.1. Thirdly, the welding parameters (voltage, current, welding speed) and the plate thickness are required. Then the cooling time $t_{8/5}$ and the HAZ hardness of this weld are calculated and displayed. A detailed list of instructions for the operation of the microprocessor is contained in Table 5.1.

It should be noted that there is no preheat involved in calculating $t_{8/5}$. In other words, the term for considering preheat has been set at 20°C in the Kohira model for calculating $t_{8/5}$. This is simply because the hardness models can only be applied for ambient conditions. Therefore, a cooling time calculated with preheat does not apply to the hardness model and can be misleading.

5.3 Accuracy Evaluation

To verify the interactive program and to show that the microprocessor is accurate enough, some cooling times $t_{8/5}$ produced by TRS80 model PC-2 have been compared to $t_{8/5}$ calculated with the central computer system (CP-6), to the original author's (Yurioka, Adrichem) calculated results and to the measured $t_{8/5}$ values. It is seen in Table 5.2 that all the calculated cooling times $t_{8/5}$ are very close to one another. Differences might be expected because there are no less than three series (one inside another) in the Kohira model and they must be truncated. Limits have been designed for the purpose but it is not clear that with the numerous calculations necessary, roundoff, and overall accuracy limitations in the small unit could accumulate to limit the accuracy of the calculated hardness. Although, there are some small differences between $t_{8/5}$ calculated with the CP-6 and those calculated with the TRS-80, they are still acceptable. Small differences probably occur, because there is less computer roundoff with the CP-6 system.

At the same time, several steels were selected for study and are contained in Table 5.3. The hardness values calculated by TRS80, CP-6 and original author together with those measured hardnesses are compared in Table 5.4 for a fixed cooling time $t_{8/5}$. There is almost no difference in the hardnesses calculated by these three systems. In effect, the hardness calculation with the Yurioka model are not lengthy for the TRS80 and there is little error encountered by roundoff.

Figure 5.1 Flow chart of microprocessor method M2 for predicting HAZ hardness

Table-5.1

**Instructions for Operating Microprocessor M2
Hardness Program**

- (1) Power the unit (on switch)
- (2) Check that the computer is in run mode, if it is not in run mode then press "mode" button until the run mode indicator is displayed
- (3) Type RUN and press "ENTER" button.
- (4) Follow the instruction shown on the display; input chemical composition and press "ENTER" after each entry, input "0" if component is not contained in the composition.
- (5) Enter cooling time $\tau_{8/5}$ (can be a measured value) when requested or "0" if it is not known.
- (6) Decide whether the weld under consideration is a "deep" weld (i.e. FZ depth to width ratio > 10); type "YES" or "NO" to answer the question, then press "ENTER" button.
- (7) Input welding parameters and plate thickness as requested by the display, follow each entry by pressing "ENTER"
- (8) Cooling time $\tau_{8/5}$ (s) and hardness (VHN) are output on the display
- (9) If further calculations are required using the same steel (i.e. other welding parameters) press "ENTER" to start from step 5. If a different steel is to be considered then type RUN and start from step 3

5.4 Comparison of Interactive Programs for The Two Microprocessor Methods

As described previously the first microprocessor method (M1) proposed by Trauttmansdorff contains the Adams-Bibby model for calculating cooling time $t_{8/5}$ and the Arata- α model for predicting HAZ hardness, while the microprocessor method (M2) presented in this thesis uses the Kohira model to calculate cooling time $t_{8/5}$ and the Yurioka model to predict the HAZ hardness of a weld. It has been shown in chapter 3 that the Kohira model is the most accurate method of calculating $t_{8/5}$. At the same time, it is shown in chapter 4 that the Yurioka model is the most accurate method for predicting HAZ hardness. As a consequence, it is clear that microprocessor method M2 is more reliable than method M1.

However, the selected welding conditions and steels contained in Table 5.2 and 5.3 are used again in here to compare the method M2 and M1. As can be seen from Table 5.5, the calculated cooling times $t_{8/5}$ using M2 are, by and large, closer to the experimental data than the results using M1. In the mean time, the predicted HAZ hardnesses using M2 show a better agreement with the measured hardnesses than the results using M1 (Table 5.6). In particular, M1 does not predict a reasonable HAZ hardness for steel V (microalloy material). This is simply because the chemical composition of steel V is beyond the range of Arata- α model and this can be a major drawback of M1 in practice.

In addition, the thermal properties used in M2 are different than those contained in model M1 as shown in Table 5.7. Inasmuch as the thermal properties suggested by Yurioka et al are considered to be better (see discussion-chapter 6) than those of Trauttmansdorff, the model M2 is once again supported.

The only disadvantage of M2 is that much more computing power is required to complete a calculation. In some cases as much as 2 minutes CPU time on the TRS80 are needed to calculate a hardness with M2 whereas the answer is almost instantaneous with the Trauttmansdorff M1 system. This is due to extensive series and eigenvalues evaluation required for the $t_{8/5}$ involved in this program. The approaches used to reduce computing time are discussed in next chapter.

Table-5.2

**Calculated Cooling Times to Demonstrate the Reliability of
the Computer Cooling Time Software**

Welding conditions (no preheat $T_0 = 20^\circ\text{C}$)	Thickness h (mm)	Cooling time $\tau_{8/5}$ (s)			
		Measured	Original author	CP6	M2
SMAW 24V-120A-3.58mm/s	20	3.1	3.0	3.1	3.2
SMAW 25V-170A-2.50mm/s	20	7.0	7.0	6.9	6.9
SMAW 29V-285A-1.83mm/s	20	24.6	25.0	30.7	31.2
SAW 32V-510A-3.75mm/s	50.8	19.7	21.1	20.2	20.9
SAW 32V-510A-3.75mm/s	12.7	96.8	152.8	141.3	142.7

CP6-Mainframe Honeywell computer

M2-TRS80 hand held unit

Table-5.3

**Chemical Composition of Five Selected Steels
Used in Evaluation of M2 Hardness Model Software**

Steel	C	Si	Mn	Ni	Cr	Mo	Cu	V	Nb	B
I	0.04	0.23	0.55	8.76	0.04	0.01	0.03			
II	0.16	0.50	1.39	0.02	0.01		0.02			
III	0.231	0.27	1.19	0.03	0.03		0.02	0.036		0.0005
IV	0.42	0.31	0.70	1.71	0.75	0.15	0.14			
V	0.018	0.16	2.01	0.32		0.30			0.052	0.001

Table-5.4

Calculated Hardness Values to Demonstrate the Reliability of the Computer Hardness Model Software

Steel	Cooling time $\tau_{8/5}$ (s)	Hardness (VHN)			
		Measured	Original author	CP8	M2
I	7.0	332	325	317.0	316.9
II	7.0	342	348	338.4	338.3
III	7.0	386	400	411.7	411.6
IV	7.0	655	634	664.6	664.5
V	7.0	285	290	287.8	287.8

Table-5.5

A Comparison of Cooling Times Calculated with M1 and M2 for Several Welding Situations

Welding conditions (no preheat $T_0=20^\circ\text{C}$)	Thickness h (mm)	Cooling time $\tau_{8/5}$ (s)		
		Measured	M1	M2
SMAW 24V-120A-3.58mm/s	20	3.1	4.0	3.2
SMAW 25V-170A-2.50mm/s	20	7.0	10.8	6.9
SMAW 29V-285A-1.83mm/s	20	24.6	75.9	31.2
SAW 32V-510A-3.75mm/s	50.8	19.7	25.7	20.9
SAW 32V-510A-3.75mm/s	12.7	96.8	246.5	142.7

Table-5.6

**A Comparison of HAZ Hardness Values Calculated
with M1 and M2 for Several Steels**

Steel	Cooling time $\tau_{8/5}$ (s)	Hardness (VHN)		
		Measured	M1	M2
I	7.0	332	310.2	316.9
II	7.0	342	315.6	338.3
III	7.0	388	438.8	411.6
IV	7.0	655	637.7	664.5
V	7.0	285	**	287.8

** : There are no hardness values because the alloy
content is beyond the range of Arata- α model.

Table-5.7

Thermal Properties Used in Microprocessors M1 and M2

Thermal properties	Microprocessor M1	Microprocessor M2
Thermal conductivity, K ($J/mm \cdot ^\circ C \cdot s$)	0.0205	0.025
Thermal diffusivity, λ (mm^2/s)	4.55	4.20

Chapter 6

DISCUSSION

As a result of the comparative study in chapter 3, 4 and 5, the Kohira and the Yurioka models have been selected for calculating cooling time $\tau_{8/5}$ and for predicting HAZ hardness in the new microprocessor method. As a result, there is considerable improvement over the previous microprocessor method. Firstly, cooling time $\tau_{8/5}$ can be calculated more precisely with the Kohira model rather than the Adams-Bibby model and without 2D-3D transition problems. Secondly, more accurate predicted HAZ hardnesses can be obtained by submitting chemical composition of workpiece to the Yurioka model rather than the Arata- α model. Thirdly, the new method applies to low carbon microalloy steels whereas there is considerable doubt about the accuracy of the previous model for these materials.

