1

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

National Library
of Canada

Bibliothèque nationale
du Canada

Canadian Theses Service Service des thèses canadiennes

Ottawa, Canada
K1A 0N4

NOTICE

The quality of this microform 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.

Reproduction in full or in part of this microform is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30, and subsequent amendments.

AVIS

La qualité de cette microforme 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.

La reproduction, même partielle, de cette microforme est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30, et ses amendements subséquents.

SOFTWARE FOR WELDING ENGINEERS

Billy Kwok-Hung Chan

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

DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING
CARLETON UNIVERSITY
OTTAWA, ONTARIO,
CANADA

December 1990.

National Library
of Canada

Bibliothèque nationale
du Canada

Canadian Theses Service Service des thèses canadiennes

Ottawa, Canada
K1A 0N4

The author has granted an irrevocable non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of his/her thesis by any means and in any form or format, making this thesis available to interested persons.

The author retains ownership of the copyright in his/her thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without his/her permission.

L'auteur a accordé une licence irrévocable et non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de sa thèse de quelque manière et sous quelque forme que ce soit pour mettre des exemplaires de cette thèse à la disposition des personnes intéressées.

L'auteur conserve la propriété du droit d'auteur qui protège sa thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

ISBN 0-315-08891-2

Canada

The undersigned recommends to the Faculty of Graduate Studies and Research, acceptance of the thesis: Software for Welding Engineers, submitted by Billy Kwok-Hung Chan, in partial fulfilment of the requirements for the Degree of Master of Engineering.

Thesis supervisor

Chairman
Department of Mechanical
and Aerospace Engineering

ABSTRACT

A software system for computing the heat-affected zone (HAZ) as-welded hardness, post weld heat treated hardness, preheat temperature to avoid underbead cracking and GMAW (gas metal arc weld) fusion zone size and shape from the chemical composition of the base plate material and welding parameters is the subject of this thesis. The mathematical models used as bases for the system can be found from the literature: as-welded hardness (Suzuki [1,2,3], Arata [4], Terasaki [5,6], Yurioka [7,8], Beckert [9], Dueren [10], Cottrell [11]), post weld heat treated HAZ hardness (Yurioka [12]), preheat temperature to avoid underbead cracking (Yurioka et al [13,14,15,16]), and weld area (Chandel [17,18,19,20]). Original contributions submitted in this thesis consist of designing a user-friendly interface to input welding parameters and chemical compositions, database technology to store and retrieve frequently used welding parameters and chemical compositions, and extensive graphics to display the computations in user friendly form. Both the traditional procedural programming approach and the object oriented philosophy are included for comparison purposes. The use and useability of this system in engineering practice is discussed at length.

ACKNOWLEDGEMENTS

I would like to express my deepest appreciation to my thesis supervisor, Dr. Malcom J. Bibby, for his continued interest, encouragement and guidance provided during this thesis and throughout my study at Carleton University. I thank him and the Department of Mechanical and Aerospace Engineering, Carleton University for their financial support.

I would like to thank all my friends and the staff of the Department of Mechanical and Aerospace Engineering at Carleton University for their help and cooperation.

Finally, I would like to present this thesis to my beloved parents.

TABLE OF CONTENTS

	Page
Abstract	1
Acknowledgement	ii
Table of Contents	iii
List of Figures	vi
List of Tables	xi
Nomenclature	xii
 1) Introduction	 1
Specific Objectives	9
 2) Models for Predicting HAZ Hardness, Preheat Temperature and Weld Shape	 12
2.1) HAZ Hardness Models	12
2.1.1) Cooling Time $T_{8/5}$	14
2.1.2) The Suzuki HAZ Hardness Model	23
2.1.3) The Arata HAZ Hardness Model (α Formulation)	25
2.1.4) The Terasaki HAZ Hardness Model	29
2.1.5) The Yurioka I HAZ Hardness Model	30
2.1.6) The Yurioka II HAZ Hardness Model	31
2.1.7) The Beckert HAZ Hardness Model	34
2.1.8) The Dueren HAZ Hardness Model	35
	iii

2.1.9)	The Cottrell HAZ Hardness Model	36
2.2)	The Reheat HAZ Hardness Model	37
2.3)	Preheat Temperature to Avoid HAZ Cold Cracking	43
2.3.1)	The Yurioka Preheat Model	44
2.3.2)	Cooling Time Equations for the Preheat Model	50
2.4)	Weld Shape	52
3)	Software Design	61
3.1)	System Requirements	61
3.2)	Software Features	62
3.2.1)	User-Friendly Interface	62
3.2.2)	Graphics Presentation	63
3.3.3)	Database	66
3.3)	Description of Software	66
3.3.1)	Program Module WH (as-welded HAZ Hardness)	67
3.3.2)	Program Module RH (Reheat HAZ Hardness)	74
3.3.3)	Program Module PH (Preheat Temperature to Avoid underbead cracking)	79
3.3.4)	Program Module WF (Weld Features)	83
4)	Discussion	89

4.1)	Calculated and Measured 800°C to 500°C Cooling Times Comparison	90
4.2)	Computed and Measured As-Welded CHC	92
4.3)	Computed and Measured PWHT CHC	96
4.4)	Different Methods for Determining the Required Preheat Temperature to Avoid Underbead Cracking	99
4.5)	Accuracy of Software WF	102
5,	Object-Oriented Versus Procedural Programming	103
5.1)	Smalltalk Version System Description	109
5.2)	Advantages of Object-Oriented Programming	111
5.3)	An Evaluation of Smalltalk vs Pascal	117
5.4)	Final Words (OOP)	118
6)	Conclusions and Contributions	119
7)	Future Work	120
	References	123

LIST OF FIGURES

Figures	Page
1.1 Principles of fusion welding	2
1.2 Typical cross-section of a fusion welded joint	2
1.3 Illustration of the variation of microstructure in a weld	4
2.1 Schematic HAZ characteristic hardness curve (CHC)	13
2.2 HAZ temperature-time cooling profile	13
2.3 Schematic diagram of a point and a line welding heat source	16
2.4 Schematic heat flow representation for the thick plate welding situation	16
2.5 Schematic representation of heat flow in the thin plate	16
2.6 Schematic diagram showing the cooling time-plate thickness relationship in the 2.5D heat flow range	18
2.7 Heat flow in the intermediate-thickness range between the 2D and 3D morphology	18
2.8 Values of C_r corresponding to H_r for computing cooling times in the transitional 2.5D heat flow range	20
2.9 Sensitivity of thermal properties to temperature change	20
2.10 Schematic characteristic hardness curve assumed by Suzuki	24

2.11 Schematic characteristic hardness curve assumed by Arata	24
2.12 Schematic sketch of hardness versus postheat time for different postheat temperature	38
2.13 Hydrogen level H_{11W} in weld	53
2.14 Schematic HAZ hardness vs fusion area	53
2.15 Definitions of weld shape	56
3.1 a Window 1, help menu	64
b Window 2, numerical results	64
c Window 3, parameters editor	64
3.2 Graphics presentation of results	64
3.3 Typical characteristic hardness curve generated by the as-welded hardness software (WH)	65
3.4 As-welded hardness software features at a glance	68
3.5 Flowchart describing the general computation scheme of the as-welded hardness software (WH)	70
3.6 Interface demonstrating the feature which allows the user to enter an experimental cooling time	71
3.7 a The database system menu	71
b Second level database menu	72
c Data set list	72
d Third level database menu	72
e Add or amend feature of the database system	72
3.8 Typical plot generated by the as-welded hardness software (WH)	75

3.9	General layout c. the reheat software (RH)	75
3.10	Flowchart describing the algorithm implementation of the reheat software (RH)	76
3.11	Typical plot generated by reheat software (RH) with both the as-welded and PWHT HAZ hardnesses	78
3.12	Plot with only PWHT HAZ hardness generated by the reheat software (RH)	78
3.13	Persudo code for implementing the uniform preheat temperature calculation	80
3.14	Persudo code for implementing the local preheat temperature calculation	81
3.15	General layout of the preheat software	82
3.16 a	Selection of 'HJIS' or 'HIIW'	82
b	Typical HIIW values	82
3.17	Typical restraint coefficient (rf)	82
3.18	Typical stress concentration factors	82
3.19 a	Graph of critical cooling time vs carbon content generated by the preheat temperature software (PH)	84
b	Graph of required preheat temperature vs carbon content generated by the preheat teperature software (PH)	84
3.20	General layout of the weld features software (WF)	86
3.21	Numerical results along with the estimated weld shape generated by the weld features software (WF)	86