However, without special care the computing time required on the TRS80 can approach 20 to 30 minutes. There are two main reasons for the long run time. The first is the slow computing speed of the TRS80 unit. The other is the extensive calculations involved in evaluating the eigenvalues and Bessel series for cooling time calculation. To reduce the lengthy computing time, a considerable effort was put into modifying the program as follows.

In Equation 11 the cooling time between 800 and 500 °C is obtained by subtracting cooling time to 800°C (τ_8) from cooling time to 500°C (τ_5). The difference between these two numbers is the 800-500°C cooling time. However, the cooling time cannot be calculated explicitly. It is obtained by setting T equal to 800°C in Equation 11 and guessing the cooling time τ_8 . It was realized that the closer the initial value of τ_8 to the real cooling time τ_8 , the less iterations and running time necessary to obtain the real cooling time τ_8 . The same argument applies to the cooling time to 500°C, τ_5 . To get a value as close as possible to cooling time τ_8 (τ_5), the Adams-Bibby model is employed to calculate initial values. First a saturation thickness is calculated according to the relationships suggested by Adams [24].

$$H_c = \sqrt{\frac{Q}{\nu C \rho (T - T_o)}} \quad (29)$$

where

H_c = saturation thickness (mm)

T = Temperature (taken as 650°C)

If plate thickness $h > H_c$, the heat flow is 3D and the cooling times are approximately

$$\tau_{5c} = \left(\frac{1}{2\pi K}\right) \left(\frac{Q}{\nu}\right) \left(\frac{1}{500 - T_o}\right) \quad (30)$$

$$\tau_{8c} = \left(\frac{1}{2\pi K}\right) \left(\frac{Q}{\nu}\right) \left(\frac{1}{800 - T_o}\right) \quad (31)$$

If $h \leq H_c$, the heat flow is 2D and the cooling times are approximately:

$$\tau_{5c} = \left(\frac{1}{4\pi K C \rho}\right) \left(\frac{Q}{\nu h}\right)^2 \left(\frac{1}{500 - T_o}\right)^2 \quad (32)$$

$$\tau_{8c} = \left(\frac{1}{4\pi K C \rho}\right) \left(\frac{Q}{\nu h}\right)^2 \left(\frac{1}{800 - T_o}\right)^2 \quad (33)$$

where

τ_{5c} = initial trial cooling time to 500°C

τ_{8c} = initial trial cooling time to 800°C

There are also run time savings in evaluating the Bessel function in Equation 11. Because of the small computer size, $K_o(X)$ is not available as library software. In general, it must be evaluated according Equations 34 and 35 [25], where X is the Bessel function argument:

If $0 < X \leq 2$

$$\begin{aligned} K_o(X) = & -\ln\left(\frac{X}{2}\right)I_o(X) - 0.57721566 + 0.42278420\left(\frac{X}{2}\right)^2 + 0.23069756\left(\frac{X}{2}\right)^4 \\ & + 0.03488590\left(\frac{X}{2}\right)^6 + 0.00262698\left(\frac{X}{2}\right)^8 + 0.00010750\left(\frac{X}{2}\right)^{10} + 0.00000740\left(\frac{X}{2}\right)^{12} \end{aligned} \quad (34)$$

If $2 \leq X < \infty$

$$K_o(X) = X^{-1} e^{-X} \left[1.25331414 - 0.07832358 \left(\frac{2}{X} \right) + 0.02189568 \left(\frac{2}{X} \right)^2 - 0.01062446 \left(\frac{2}{X} \right)^3 + 0.00587872 \left(\frac{2}{X} \right)^4 - 0.00251540 \left(\frac{2}{X} \right)^5 + 0.00053208 \left(\frac{2}{X} \right)^6 \right] \quad (35)$$

where

$$I_o(X) = 1 + 3.5156229t^2 + 3.0899424t^4 + 1.2067492t^6 + 0.2659732t^8 + 0.0360768t^{10} + 0.0045813t^{12}$$

$$t = \frac{X}{3.75}$$

However, it requires considerable time to evaluate $K_o(X)$ by these polynomial approximations. A further modification of K_o is proposed by Graville [26]. For an argument $X \geq 10$, $K_o(X)$ can be calculated by Equation 36:

If $X \geq 10$

$$K_o(X) = \exp(-X) \sqrt{\frac{\pi}{2X}} \quad (36)$$

In fact, most arguments are larger than 10. This has also been tested as shown in Table 6.1. There is little difference between $K_o(X)$ values calculated by Equations 35 and 36.

In general, it is not easy to identify how many terms should be summed in Equation 11. To save the computing time, the series is truncated by using one command in the program, when $A/S < 0.01\%$, where A is a new term and S is the original summation.

The eigenvalues (U_n) in Equation 11 is defined as the values satisfying Equation 37:

$$\tan U_n = \frac{2hdU_n}{(U_n^2 - h^2d^2)} \quad (37)$$

Due to the characteristics of eigenvalues they must be evaluated by iterative calculation. The initial value for iteration is important in reducing the computing time. At the same time, it can be shown that significant eigenvalues are small. Based on the concept that $\tan U_n \simeq U_n$ for small angles, the initial trial value is given by:

$$U_* = \sqrt{2hd + h^2d^2} \quad (38)$$

Furthermore, it was realized that the eigenvalues are only dependent on plate thickness and welding process. Thus, there is no need to calculate the eigenvalues again in a cooling time calculation without changing plate thickness and welding process. One command is used for this purpose to keep in memory the calculated eigenvalues and save computing time when multiple welding condition calculations are required.

Through these modifications to the program, the computing time has been considerably reduced from roughly 15 minutes to 2 minutes. Second time calculations where the plate thickness and welding process are the same, the computing time is reduced to about 1 minute. A 15 minute calculation time is too long but 1-3 minutes is considered to be acceptable in practice.

Thermal properties play a critical role in determining cooling time $\tau_{8/5}$. The thermal constants (Yurioka II) used in the new microprocessor method are shown in Table 2.2. In addition, five sets of thermal constants (Yurioka I, Yurioka II, Adams, Bibby and EB) proposed by different authors [2,10,24,27] (see Table 6.2) were investigated to determine their effect of thermal properties on cooling time $\tau_{8/5}$ calculations. Because the surface conductance is not given in sources 10 and 26, for three sets of thermal constants (Adams, Bibby and EB) it was assigned to the same value as in Yurioka II. The analysis was carried out only with the Kohira model because it has been shown to be the most accurate method for calculating $\tau_{8/5}$. Calculated cooling times were compared with measured values for a relatively wide range of welding conditions. As shown in Figure 6.1 the calculated values of $\tau_{8/5}$ using Yurioka II thermal constants are the closest to the measured values. This illustrates that the Yurioka II thermal constants are the most appropriate thermal constants for calculating cooling time $\tau_{8/5}$ among those available in the literatures. This set thermal constants has been used in the microprocessor method presented in this thesis. Furthermore, taking a view of Figure 3.7 and the statistical results in Table 3.3, it is observed that most of the calculated cooling times ($\tau_{8/5}$) are higher than the measured values. This could be improved by increasing the value of the thermal conductivity.

Table-6.1

**A Comparison of Bessel Function $K_0(X)$
Calculated with Two Different Equations**

Argument X	$K_0(X)$ Equation (35)	$K_0(X)$ Equation (36)
10	1.778×10^{-5}	1.799×10^{-5}
11	6.243×10^{-6}	6.311×10^{-6}
12	2.201×10^{-6}	2.223×10^{-6}
15	9.820×10^{-8}	9.899×10^{-8}
20	5.741×10^{-10}	5.776×10^{-10}

Table-6.2

**Various Thermal Properties for Calculating
Cooling Time between 800 and 500°C**

Thermal properties	Yurioka I	Yurioka II	Adams	Bibby	EB
Thermal conductivity, K (J/mm °C s)	0.061	0.025	0.028	0.0205	0.041
Thermal diffusivity, λ (mm ² /s)	14.6	4.20	6.36	4.55	9.10
Surface conductance at weld, α_w (J/mm ² °C s)	1.46×10^{-5}	8.37×10^{-5}	8.37×10^{-5}	8.37×10^{-5}	8.37×10^{-5}
Surface conductance at plate, α_p (J/mm ² °C s)	1.46×10^{-5}	8.37×10^{-5}	8.37×10^{-5}	8.37×10^{-5}	8.37×10^{-5}

Figure 6.1 Kohira model calculated cooling time $\tau_{3/5}$ using 5 sets different thermal constants plotted against measured values from source [2].