3.22 Weld shape dependence on shielding gas and electrode polarity	87
3.23 Typical plot generated by the weld features software (WF)	87
3.24 Weld shape variation due to welding speed	88
4.1 The graph showing the measured and calculated cooling times	91
4.2 Characteristic hardness curves computed for steel A (+ measured values)	93
4.3 Characteristic hardness curves computed for steel B (+ measured values)	94
4.4 Characteristic hardness curves computed for steel C (+ measured values)	95
4.5 Characteristic hardness curve computed for steel A after PWHT	97
4.6 Characteristic hardness curve computed for steel B after PWHT	98
4.7 Characteristic hardness curve computed for steel C after PWHT	98
4.8 Preheat temperature predicted by the Yurioka and Seferian models for uniform preheat	101
4.9 Preheat temperature predicted by the Yurioka and Seferian models for local preheat	101
4.10 Comparison of the Chandel and estimated fusion area	105
4.11 Comparison of the Chandel and estimated deposit area	106

4.12 Comparison of the Chandel and estimated reinforced boundary length	106
4.13 Comparison of the Chandel and estimated fusion boundary length	107
5.1 Smalltalk interface	110
5.2 General layout of object-oriented programming (OOP) module interface for computing as-welded HAZ hardness	112
5.3 Characteristic hardness curve generated by OOP Smalltalk	113
5.4 Carbon content versus Suzuki hardness generated with Smalltalk to demonstrate parameter study	114
5.5 a Characteristic hardness curve generated with Pascal	115
b Carbon content versus Suzuki hardness generated with Pascal to demonstrate parameter study	115

LIST OF TABLES

Tables	Page
2.1 Tabulated Values of the Ratio of the Thick Plate Cooling Time to that of the Finite Plate (Cr) Corresponding to the Relative Thickness (Hr)	19
2.2 Criteria for Selecting the Appropriate Weld Cooling Time Equation	21
2.3 Summary of Welding Process Efficiencies for Commonly Used Welding Heat Sources	22
2.4 Chemical Composition Limits for the Arata Relationships	29
2.5 Alloy Limits for the Yurioka II Model	32
2.6 ΔH Values Corresponding to Boron Content	34
2.7 Alloy Limits for the Cottrell Model	37
2.8 Alloy Limits for the Reheat Model	42
2.9 Values of Coefficient of Restraint Intensity for Various Joint Configuration	48
2.10 Stress Concentration Factors at Root and Toe Weld Positions in Various Weld Joints	49
2.11 Coefficients for the Weld Features Equation	58
2.12 Coefficients for Melting Rate Equation	60
4.1 Chemical Compositions of the Three Experimental Steels (in wt%)	97
4.2 Calculations of Preheat Temperature for Linnert Method	100

NOMENCLATURE

HAZ	= heat-affected zone
PWHT	= post weld heat treatment
VHN	= Vickers hardness number
EBW	= electron beam weld
GMAW	= gas metal arc weld
GTAW	= gas tungsten arc weld
SAW	= submerged arc weld
SMAW	= shielded metal arc weld
CHC	= characteristic hardness curve
OOP	= object-oriented programming
wt%	= weight percent
B	= Boron content (wt%)
C	= carbon content (wt%)
Cr	= Chromium content (wt%)
Cu	= Copper content (wt%)
Mn	= Manganese content (wt%)
Mo	= Molybdenum content (wt%)
Ni	= Nickel content (wt%)
Nb	= Niobium content (wt%)
N	= Nitrogen content (wt%)
Si	= Silicon content (wt%)
S	= Sulphur content (wt%)

V	= Vanadium content (wt%)
$T_{8/5}[3D]$	= 3D cooling time from 800°C to 500°C (s)
k	= thermal conductivity (J/(s mm K))
Q	= heat input rate (J/s)
v	= welding speed (mm/s)
T_o	= plate initial temperature (°C)
$T_{8/5}[2D]$	= 2D cooling time from 800°C to 500°C (s)
C	= specific heat (J/(kg K))
ρ	= density of base metal (kg/mm ³)
h	= plate thickness (mm)
$T_{8/5}[2.5D]$	= 2.5D cooling time from 800°C to 500°C (s)
C_r	= ratio of cooling time on thick plate to that on finite plate
H_r	= relative thickness
T	= 650°C, i.e. average of 800°C and 500°C
η	= welding process efficiency (%)
V	= welding voltage (Volt)
I	= arc current (Amp)
H_{max}	= HAZ hardness in Suzuki model (VHN)
H_{bm}	= base metal hardness (VHN)
$T_{8/5}$	= weld centre line 800°C to 500°C cooling time (s)
K, a, Y	= backward logistic constants in Suzuki model
H_{vTM100}	= HAZ hardness of 100% martensite (VHN)
H_{vTM0}	= HAZ hardness of 0% martensite (VHN)
T_{M100}	= $T_{8/5}$ for 100% martensite transformation (s)

T_{M0}	= $T_{8/5}$ for 0% martensite transformation (s)
H_1, H_2	= constants in Arata model
H_{VM}	= HAZ hardness of 100% martensite (VHN)
H_{V0}	= HAZ hardness of 0% martensite (VHN)
T_M	= $T_{8/5}$ for 100% martensite transformation (s)
$C_{eq}, C_{eqI}, C_{eqII}, C_{eqIII}$	= carbon equivalents
C_p	= effective carbon
ΔH	= increase in hardenability due to Boron
fn	= constant for determining ΔH
H_{VB}	= HAZ hardness of 100% bainite material (VHN)
r	= 800 to 500°C cooling rate (K/s)
H_M	= hardness of 100% martensite transformation (VHN)
H_B	= HAZ hardness of 0% martensite transformation (VHN)
T_B	= $T_{8/5}$ for 0% martensite transformation (s)
ΔH_V	= change in hardness due to PWHT (VHN)
H_{PWHT}	= HAZ hardness after PWHT (VHN)
H_{VAW}	= as-welded HAZ hardness (VHN)
M	= volumetric ratio of martensite structure in HAZ
TP	= temper parameter
T_{RH}	= reheat temperature (K)
t_{RH}	= duration of PWHT (hr)
CE	= carbon equivalent
R_f	= restraint intensity factor
r_f	= restraint coefficient (N/mm ³)

σ_w	= nominal tensile stress acting on the weld metal (N/mm ²)
σ_y	= yield strength of the weld metal (N/mm ²)
K_t	= stress concentration factor
H_{JIS}	= hydrogen level by 'glycerin method'
H_{IIW}	= hydrogen level by 'mercury method'
CI	= cracking index
T_{cr}	= 1500°C to 100°C critical cooling time (s)
$T_{15/1}$	= 1500°C to 100°C weld cooling time (s)
T_{PH}	= preheat temperature (K)
α	= thermal diffusivity (mm ² /s)
S	= total surface area of the workpiece (mm ²)
V_w	= total volume of the workpiece (mm ³)
erf	= error function
b	= heater width (mm)
q	= heat input of heater (J/s)
t_{PH}	= preheat time (s)
$\beta_1, \beta_2, \beta_3$	= constants in preheat model
D	= electrode diameter (mm)
L	= electrode extension (mm)
MR	= melting rate (kg/hr)
W	= bead width (mm)
H	= bead height (mm)
P	= penetration (mm)
A _l	= deposit material area (mm ²)

A ₂	= plate fusion area (mm ²)
A	= total fusion area (mm ²)
C ₁	= length of the reinforcement boundary (mm)
C ₂	= length of the fusion boundary (mm)
T _p	= preheat temperature (°C)
C _c	= chemical carbon equivalent
x	= horizontal distance from the far left hand corner of the weld bead (mm)

CHAPTER ONE

INTRODUCTION

In the structural world or for that matter in manufacturing, the two principal methods of joining metals are bolting and welding. The integrity of bolted joints is limited by the shear strength of the bolts and the frictional forces of the parts to be joined. In welding, the component parts are held together with interatomic metallic bonds that form the joint. The joint has nearly the same composition as the base material and the strength is generally equal to or higher than that of the constituent parts [21].