Thermal constants: + - Yurioka I Δ - Yurioka II ⊙ - Adams ◆ - Bibby x - EB

During the study of the Kohira method, it was noted that this model includes a consideration of surface transfer in calculating $\tau_{8/5}$. Yet the value suggested by Yurioka is in some doubt. At the same time surface heat transfer is not supposed to be very significant for 800 to 500°C cooling time (i.e. it is generally thought to be insignificant by most researchers in this field). This seems to be significant for determining $\tau_{8/5}$ cooling times of high heat input welds (i.e. long cooling time $\tau_{8/5}$) usually where preheat is used. The effect of surface heat transfer on the 800 to 500°C cooling time was investigated by decreasing surface conductance (α) from 8.37×10^{-5} to 8.37×10^{-9} ($J/mm^2 \text{ } ^\circ C \text{ } s$) for low heat and high heat input welds with and without preheat (see Table 6.3). It was also trying to set $\alpha=0$ to eliminate surface heat transfer. But due to the mathematical problem, α cannot be 0 in the Kohira model (Equation 11).

Table-6.3

**A Comparison of Calculated Cooling Time between 800 and 500°C
with Decreasing Surface Conductance**

Welding conditions	α $\tau_{8/5}$ (s)	Surface Conductance ($J/mm^2 \text{ } ^\circ C \text{ } s$)					
		8.37×10^{-5}	8.37×10^{-6}	4.18×10^{-6}	8.37×10^{-7}	8.37×10^{-8}	8.37×10^{-9}
SMAW, 24V-120A 3.58mm/s·h=20mm $T_0 = 20^\circ C$		3.1	3.3		3.3	3.4	3.5
SAW, 32V-350A 10.0mm/s·h=50.8mm $T_0 = 20^\circ C$				5.5	5.5	5.5	5.6
SAW, 32V-510A 3.75mm/s·h=12.7mm $T_0 = 20^\circ C$				142.9	148.8	152.8	152.8
SMAW, 29V-285A 1.83mm/s·h=20mm $T_0 = 200^\circ C$		70.0	126.6		147.5	162.8	181.0

As shown in Table 6.3, the welding conditions of two low heat input welds and two high heat input welds with and without preheat were selected from sources [2] and [14] for study. The calculated results corresponding to a variety of surface heat transfer coefficient are also contained in Table 6.3. Figures 6.2(a) and (b) show that cooling time $\tau_{8/5}$ increases slightly as surface transfer decreases in low heat input welds without preheat. For a weld of high heat input without preheat, the cooling time $\tau_{8/5}$ increases significantly as α decreases as shown in Figure 6.2(c). Moreover, Figure 6.2(d) shows a considerable increase in $\tau_{8/5}$ when α decreases for a high heat input and 200°C preheat weld. It would seem, therefore, that those models that do not include surface heat transfer can be in error for high heat welds or where preheat is involved.

Since the Kohira model was developed from Rosenthal's moving heat source theory, a point heat source is used to idealize the heat source of conventional arc welds. However, in reality, the heat flux of arc welding distributes in the workpiece over certain region (see Figure 6.3). By and large, this approximation for the heat source can result in considerable error. A more realistic heat source simulated by numerical analysis (such as FEM) is required to obtain more accurate cooling time $\tau_{8/5}$ calculations.

In practice, the joint configuration must be taken into account when determining the heat input to a weld. For example, comparing a butt weld and a fillet weld of equal thickness (see Figure 6.4 (a) and (b)), there are two paths for the heat to follow in the butt weld and three paths in the fillet weld. Therefore, the heat absorbed by the base plate should be only $\frac{2}{3}$ of the total heat input in a fillet weld. In other words, a correction factor ($\frac{2}{3}$) should be included in determining the heat input to the base plate.

In summary, it can be said that the microprocessor method M2 suggested in this thesis is the best yet available i.e. the calculated HAZ hardness values are more reliable than the previous method (M1) and the range of compositions that can be handled is greater. Such a microprocessor unit should be quite useful in engineering design and practice.

Figure 6.3 Kohira model calculated cooling time $t_{8/5}$ plotted against surface conductance. (a) low heat input weld, thin plate (0.8 KJ/mm) (b) low heat input weld, thick plate (1.1 KJ/mm) (c) high heat input weld, without preheat (4.4 KJ/mm) (d) high heat input weld, with preheat (4.5 KJ/mm, $T_0 = 200^\circ C$)

† Indicates the value used in this investigation

Figure 6.3 Schematic diagram of a bead-on plate weld to show the actual heat source configuration of a weld.

Figure 6.4 Schematic diagram to show the effect of joint configuration on heat flow
(a) Butt weld (b) Fillet weld.

Chapter 7

CONCLUSIONS

- (1) A comparative study of four independent models (Adams-Bibby, Chakravarti, Adams-2.5D and Kohira) for calculating cooling time $\tau_{8/5}$ shows the Kohira model is the most reliable model to use for a microprocessor M2. The calculated cooling time $\tau_{8/5}$ is on average 11% higher than measured values together with a standard deviation of $\pm 21\%$ based on a comparison with 55 experimental measurements for a wide range welding conditions.
- (2) The Yurioka model is the most accurate model for predicting HAZ hardness when compared with Arata- α and Terasaki models. A difference of approximately -1.9% on average $\pm 10\%$ has been found between the hardnesses predicted by Yurioka model and 176 measured HAZ values.
- (3) An interactive program which contains the Kohira model for calculating cooling time $\tau_{8/5}$ and the Yurioka model for predicting HAZ hardness has been assembled in microprocessor M2. This program is easy to use for predicting welding HAZ hardnesses and is recommended for design and perhaps shop practice.
- (4) Microprocessor M2 can predict more accurate HAZ hardness values than microprocessor M1. However, the time required by M2 to complete a HAZ hardness calculation is considerably more than the time required by M1.
- (5) Mean values of thermal conductivity of $0.025 \text{ J/mm } ^\circ\text{C}$ and thermal diffusivity of $4.2 \text{ mm}^2/\text{s}$ are most appropriate in calculating cooling time $\tau_{8/5}$.
- (6) While surface transfer does not significantly affect the calculating cooling time $\tau_{8/5}$ for low heat input welds, it considerably influences the calculated $\tau_{8/5}$ cooling time for high heat input welds.

Chapter 8

FUTURE WORK

- (1) Using the thermal constants suggested by Yurioka the calculated cooling times are on average some 11% high. By increasing the mean thermal conductivity somewhat (perhaps 5%) the calculated cooling times should be close to the experimental values. This should be investigated.
- (2) To precisely analyze the weld heat source, the finite element method should be employed to calculate cooling time between 800 and 500°C. A work station model combining FEM cooling time calculations and the Yurioka model is thought to have considerable potential.
- (3) There is a considerable need for a model that is capable of predicting HAZ hardness in the presence of preheat. Such a model is not available yet hardness limits often appear in engineering codes and the only means of obtaining required hardness level is by pre or post heat treatments. Such an investigation, however, is expected to be lengthy, perhaps requiring several man years of effort.

- [17] Stout R. D., *Hardness as an Index of the Weldability and Service Performance of Steel Weldments*, WRC (Welding Research Council) Bullentin 189.
- [18] Bastien P., Dollet J., Maynier Ph., *Prediction of the Structure and Mechanical Properties in the Heat-Affected Zone of High Yield Weldable Steels*, Metal Construction and British Welding Journal, Vol. 2, p. 9, January 1970.
- [19] Beckert M., Holz R., *Schweiss Technik*, Vol. 23, No. 8, p. 344, 1973
- [20] Seyffarth P., *Schweiss Technik*, Vol. 27, No. 2, p. 58, 1979.
- [21] Rosenthal D., *The Theory of Moving Sources of Heat and Its Application to Metal Treatments*, Transactions of the A.S.M.E., p. 849, November 1946.
- [22] Christensen N., Davies V. de L., Gjermundsen K., *Distribution of Temperatures in Arc Welding*, British Welding Journal, p. 54, February 1965.
- [23] Bibby M. J., Eastman K., Goldak J. A., *The Cooling Behavior of Deep Penetration Welds Undergoing Austenite-Ferrite Transformation*, Metallurgical Transactions B, Vol. 14B, p483-486, September 1983.
- [24] Adams C. M., *Heat Flow in Welding*, Welding Handbook Vol. 1, p. 80, 1976.
- [25] Abramowitz M., Stegun I. A., *Handbook of Mathematical Functions*, published by National Bureau of Standards, 1964.
- [26] Graville B. A., *The Principles of Cold Cracking Control in Welds*, published by Dominion Bridge Company, Montreal, p. 27, April 1975.
- [27] Yurioka N., Okumura M., Ohshita S., Saito S., *On the Methods Determining Preheating Temperature Necessary to Avoid Cold Cracking in Steel Welding*, IIW, Doc. XII-E-10-81.