Welding is a particularly important process for joining steels. Welding processes may be divided into two main categories: solid-phase welding or fusion welding. In solid-phase welding, two clean solid metal surfaces are brought into close contact and metallic bonds form spontaneously. On the other hand, when the two surfaces to be joined are heated to the melting point, the process is termed fusion welding. A diagram that demonstrates the principles of fusion welding is illustrated in Figure 1.1. Usually a molten filler metal is added to the gap between the parts to be joined. The base metal near the joint is melted by the heat source which is usually created by a flow of electricity through an arc between an electrode and the joint metal. Since the temperature of the

Figure 1.1 Principles of fusion welding [22].

Figure 1.2 Typical cross section of a fusion welded joint.

weld is somewhat above the melting point of steel, 1600 °C, a protective shielding gas or flux is used to prevent the molten metal from oxidation.

Solid-phase welding may be accomplished at room temperature and there is little change in the base metal structure near the joint. However in fusion welding, joints are subjected to elevated temperatures. The microstructure across the joint varies with position according to peak temperature. Three major metallurgical zones can be observed in the neighbourhood of the joint as illustrated in Figure 1.2. They are the fusion zone, the heat-affected zone (HAZ) and unaffected parent metal. Since mechanical properties depend on microstructure, they also vary with position across the joint.

A more detailed illustration of the variation of microstructure is included in Figure 1.3. The highest temperature occurs in the fusion zone which is about 1600 °C. Usually dendrite and coarse grained solidified structures appear in this region as shown in region (a) of Figure 1.3. The HAZ is divided into four sub-zones, namely the grain growth zone (b), the recrystallized zone (c), the partially transformed zone (d) and a tempered zone (e). The peak temperature of the grain growth zone is in the range from 1500°C at the fusion zone boundary to a temperature of about 1100°C where grain stabilization precipitates dissolve. It is in this zone that excessive grain coarsening occurs. The

Figure 1.3 Illustration of variation of microstructure in a weld [22].

temperature of the recrystallized zone ranges from about 1100°C to the A_3 (austenitic-ferrite phase boundary). The microstructure in the recrystallized zone is fine-grained because of austenite and ferrite phase transformations. A partially transformed zone can be found in the joint where the iron experiences a peak temperature range between A_3 and A_1 (the eutectoid temperature). These temperatures are below those for full annealing and mixed grains co-exist in this region. The tempered zone usually has a temperature range between A_1 (approximately 720°C) and about 580°C (the lower limit of significant thermal activity in steels). Finally below 580 °C, the base material is generally unaffected [22,23]. The microstructure and zone width depend on the thermal cycle of the welded joint. Microstructure changes in the HAZ also depend on the prior thermal and mechanical history of the material. In addition, the temperatures stated above are dependent to some extent on the base metal composition, i.e. the phase diagram of the base material.

Among the zones found in the neighbourhood of a welded joint, the grain growth region and the partially transformed zone have the poorest mechanical properties. Hard martensitic structures often form in the grain growth zone because large grains have less nucleation sites for ferrite and pearlite. On the other hand, the partially transformed zone exhibits inhomogeneous properties that can cause difficulties.

Microstructure variability across the HAZ is not the only factor that affects the quality of the joint. Due to high temperatures and rapid cooling in the neighbourhood of the joint, residual stresses and strains are generated. Stresses are also induced by the austenite to ferrite phase transformation. In the fusion zone, crystal growth, segregation and cellular and dendritic solidification which add yet other factors that influence the behaviour of the joint.