APPENDIX A

Program Variable Description for
Adams-Bibby, Chakravarti and Adams-2.5D Models

Computer Program of Adams-Bibby Model for
Calculating Cooling Time between 800 and 500°C

Table A-1

**Program Variable Description for
Adams-Bibby, Chakravarti and Adams-2.5D Models**

AMP	Welding current (Amperes)
COOLT	Cooling time between 800 and 500°C (s)
COOLT2	Cooling time between 800 and 500°C for two-dimensional heat flow (s)
COOLT3	Cooling time between 800 and 500°C for three-dimensional heat flow (s)
CP	Volumetric specific heat capacity ($J/mm^3 \text{ } ^\circ C$)
ETA	Welding efficiency (%)
H	Plate thickness (mm)
K	Thermal conductivity ($J/mm \text{ } ^\circ C \text{ } s$)
PRET	Preheat temperature ($^\circ C$)
V	Welding speed (mm/s)
VOLT	Welding voltage (Volts)

```

C *****
C *   PROGRAM TO CALCULATE COOLING TIME BETWEEN 800 AND 500 C   *
C *                   USING ADAMS-BIBBY METHOD                   *
C *****

REAL K,ETA,CP,H,COOLT2,COOLT3,AMP,VOLT,V,PRET
DIMENSION AMP(3),VOLT(3),V(3),PRET(3)
READ (5,100) (AMP(I),VOLT(I),V(I),I=1,3)
READ (5,110) (PRET(J),J=1,3)
READ (5,120) ETA,K,H,CP
WRITE (6,130)
WRITE (6,120) ETA,K,H,CP
DO 3 I=1,3
  AAMP=AMP(I)
  AVOLT = VOLT(I)
  AV = V(I)
  AQ = AAMP * AVOLT * ETA
  WRITE (6,140)
  DO 2 J=1,3
    APRET = PRET(J)
    AK = K
    ACP = CP
    AH = H
    COOLT2 = (1/(4*3.14159*AK*ACP)) * ((AQ/(AV*AH))**2)
1    * ((1/(500-APRET)**2) - (1/(800-APRET)**2))
    COOLT3=(1/(2*3.14159*AK)) * (AQ/AV) * (1/(500-APRET)
1    -1/(800-APRET))
    WRITE (6,150) COOLT2,COOLT3
    IF (COOLT2.GT.COOLT3) GOTO 1
    WRITE (6,160) AAMP,AVOLT,AV,AQ,APRET,COOLT3
    GOTO 2
1    WRITE (6,170) AAMP,AVOLT,AV,AQ,APRET,COOLT2
2    CONTINUE
3    CONTINUE
100  FORMAT(3F10.6)
110  FORMAT(3(F5.0)) ,
120  FORMAT(3F10.2,E10.2)
130  FORMAT(7X,1HN,9X,1HK,9X,1HH,9X,2HCP)
140  FORMAT(6X,5HADAMS,10X,4HAAMP,6X,5HAVOLT,5X,2HAV,8X,2HAQ,8X,
15HADAPRET,5X,5HCOOLT)
150  FORMAT (2F10.2)
160  FORMAT(1X,2H3D,1X,9HCONDITION,3X,2F10.2,F10.5,3F10.2/)
170  FORMAT(1X,2H2D,1X,9HCONDITION,3X,2F10.2,F10.5,3F10.2/)
STOP
END

```

APPENDIX B

**Computer Program of Chakravarti Model for
Calculating Cooling Time between 800 and 500°C**


```

C *****
C * PROGRAM TO CALCULATE COOLING TIME BETWEEN 800 AND 500 C *
C * USING CHAKRAVARTI METHOD *
C *****

REAL COOLT,AMP,VOLT,V,APRET,AE
DIMENSION AMP(10),VOLT(10),V(10)
READ (5,100) (AMP(I),VOLT(I),V(I),I=1,9)
DO 1 I=1,9
    AAMP=AMP(I)
    AVOLT = VOLT(I)
    AV = V(I)
    AE = AAMP * AVOLT
    WRITE (6,110)
    READ (5,120) APRET
    COOLT = (4.125 / 10**4) * ((AVOLT * AAMP)**1.235) / (AV**.765)
1    + (0.037*APRET) - 1.71
    WRITE (6,130) AAMP,AVOLT,AV,AE,APRET,COOLT
1    CONTINUE
100    FORMAT(3F10.6)
110    FORMAT(7X,4HCHAK,10X,4HAAMP,6X,5HAVOLT,5X,2HAV,8X,2HAE,8X,
15HAPRET,5X,5HCOOLT)
120    FORMAT(F5.0)
130    FORMAT(16X,2F10.2,F10.5,3F10.2/)
    STOP
    END

```

APPENDIX C

**Computer Program of Adams-2.5D Model for
Calculating Cooling Time between 800 and 500° C**

```

C *****
C * PROGRAM TO CALCULATE COOLING TIME BETWEEN 800 AND 500 C *
C * USING ADAMS-2.5D METHOD *
C *****

```

```

REAL K,ETA,CP,H,COOLT,AMP,VOLT,V,PRET
DIMENSION AMP(6),VOLT(6),V(6),PRET(3)
READ (5,100) (AMP(I),VOLT(I),V(I),I=1,6)
READ (5,110) (PRET(J),J=1,1)
READ (5,120) ETA,K,H,CP
WRITE (6,130)
WRITE (6,120) ETA,K,H,CP
DO 12 I=1,6
  AAMP=AMP(I)
  AVOLT = VOLT(I)
  AV = V(I)
  AQ = AAMP * AVOLT * ETA
  WRITE (6,140)
  DO 11 J=1,1
    APRET = PRET(J)
    AK = K
    ACP = CP
    AH = H
    TEST = ACP * AH**2 * (650 - APRET) * AV/AQ
    IF (TEST .GT. 1.0) GOTO 7
    IF (TEST .LT. 0.314) GOTO 8
    IF (TEST .GT. 0.4) GOTO 1
    C = 0.314 + (TEST - 0.314) * (0.43-0.314)/0.114
    GOTO 10
1  IF (TEST .GT. 0.5) GOTO 2
    C = 0.43 + (TEST - 0.4) * (0.63-0.43)/0.1
    GOTO 10
2  IF (TEST .GT. 0.6) GOTO 3
    C = 0.63 + (TEST - 0.5) * (0.76-0.63)/0.1
    GOTO 10
3  IF (TEST .GT. 0.7) GOTO 4
    C = 0.76 + (TEST - 0.6) * (0.85-0.76)/0.1
    GOTO 10
4  IF (TEST .GT. 0.8) GOTO 5
    C = 0.85 + (TEST - 0.7) * (0.91-0.85)/0.1
    GOTO 10
5  IF (TEST .GT. 0.9) GOTO 6
    C = 0.91 + (TEST - 0.8) * (0.94-0.91)/0.1
    GOTO 10
6  IF (TEST .LE. 1.0) GOTO 9

```

```

7      COOLT=(1/(2*3.14159*AK))*(AQ/AV)*(1/(500-APRET)
1      -1/(800-APRET))
      WRITE (6,150) AAMP,AVOLT,AV,AQ,APRET,COOLT,TEST
      GOTO 11
8      COOLT = (1/(4*3.14159*AK*ACP))*((AQ/(AV*AH))**2)
1      *((1/(500-APRET)**2)-(1/(800-APRET)**2))
      WRITE (6,160) AAMP,AVOLT,AV,AQ,APRET,COOLT,TEST
      GOTO 11
9      C = 0.94 + (TEST - 0.9)*(0.97-0.94)/0.1
10     COOLT=(1/(2*3.14159*AK))*(AQ/AV)*(1/(500-APRET)
1      -1/(800-APRET))*(1/C)
      WRITE (6,170) AAMP,AVOLT,AV,AQ,APRET,COOLT,TEST,C
11     CONTINUE
12     CONTINUE
100    FORMAT(3F10.7)
110    FORMAT(3(F5.0))
120    FORMAT(3F10.6,E10.2)
130    FORMAT(7X,1HN,9X,1HK,9X,1HH,9X,2HCP)
140    FORMAT(6X,5HADAMS,10X,4HAAMP,6X,5HAVOLT,5X,2HAV,8X,2HAQ,8X,
15HAPRET,5X,5HCOOLT,5X,4HTEST)
150    FORMAT(1X,2H3D,1X,9HCONDITION,3X,2F10.4,F10.5,4F10.3/)
160    FORMAT(1X,2H2D,1X,9HCONDITION,3X,2F10.4,F10.7,4F10.3/)
170    FORMAT(1X,4H2.5D,1X,9HCONDITION,3X,2F10.4,F10.7,5F10.3/)
      STOP
      END

```

APPENDIX D

Program Variable Description for Kohira Model

Computer Program of Kohira Model for Calculating Cooling Time between 800 and 500°C

Table D- 1

Program Variable Description for Kohira Model

AK	Thermal diffusivity (mm^2/s)
AW	Surface conductance at weld ($J/mm^2 \cdot ^\circ C \cdot s$)
AP	Surface conductance at plate ($J/mm^2 \cdot ^\circ C \cdot s$)
AMP	Welding current (Amperes)
AI1	Initial value of cooling time to 500°C for iterative calculation (s)
AI2	Initial value of cooling time to 800°C for iterative calculation (s)
AINC	Increment of cooling time iterative calculation
BI	Initial eigenvalue for iterative calculation
BINC	Increment of eigenvalue iterative calculation
COND	Thermal conductivity ($J/mm \cdot ^\circ C \cdot s$)
COOLT	Cooling time between 800 and 500°C (s)
ETA	Welding efficiency (%)
FAC1	Factor in calculating cooling time to 500°C to avoid computer mathematical limits
FAC2	Factor in calculating cooling time to 800°C to avoid computer mathematical limits
H	Plate thickness (mm)
M	Number of summation items
N	Maximum iteration cycles for calculating cooling time
NN	Maximum iteration cycles for calculating eigenvalues
T0	Preheat temperature ($^\circ C$)
TA	Ambient temperature ($^\circ C$)
TX	Transient temperature (500°C)
TY	Transient temperature (800°C)
U	Tolerance of temperature for calculating cooling time
V	Welding speed (mm/s)
VOLT	Welding voltage (Volts)

```

C *****
C *   PROGRAM TO CALCULATE COOLING TIME BETWEEN 800 AND 500 C   *
C *                   USING KOHIRA METHOD                       *
C *****

REAL VOLT,AMP,V,TO,ATO,N,QP,NN,M,H,BI,BINC,AI1,AI2,AINC,TA,TX,
1TY,AK,ETA,COND,AW,AP
COMMON /COOLT/ VOLT(5),AMP(5),V(5),TO(5),UN(30),XUN(30),YUN(30),
1SUMXX,SUMYY,T500,T800,BI,BINC,H,AW,AP,AV,AK,COND,X,M,NN,NX,IA
2AUN,RESULT,XX,S,DIF,XA,YA,FKO,FAC1,FAC2,IB,AWN,APN,BUN,DW,DP,N
READ (5,100) ETA,COND,AK,AW,AP
READ (5,100) H,TX,TY,TA,AI1,AI2,AINC,U
READ (5,100) M,N,NN,BI,BINC,FAC1,FAC2
WRITE (6,110)
WRITE (6,120) ETA,COND,AK,AW,AP
READ (5,130) (VOLT(I),AMP(I),V(I),I=1,1)
READ (5,140) (TO(J),J=1,1)
TX1 = TX-TA
TX2 = TY-TA
DW = AW/COND
DP = AP/COND
II = 0
DO 5 IA = 1,M
  IF (IA .GT. 1) GOTO 2
  AUN = BI
  DO 1 J = 1,NN
    XA = TAN(AUN)
    YA = 2. * H * DW * AUN / (AUN**2 - H**2 * DW**2)
    DIF = ABS(XA-YA)
    IF (DIF .LE. 0.001) GOTO 4
    AUN = AUN + BINC
1  CONTINUE
2  UN(IA) = 3.14159 * FLOAT(IA-1)
   AUN = UN(IA)
   DO 3 K = 1,NN
     XA = TAN(AUN)
     YA = 2. * H * DW * AUN / (AUN**2 - H**2 * DW**2)
     DIF = ABS(XA-YA)
     IF (DIF .LE. 0.001) GOTO 4
     AUN = AUN + BINC
3  CONTINUE
4  NX = II + 1
   XUN(NX) = AUN
   WRITE (6,220) AUN,XA,YA,DIF
   II = II + 1
5  CONTINUE

```

```

WRITE (6,150) (XUN(I),I=1,NX)
JJ = 0
DO 10 IB = 1,M
  IF (IB .GT. 1) GOTO 7
  BUN = BI
  DO 6 J = 1,NN
    XA = TAN(BUN)
    YA = 2. * H * DP * BUN / (BUN**2 - H**2 * DP**2)
    DIF = ABS(XA-YA)
    IF (DIF .LE. 0.001) GOTO 9
    BUN = BUN + BINC
6  CONTINUE
7  UN(IB) = 3.14159 * FLOAT(IB-1)
  BUN = UN(IB)
  DO 8 K = 1,NN
    XA = TAN(BUN)
    YA = 2. * H * DP * BUN / (BUN**2 - H**2 * DP**2)
    DIF = ABS(XA-YA)
    IF (DIF .LE. 0.001) GOTO 9
    BUN = BUN + BINC
8  CONTINUE
9  NX = JJ + 1
  YUN(NX) = BUN
  WRITE (6,220) BUN,XA,YA,DIF
  JJ = JJ + 1
10 CONTINUE
WRITE (6,150) (YUN(I),I=1,NX)
DO 16 I=1,1
  AVOLT = VOLT(I)
  AAMP = AMP(I)
  AV = V(I)
  QP = 0.24 * ETA * AVOLT * AAMP
  X = QP/(3.14159 * COND * H)
  WRITE (6,160)
  WRITE (6,170)
  DO 15 J=1,1
    ATO = TO(J)
    WRITE (6,180) AVOLT,AAMP,AV, TX, TY, TA, ATO, H
    T500 = AII
    DO 11 L=1,N
      Y1 = AV**2 * T500/(2 * AK) - FAC1
      AAI = X * EXP(Y1)

      CALL COOLT500
      TY1 = AAI * SUMXX + 2 * (ATO-TA) * SUMYY
      DIF1 = ABS(TX1-TY1)
      IF (DIF1 .LE. U) GOTO 12
      T500 = T500 + AINC
11 CONTINUE

```



```

12      WRITE (6,220) T500, TX1, TY1, DIF1, L
        WRITE (6,190)
        WRITE (6,220) AUN, XA, YA, DIF, X, Y1, DW, QP, AA1, M
        WRITE (6,200)
        WRITE (6,220) I, SUMXX, SUMYY, AUN, AWN, XX, YY, S, FKO
        T800 = AI2
        DO 13 K=1, N
            Y2 = AV**2 * T800 / (2 * AK) - FAC2
            AA2 = X * EXP(Y2)

            CALL COOLT800
            TY2 = AA2 * SUMXX + 2 * (ATO-TA) * SUMYY
            DIF2 = ABS(TX2-TY2)
            IF (DIF2 .LE. U) GOTO 14
            T800 = T800 + AINC
13      CONTINUE
14      WRITE (6,220) T800, TX2, TY2, DIF2, K
        WRITE (6,210)
        WRITE (6,220) AUN, XA, YA, DIF, X, Y2, DW, QP, AA2, M
        WRITE (6,200)
        WRITE (6,220) I, SUMXX, SUMYY, AUN, AWN, XX, YY, S, FKO
        COOLT = T500 - T800
        WRITE (6,230) COOLT
15      CONTINUE
16      CONTINUE
        STOP
100     FORMAT(10G)
110     FORMAT (2X, 'THERMAL CONSTANTS:')
120     FORMAT(48H   ETA      COND      AK      AW      AP      /
1(F6.2,4F10.5) //)
130     FORMAT(3(3G))
140     FORMAT(3(G))
150     FORMAT(2X,2(10G))
160     FORMAT (2X, 'WELDING CONDITIONS')
170     FORMAT(3X,5HAVOLT,3X,4HAAMP,6X,2HAV,6X,2HTX,6X,2HTY,6X,2HTA,6X,
13HATO,5X,1HH/)
180     FORMAT(8F8.3/)
190     FORMAT (4X,3HAUN,9X,2HXA,10X,2HYA,10X,3HDIF,10X,1HX,9X,2HY1,
110X,2HDW,7X,2HQP,10X,3HAA1,8X,1HM)
200     FORMAT(2X,1HI,5X,5HSUMXX,6X,5HSUMYY,3X,3HAUN,9X,3HAWN,10X,
12HXX,8X,2HYY,11X,1HS,7X,3HFKO)
210     FORMAT (4X,3HAUN,9X,2HXA,10X,2HYA,10X,3HDIF,11X,1HX,9X,2HY2,
110X,2HDW,7X,2HQP,7X,3HAA2,8X,1HM)
220     FORMAT(2X,10G)
230     FORMAT(2X, 'COOLING TIME FROM 800 TO 500 C, COOLT=', F7.2/)
        END