In addition to the possibility of poor mechanical properties caused by unfavourable microstructure formation, the HAZ is sensitive to cracking and corrosion problems. So-called cold cracks form in the coarse grained region of the HAZ as it cools. The mechanism of formation appears to be driven by the appearance of high tensile shrinkage stresses. At the same time hardened microstructures of limited ductility and toughness such as bainite or martensite appear in this region as a result of the thermal cycle. Often such microstructures cannot resist the shrinkage action and cracks appear. They are termed cold cracks because they generally form below the M_s (martensite start) temperature which is in the range of 200°C to 400°C for most steels.

Even when a steel joint is free from defects such as cold cracks, it is often extremely sensitive to corrosion and in particular to stress corrosion cracking in service. The corrosion mechanism is not well known but seems to be generally

related to the formation of sensitive microstructures. In a general sense, hardened bainite and martensite seem to be the most sensitive microstructure to the corrosion problem [24].

As a result of the foregoing discussion it would seem that the hardness of the coarse grained HAZ is in some sense an indication of the sensitivity of the region to potential cold cracking and corrosion problems [24]. Furthermore, hardness is closely related to strength and toughness. As the hardness increases so does the strength but the toughness decreases [25]. It would seem, therefore, that hardness is in some sense a measure of the quality of a weld. In the industry, the maximum HAZ hardness of welded joint is often limited by specification (e.g. 320 VHN for offshore structures) [24]. This is primarily because of the relationship between hardness and cold cracking but is in addition related to the toughness and corrosion sensitivity of the joint.

The maximum HAZ hardness that develops in the HAZ depends on the base metal chemical composition and the weld thermal cycle. The chemical composition of the steel has a profound effect on the microstructure and hence hardness during the weld thermal cycle. The most significant chemical component is carbon. Often a carbon equivalent (Ceq) is assigned to reflect the effect of chemical composition on the weldability of a steel. The weld thermal cycle (both heating and cooling) depends on the arc voltage, current, welding speed, thermal

efficiency, the initial temperature and joint geometry. Semi-empirical relationships are available that combine chemical composition through a carbon equivalent and the thermal cycle through a cooling time from 800°C to 500°C to predict the HAZ hardness.

If the predicted as-welded HAZ hardness level is not appropriate for practice, welding engineers may specify preheat or post-heat to avoid HAZ cracking and ensure adequate joint properties. A mathematical model [12] is available to estimate the HAZ hardness of a weld after post weld treating. In addition, relatively comprehensive methods [13,14,15] are available for calculating the preheat temperature required to prevent cold cracking. However, the calculations involved are lengthy and troublesome. Consequently, welding engineers seldom use the available models in specifying operational parameters. Instead experimental trial and error techniques are often the method of choice. One of the objectives of this thesis is to generate a user friendly software system to encourage busy practising engineers to use the computational tools available to the welding industry.

Weld fusion area is said to be closely related to the HAZ mechanical properties [26]. In addition weld area is important to welding engineers as a measure of manufacturing or joining productivity. Chandel [17,18,19] has developed a mathematical system for predicting the size and shape of gas metal arc welds

(GMAW) from the welding conditions. The fusion area, deposit area, bead height, bead width, fusion penetration, fusion zone boundary length and reinforced material boundary length of a bead-on-plate weld can be approximated from the welding parameters: the arc voltage, current, speed, electrode diameter, electrode extension, electrode polarity and the type of shielding gas. A further objective of this thesis, therefore, is to develop the same kind of user friendly software system for computing weld areas as for computing HAZ hardness and preheat temperature.

SPECIFIC OBJECTIVES

In recent years, the use of low cost personal computer as an engineering tool has become commonplace. For those engineers involved in welding fabrication, lengthy calculations involving HAZ hardness, preheat temperature and weld area computations can be reduced to manageable levels with microcomputers if user friendly software is available. In this thesis particular attention is given to the development of a user friendly interface to input the welding parameters or weld cooling data, chemical composition, and for receiving graphical output. Database concepts are included for storing and retrieving frequently used compositions, welding parameters, etc.. In

addition, extensive graphics has been included to display the computations in user friendly form.