```

22
OF / DE

```

C *****
C               SUBROUTINE COOLT500
C   SUBPROGRAM TO CALCULATE COOLING TIME TO 500C
C *****

REAL NN,M,BI,BINC,UN
COMMON /COOLT/ VOLT(5),AMP(5),V(5),TO(5),UN(30),XUN(30),YUN(30),
1SUMXX,SUMYY,T500,T800,BI,BINC,H,AW,AP,AV,AK,COND,X,M,NN,NX,IA
2AUN,RESULT,XX,S,DIF,XA,YA,FKO,FAC1,FAC2,IB,AWN,APN,BUN,DW,DP,N
SUMXX = 0
SUMYY = 0
DO 4 I = 1,NX
  AUN = XUN(I)
  BUN = YUN(I)
  ZZ = (AV * H/(2 * AK))**2
  AWN = AUN**2/(AUN**2 + H**2 * DW**2 + 2 * H * DW)
  APN = BUN**2/(BUN**2 + H**2 * DP**2 + 2 * H * DP)
  Z = AV * T500 * (AUN**2 + ZZ)**0.5/H
  S = AK * BUN**2 * T500/H**2
  IF (Z-2.0) 1,1,2
1  T = Z/3.75
  W = Z/2.0
  FIO = 1.0 + 3.5156229 * T**2 + 3.0899424 * T**4 +
1      1.2067492 * T**6 + 0.2659732 * T**8 +
2      0.0360768 * T**10 + 0.0045813 * T**12
  FKO = -ALOG(W) * FIO - 0.57721566 + 0.4227842 * W**2 +
1      0.23069756 * W**4 + 0.0348859 * W**6 + 0.00262698 * W**8
2      + 0.0001075 * W**10 + 0.0000074 * W**12
  GOTO 3
2  Y = 2.0/Z
  FK = 1.25331414 - 0.07832358 * Y + 0.02189568 * Y**2 -
1      0.01062446 * Y**3 + 0.00587872 * Y**4 - 0.0025154 * Y**5
2      + 0.00053208 * Y**6
  ZF = Z - FAC1
  FKO = EXP(-ZF) * FK / SQRT(Z)
3  XX = AWN * FKO
  WW = SIN(BUN)/BUN - H * DP * (COS(BUN)-1)/BUN**2
  YY = APN * EXP(-S) * WW
  SUMXX = SUMXX + XX
  SUMYY = SUMYY + YY
4  CONTINUE
  RETURN
  END

```

```

C *****
C               SUBROUTINE COOLT800
C   SUBPROGRAM TO CALCULATE COOLING TIME TO 800C
C *****

REAL NN,M,BI,BINC,UN
COMMON /COOLT/ VOLT(5),AMP(5),V(5),TO(5),UN(30),XUN(30),YUN(30),
1SUMXX,SUMYY,T500,T800,BI,BINC,H,AW,AP,AV,AK,COND,X,M,NN,NX,IA
2AUN,RESULT,XX,S,DIF,XA,YA,FKO,FAC1,FAC2,IB,AWN,APN,BUN,DW,DP,N
SUMXX = 0
SUMYY = 0
DO 4 I = 1,NX
  AUN = XUN(I)
  BUN = YUN(I)
  ZZ = (AV * H/(2 * AK))**2
  AWN = AUN**2/(AUN**2 + H**2 * DW**2 + 2 * H * DW)
  APN = BUN**2/(BUN**2 + H**2 * DP**2 + 2 * H * DP)
  Z = AV * T800 * (AUN**2 + ZZ)**0.5/H
  S = AK * BUN**2 * T800/H**2
  IF (Z-2.0) 1,1,2
1  T = Z/3.75
  W = Z/2.0
  FIO = 1.0 + 3.5156229 * T**2 + 3.0899424 * T**4 +
1    1.2067492 * T**6 + 0.2659732 * T**8 +
2    0.0360768 * T**10 + 0.0045813 * T**12
  FKO = -ALOG(W) * FIO - 0.57721566 + 0.4227842 * W**2 +
1    0.23069756 * W**4 + 0.0348859 * W**6 + 0.00262698 * W**8
2    + 0.0001075 * W**10 + 0.0000074 * W**12
  GOTO 3
2  Y = 2.0/Z
  FK = 1.25331414 - 0.07832358 * Y + 0.02189568 * Y**2 -
1    0.01062446 * Y**3 + 0.00587872 * Y**4 - 0.0025154 * Y**5
2    + 0.00053208 * Y**6
  ZF = Z - FAC2
  FKO = EXP(-ZF) * FK / SQRT(Z)
3  XX = AWN * FKO
  WW = SIN(BUN)/BUN - H * DP * (COS(BUN)-1)/BUN**2
  YY = APN * EXP(-S) * WW
  SUMXX = SUMXX + XX
  SUMYY = SUMYY + YY
4  CONTINUE
  RETURN
  END

```

APPENDIX E

Program Variable Description for
Arata- α , Terasaki and Yurioka Models

Computer Program of Arata- α Model for
Predicting Weld HAZ Hardnesses

Table E-1

**Program Variable Description for
Arata- α , Terasaki and Yurioka Models**

C	Carbon
MN	Manganese
SI	Silicon
NI	Nickel
CR	Chromium
MO	Molybdenum
V	Vanadium
CU	Copper
B	Boron
NB	Niobium
COOLT	Cooling time between 800 and 500°C (s)
CEQ	Carbon equivalent in Terasaki model
CEQ1,CEQ2	Carbon equivalent in Yurioka model
HV	Hardness (VHN)

```

C *****
C *          PROGRAM TO CALCULATE WELD HAZ HARDNESS          *
C *          USING ARATA-ALPHA MODEL                          *
C *****

REAL C,SI,MN,NI,CR,MO,CU,V,NB,B,COOLT
DIMENSION C(10),SI(10),MN(10),NI(10),CR(10),MO(10),CU(10),
1 V(10),NB(10),B(10),COOLT(15)
READ (5,100)M,N
READ (5,100)(C(I),SI(I),MN(I),NI(I),CR(I),MO(I),CU(I),V(I),NB(I),
1 B(I),I=1,M)
READ (5,110)(COOLT(J),J=1,N)
100 FORMAT(10G)
110 FORMAT(15G)
DO 8 I=1,M
  AC = C(I)
  ASI = SI(I)
  AMN = MN(I)
  ANI = NI(I)
  ACR = CR(I)
  AMO = MO(I)
  ACU = CU(I)
  AV = V(I)
  ANB = NB(I)
  AB = B(I)
  WRITE (6,120)
  SUM = ANI + ACR + AMO + ACU + AV + AB + ANB
  X = 10.0
  IF (SUM.NE.0)GOTO 4
  TM100 = 10**(2.55*(AC + AMN/6.3 + ASI/3.6) - 0.92)
  TM0 = 10**(1.02 - 0.37*(AC - AMN/1.1 - ASI/0.44))
  HTM100 = 835 * AC + 287
  HTM0 = 273 * (AC + AMN/13 + ASI/9.7) + 133
  WRITE (6,130)AC,ASI,AMN,ANI,ACR,AMO,ACU,AV,ANB,AB,TM100
  H1 = HTM100 - 150
  H2 = HTM0 - 150
  ACS = (H1**ALOG(X)*TM100 - H2**ALOG(X)*TM0)/(H2**ALOG(X)
1 - H1**ALOG(X))
  BCS = H1 * EXP(ALOG10(TM100 + ACS))
  DO 3 J=1,N
    ACOOLT = COOLT(J)
    IF (ACOOLT.GT.TM100)GOTO 1
    HV = HTM100
    GOTO 2
1    HV = BCS/(EXP(ALOG10(ACOOLT + ACS))) + 150
2    WRITE (6,140)
    WRITE (6,150)ACOOLT,HV,ACS,BCS
3    CONTINUE

```

```

      GOTO 8
4    TM100 = 10** ( 5.9 * (AC + AMN/19 + ASI/14 + ANI/37 + ACR/19 +
1      AMO/9.1 - AV/49 + AB/0.31) - 1.13)
    TM0 = 10** (1.60 - 0.2* (AC - AMN/4.3 - ASI/0.4 - ANI/0.58 + ACR/0.45
1      - AMO/0.49 + AV/240 - AB/0.0024))
    HTM100 = 835 * AC + 287
    HTM0 = 500 * (AC - AMN/38 - ASI/68 - ANI/45 + ACR/9 + AMO/9.9
1      + AV/2.1 + AB/0.48) + 153
    WRITE (6,130) AC,ASI,AMN,ANI,ACR,AMO,ACU,AV,ANB,AB,TM100
    H1 = HTM100 - 160
    H2 = HTM0 - 160
    AHT = (H1**ALOG(X)*TM100 - H2**ALOG(X)*TM0)/(H2**ALOG(X)
1      - H1**ALOG(X))
    BHT = H1 * EXP(ALOG10(TM100 + AHT))
    DO 7 J=1,N
      ACOOLT = COOLT(J)
      IF (ACOO LT.GT.TM100) GOTO 5
      HV = HTM100
      GOTO 6
5      HV = BHT/(EXP(ALOG10(ACOO LT + AHT))) + 160
6      WRITE (6,160)
      WRITE (6,150) ACOOLT,HV,AHT,BHT,TM100,TM0,HTM100,HTM0,H1,H2
7      CONTINUE
8      CONTINUE
120  FORMAT(5X,2HAC,4X,3HASI,4X,3HAMN,4X,3HANI,4X,3HACR,4X,3HAMO,4X,
130  13HACU,5X,2HAV,4X,3HANB,5X,2HAB,3X,5HTM100)
130  FORMAT(10F7.4,F7.3/)
140  FORMAT(6X,6HACOO LT,5X,2HHV,7X,3HACS,7X,3HBCS)
150  FORMAT(1X,4F10.3,6F10.3/)
160  FORMAT(6X,6HACOO LT,5X,2HHV,7X,3HAHT,7X,3HBHT)
    STOP
  END

```


APPENDIX F

Computer Program of Terasaki Model for Predicting Weld HAZ Hardnesses

```

C *****
C *          PROGRAM TO CALCULATE WELD HAZ HARDNESS          *
C *          USING TERASAKI MODEL                            *
C *****

REAL C,SI,MN,NI,CR,MO,CU,V,NB,B,COOLT
DIMENSION C(10),SI(10),MN(10),NI(10),CR(10),MO(10),CU(10),
1V(10),NB(10),B(10),COOLT(15)
READ (5,100)M,N
READ (5,100) (C(I),SI(I),MN(I),NI(I),CR(I),MO(I),CU(I),V(I),NB(I),
1  B(I),I=1,M)
READ (5,110) (COOLT(J),J=1,N)
100  FORMAT(10G)
110  FORMAT(15G)
DO 4 I=1,M
  AC = C(I)
  ASI = SI(I)
  AMN = MN(I)
  ANI = NI(I)
  ACR = CR(I)
  AMO = MO(I)
  ACU = CU(I)
  AV = V(I)
  ANB = NB(I)
  AB = B(I)
  WRITE (6,120)
  CEQ = AC + AMN/3 + ANI/8 + ACR/12 + AMO/2 + ACU/5
  COOLTM = 10**(2.5*CEQ - 1.21)
  WRITE (6,130) AC,ASI,AMN,ANI,ACR,AMO,ACU,AV,ANB,AB,COOLTM
  DO 3 J=1,N
    ACOOLT = COOLT(J)
    IF (ACOOULT.GT.COOLTM)GOTO 1
    HV = 812 * AC + 293
    GOTO 2
1    HV = (992 * AC - 230 * CEQ + 250) * EXP((-3 * ACOOLT)
1      /310**CEQ)+ 188 * CEQ + 80
2    WRITE (6,140)
    WRITE (6,150) ACOOLT,HV
3    CONTINUE
4    CONTINUE
120  FORMAT(5X,2HAC,4X,3HASI,4X,3HAMN,4X,3HANI,4X,3HACR,4X,3HAMO,4X,
13HACU,5X,2HAV,4X,3HANB,5X,2HAB,2X,6HCOOLTM)
130  FORMAT(10F7.4,F7.3/)
140  FORMAT(6X,6HACOOLT,5X,2HHV)
150  FORMAT(1X,2F10.3/)
STOP
END

```

```

C *****
C *          PROGRAM TO CALCULATE WELD HAZ HARDNESS          *
C *          USING YURIOKA MODEL                             *
C *****

REAL C,SI,MN,NI,CR,MO,CU,V,NB,B,COOLT
DIMENSION C(10),SI(10),MN(10),NI(10),CR(10),MO(10),CU(10),
1V(10),NB(10),B(10),COOLT(15)
READ (5,100)M,N
READ (5,100) (C(I),SI(I),MN(I),NI(I),CR(I),MO(I),CU(I),V(I),NB(I),
1  B(I),I=1,M)
READ (5,110) (COOLT(J),J=1,N)
100  FORMAT(10G)
110  FORMAT(15G)
DO 2 I=1,M
  AC = C(I)
  ASI = SI(I)
  AMN = MN(I)
  ANI = NI(I)
  ACR = CR(I)
  AMO = MO(I)
  ACU = CU(I)
  AV = V(I)
  ANB = NB(I)
  AB = B(I)
  WRITE (6,120)
  WRITE (6,130) AC,ASI,AMN,ANI,ACR,AMO,ACU,AV,ANB,AB
  CEQ1 = AC + ASI/24 + AMN/6 + ANI/40 + ACR/6 + AMO/4 + ACU/15
1    + (ANB+AV)/5 + 10*AB
  CEQ2 = AC - ASI/30 + AMN/5 + ANI/20 + ACR/4 + AMO/6 + ACU/5 + 10*AB
  DO 1 J=1,N
    ACOOLT = COOLT(J)
    HV = .406*AC + 164 * CEQ1 + 183 - (369*AC - 149*CEQ1 + 100)
1      *ATAN((ALOG10(ACOOULT) - 2.822*CEQ2 + 0.262)
2      /(0.526 - 0.195*CEQ2))
    WRITE (6,140)
    WRITE (6,150) ACOOLT,HV
1    CONTINUE
2    CONTINUE
F20  FORMAT(6X,2HAC,5X,3HASI,5X,3HAMN,5X,3HANI,5X,3HACR,5X,3HAMO,5X,
13HACU,6X,2HAV,5X,3HANB,6X,2HAB)
130  FORMAT(10F8.4/)
140  FORMAT(6X,6HACOOULT,5X,2HHV)
150  FORMAT(1X,2F10.3/)
STOP
END

```

APPENDIX H

Program Variable Description for Microprocessor Method M2

Computer Program in Microprocessor M2 for Predicting Weld HAZ Hardnesses

Table H-1

**Program Variable Description for
Microprocessor Method M2**

C	Carbon	
MN	Manganese	
SI	Silicon	
NI	Nickel	
CR	Chromium	
MO	Molybdenum	
V	Vanadium	
CU	Copper	
B	Boron	
NB	Niobium	
A	Thermal conductivity	($J/mm \cdot ^\circ C \cdot s$)
A1	Initial value of cooling time to 500°C for iterative calculation	(s)
A2	Initial value of cooling time to 800°C for iterative calculation	(s)
A3	Eigenvalues	
B1	Initial eigenvalue for iterative calculation	
C2,C3	Carbon equivalents	
CP	Volumetric specific heat capacity	($J/mm^3 \cdot ^\circ C$)
E	Welding efficiency	(%)
H	Plate thickness	(mm)
H0	Hardness	(VHN)
I	Welding current	(Amperes)
I0	Tolerance of temperature for calculating cooling time	
I1	Increment of eigenvalue iterative calculation	
K	Thermal diffusivity	(mm^2/s)
N1	Maximum iteration cycles for calculating eigenvalues	

N2	Maximum iteration cycles for calculating cooling time
N3	Number of summation items
P	Welding voltage (Volts)
S1	Surface conductance ($J/mm^2 \text{ } ^\circ C \text{ s}$)
T	Cooling time between 800 and 500°C (s)
T0	Ambient temperature ($^\circ C$)
T5	Cooling time to 500°C (s)
T8	Cooling time to 800°C (s)
W	Welding speed (mm/s)

```

*****
* INTERACTIVE PROGRAM IN MICROPROCESSOR METHOD M2 COMBINING *
* THE KOHIRA MODEL FOR CALCULATING COOLING TIME FROM 800 TO *
* 500 C AND THE YURIOKA MODEL FOR PREDICTING HAZ HARDNESSES *
*****

```

```

10 DIM X2(30),Y2(30)
20 C=0:M=0:S=0:N=0:C0=0:M0=0:V=0:C1=0:B=0:N0=0
30 INPUT "%C=";C,"%MN=";M,"%SI=";S,"%NI=";N,"%CR=";C0
40 INPUT "%MO=";M0,"%V=";V,"%CU=";C1,"%B=";B,"%NB=";N0
42 S7=N+C0+M0+V+C1+B+N0
43 IF S7>0.1 GOTO 48
45 PAUSE "CONVENTIONAL STEEL"
46 GOTO 50
48 PAUSE "HT TYPE STEEL"
50 INPUT "COOLING TIME (SEC) OR (0)=";T
60 IF T<>0 GOTO 1160
62 INPUT "DEEP WELD (YES/NO)";AS
64 IF AS="YES" GOTO 68
66 A=0.06:K=0.042
67 GOTO 70
68 A=0.098:K=0.091
70 INPUT "WELDING EFFICIENCY=";E
80 IF E=0.95 GOTO 120
90 S1=0.002
110 GOTO 150
120 S1=C.0001
150 INPUT "THICKNESS (MM)=";H:H=H/10
155 T1=500:T2=800:I1=0.001:N1=1000
160 N2=1000:I0=1:N3=10:CP=1.4285714:T0=20
165 T3=T1-T0
166 T4=T2-T0
170 INPUT "VOLTS=";P,"AMPS=";I,"WELD SPEED (MM/S)=";W:W/10
180 Q=0.24*E*P*I
190 HC=SQR(Q/(W*CP*630))
200 IF H>HC GOTO 235
205 KK=1
210 A1 = (1/(4*PI*A*CP))*(Q/(W*H))**2*(1/T3)**2
220 A2 = (1/(4*PI*A*CP))*(Q/(W*H))**2*(1/T4)**2
230 GOTO 270
235 KK=0
240 A1 = (1/(2*PI*A))*(Q/W)*(1/T3)
250 A2 = (1/(2*PI*A))*(Q/W)*(1/T4)
270 D1 = S1 / A
275 G=D1*H
280 IF G=G1 GOTO 880
285 G1=C
290 I3=0

```

```

300 FOR J1 = 1 TO N3 STEP 1
310 IF J1 > 1 GOTO 430
320 B1=SQR(2*H*D1-H^2*D1^2)
321 A3=B1
330 FOR J2 = 1 TO N1 STEP 1
340 IF J2 < N1 GOTO 370
350 PRINT "NO EIGEN VALUE OF WELD CAN BE FOUND"
351 PRINT "TRY LOWER INITIAL VALUE OR MORE ITERATION CYCLES"
360 STOP
370 X1 = TAN(A3)
380 Y1 = 2 * H * D1 * A3 / (A3 ^ 2 - H ^ 2 * D1 ^ 2)
390 D3 = ABS(X1 - Y1)
400 IF D3 <= 0.001 GOTO 540
410 A3 = A3 + I1
420 NEXT J2
430 A3 = 3.14159 * (J1 - 1)
440 FOR J3 = 1 TO N1 STEP 1
450 IF J3 < N1 GOTO 480
460 PRINT "NO EIGEN VALUE OF WELD CAN BE FOUND"
461 PRINT "TRY LOWER INITIAL VALUE OR MORE ITERATION CYCLES"
470 STOP
480 X1 = TAN(A3)
490 Y1 = 2 * H * D1 * A3 / (A3 ^ 2 - H ^ 2 * D1 ^ 2)
500 D3 = ABS(X1 - Y1)
510 IF D3 <= 0.001 GOTO 540
520 A3 = A3 + I1
530 NEXT J3
540 J = I3 + 1
550 X2(J) = A3
560 I3 = I3 + 1
570 NEXT J1
880 X = Q / (3.14159 * A * H)
890 T5 = A1
900 FOR L1=1 TO N2 STEP 1
910 IF L1 < N2 GOTO 940
920 PRINT "NO COOLING TIME TO 500C CAN BE FOUND"
921 PRINT "TRY LOWER INITIAL VALUE OR MORE ITERATION CYCLES"
930 STOP
940 GOSUB 1250
950 Y3 = W ^ 2 * T5 / (2*K) - F1
960 A5 = X * EXP(Y3)
970 Y4 = A5 * S3
980 D4 = ABS (T3 - Y4)
990 IF D4 <= 10 GOTO 1020
991 IF KK=1 GOTO 1000
992 T5 = T5 * (Y4/T3)
993 GOTO 1010
1000 T5 = T5 * SQR(Y4/T3)
1010 NEXT L1

```



```

1020 T8 = A2
1030 FOR L2=1 TO N2 STEP 1
1040 IF L2 < N2 GOTO 1070
1050 PRINT "NO COOLING TIME TO 800C CAN BE FOUND"
1051 PRINT "TRY LOWER INITIAL VALUE OR MORE ITERATION CYCLES"
1060 STOP
1070 GOSUB 1690
1080 Y5 = W ^ 2 * T8 / (2*K) - F2
1090 A6 = X * EXP(Y5)
1100 Y6 = A6 * S5
1110 D5 = ABS (T4 - Y6)
1120 IF D5 <= I0 GOTO 1150
1121 IF KK=1 GOTO 1130
1122 T8 = T8 * (Y6/T4)
1123 GOTO 1140
1130 T8 = T8 * SQR(Y6/T4)
1140 NEXT L2
1150 T = T5 - T8
1160 C2 = C + S/24 + M/6 + N/40 + C0/6 + M0/4 + C1/15 + (N0+V)/5 + 10*B
1170 C3 = C - S/30 + M/5 + N/20 + C0/4 + M0/6 + C1/5 + 10*B
1180 W4 = (LOG(T)-2.822*C3+0.262)/(0.526-C.195*C3)
1190 H0 = 406*C+164*C2+183-(369*C-149*C2+100)*ATN(W4)
1200 PAUSE "COOLING TIME T=";USING "####.##";T
1220 BEEP 5,64,160
1230 PRINT "HARDNESS(VHN)=";USING "####.##";H0
1240 GO TO 50

```

1250 REM SUBPROGRAM TO CALCULATE COOLING TIME TO 500 C

```

1260 Z = (W * H/(2 * K)) ^ 2
1270 R = X2(2)
1280 Z8 = W * T5 * (R^2 + Z) ^ 0.5 / H
1290 F1 = 0
1300 IF Z8 <= 225 GOTO 1360
1310 FOR R1=1 TO 20 STEP 1
1320 F1=150*R1
1330 Z9 = Z8 - F1
1340 IF Z9 <= 225 GOTO 1360
1350 NEXT R1
1360 S3 = 0
1380 FOR U1=1 TO J STEP 1
1390 A3 = X2(U1)
1410 W1 = A3 ^ 2 / (A3 ^ 2 + H ^ 2 * D1 ^ 2 + 2 * H * D1)
1430 Z1 = W * T5 * SQR(A3^2 + Z) / H
1450 Z3 = Z1 - 2.0
1460 IF Z3 > 0 GOTO 1555
1470 Z4 = Z1/3.75
1480 Z5 = Z1/2.0
1490 V1 = 1.0+3.5156299*Z4^2+3.0399424*Z4^4+1.2067492*Z4^6
1500 V2 = 0.2659732*Z4^8+0.0360768*Z4^10+0.0045813*Z4^12
1510 F3 = V1 + V2

```

```

1520 V3=-LN(Z5)*F3-0.57721566+0.4227842*Z5^2+0.23069756*Z5^4
1530 V4 = 0.0348859*Z5^6+0.00262698*Z5^8+0.0001075*Z5^10+0.0000074*Z5^12
1540 F4 = V3 + V4
1550 GOTO 1620
1555 IF Z3 > 8 GOTO 1612
1560 Z6 = 2.0/Z1
1570 V5 = 1.25331414-0.07832358*Z6+0.02189568*Z6^2-0.01062446*Z6^3
1580 V6 = 0.00587872*Z6^4-0.0025154*Z6^5+0.00053208*Z6^6
1590 F5 = V5 + V6
1600 Z7 = Z1 - F1
1610 F4 = EXP(-Z7)*F5/SQR(Z1)
1611 GOTO 1620
1612 Z7 = Z1 - F1
1613 F4 = EXP(-Z7) * SQR(PI/(2*Z1))
1620 X3 = W1 * F4
1650 S3 = S3 + X3
1660 R3 = X3/S3
1665 IF R3 < 0.0001 GOTO 1680
1670 NEXT U1
1680 RETURN

1690 REM SUBPROGRAM TO CALCULATE COOLING TIME TO 800 C

1700 Z = (W * H/(2 * K)) ^ 2
1710 R = X2(2)
1720 Z8 = W * T8 * (R^2 + Z) ^ 0.5 / H
1730 F2 = 0
1740 IF Z8 <= 225 GOTO 1800
1750 FOR R2=1 TO 20 STEP 1
1760 F2=150*R2
1770 Z9 = Z8 - F2
1780 IF Z9 <= 225 GOTO 1800
1790 NEXT R2
1800 S5 = 0
1820 FOR U2=1 TO J STEP 1
1830 A3 = X2(U2)
1850 W1 = A3 ^ 2 / (A3 ^ 2 + H ^ 2 * D1 ^ 2 + 2 * H * D1)
1870 Z1 = W * T3 * (A3^2 + Z) ^ 0.5 / H
1890 Z3 = Z1 - 2.0
1900 IF Z3 > 0 GOTO 1995
1910 Z4 = Z1/3.75
1920 Z5 = Z1/2.0
1930 V1 = 1.0+3.5156299*Z4^2+3.0899424*Z4^4+1.2067492*Z4^6
1940 V2 = 0.2659732*Z4^8+0.0360768*Z4^10+0.0045813*Z4^12
1950 F3 = V1 + V2
1960 V3 = -LN(Z5)*F3-0.57721566+0.4227842*Z5^2+0.23069756*Z5^4
1970 V4 = 0.0348859*Z5^6+0.00262698*Z5^8+0.0001075*Z5^10+0.0000074*Z5^12
1980 F4 = V3 + V4

```

```
1990 GO TO 2060
1995 IF Z3 > 8 GOTO 2052
2000 Z6 = 2.0/Z1
2010 V5 = 1.25331414-0.07832358*Z6+0.02189568*Z6^2-0.01062446*Z6^3
2020 V6 = 0.00587872*Z6^4-0.0025154*Z6^5+0.00053208*Z6^6
2030 F5 = V5 + V6
2040 Z7 = Z1 - F2
2050 F4 = EXP(-Z7)*F5/SQR(Z1)
2051 GOTO 2060
2052 Z7 = Z1 - F2
2053 F4 = EXP(-Z7) * SQR(PI/(2*Z1))
2060 X3 = W1 * F4
2090 S5 = S5 + X3
2100 R4 = X3/S5
2105 IF R4 < 0.0001 GO TO 1850
2110 NEXT U2
2120 RETURN
2190 STOP
2200 END
```

END

21-02-86

FIN