Four software modules have been developed :

- 1) **An as-welded HAZ hardness computational system (WH) based on eight semi-empirical HAZ hardness models proposed for this purpose:** Suzuki [1,2,3], Arata [4], Terasaki [5,6], Yurioka I [7] & II [8], Beckert [9], Dueren [10] and Cottrell [11]. The welding parameters, current, voltage, and welding speed are used to compute an 800°C to 500°C cooling time from the Adams [27,28] cooling time model. This is then submitted as input to the hardness models listed above to make the computation. Experimental cooling times if available can be submitted in lieu of the welding conditions.
- 2) **A reheat HAZ hardness computational system (RH) based on the reheat model of Yurioka et al. [12]:** the as-welded HAZ hardness is first calculated. The PWHT (post weld heat treated) hardness is then calculated from the post weld heat treatment temperature and time.
- 3) **A preheat temperature software system (PH) based on the work of Yurioka et al [13,14,15] for computing the minimum preheat temperature required to avoid cold cracking in the HAZ:** the input consists of chemical composition, welding condition, fusion zone hydrogen content, stress level and

geometry of the joint and the 1500°C to 100°C cooling time. The cooling time computation is estimated from a model proposed by Satoh and Matsui [29].

- 4) **A weld features software system (WF) to predict the weld bead size and shape of GMAW (gas metal arc welds) given the voltage, current, welding speed, electrode extension and diameter, type of shielding gas and electrode polarity:** the mathematical model for doing this was first derived by Chandel [17,18,19].

The use of these software modules in practice is discussed extensively. Finally some experimental hardness values are compared with predicted values [30] to provide an evaluation of the usefulness of these modules in practice. Computations of preheat temperatures to avoid cold cracking are compared with similar calculations from the early work of Seferian [31]. Weld area computations are discussed in terms of the experimental measurements of Chandel [17,18,19].

It has been suggested that object oriented programming technology might have some advantages for this kind of application. To test this hypothesis the as-welded HAZ hardness algorithm is implemented with SMALLTALK, an object-oriented language. The SMALLTALK version is compared with the procedural PASCAL version and discussed.

CHAPTER TWO
MODELS FOR PREDICTING HAZ
HARDNESS, PREHEAT TEMPERATURE
AND WELD SHAPE

The following is a description of the semi-empirical models used to compute the as-welded HAZ hardness, cooling time, reheat HAZ hardness, preheat temperature to avoid underbead cracking, and GMA weld size and shape.

2.1 HAZ HARDNESS MODELS

The computational structure of the first software module, WH, for predicting HAZ hardness is based on the information presented in this section. As mentioned in Chapter 1, the HAZ hardness depends on a number of parameters. The most significant parameters are the weld centre line 800°C to 500°C cooling time $T_{8/5}$ and the base metal chemical components. The 800°C to 500°C cooling time is used in the calculation because austenite decomposes to hardened bainite or martensite in this temperature range. In modern steels, alloying contributes to HAZ hardening in addition to the carbon content. A carbon equivalent, C_{eq} , is usually assigned to reflect the hardenability effect of the alloy constituents in addition to carbon present in the steel. While different models use

Figure 2.1 Schematic HAZ characteristic hardness curve (CHC).

Figure 2.2 HAZ temperature-time cooling profile.

different carbon equivalent formulae. They are all based on the same general principles. The upper limit of hardness is considered to be that of a fully hardened HAZ containing one hundred percent martensite. The lower HAZ hardness limit is that of a slowly cooled steel with zero percent martensite in the HAZ. Between these limits the hardness varies according to the martensite level. A typical HAZ hardness characteristic curve is shown in Figure 2.1. While hardness varies across the HAZ according to the microstructure in each sub-zone, usually the maximum hardness near the fusion zone is used to describe the hardening of a welded joint since this is the worst case area.

2.1.1 COOLING TIME $T_{8/5}$

All hardening models implemented in WH use the 800°C to 500°C cooling time $T_{8/5}$ and a carbon equivalent C_{eq} to compute the maximum HAZ hardness. The conventional view of heat flow associated with a weld has been described by Rosenthal [32,33]. A schematic sketch of the HAZ temperature-time profile is illustrated in Figure 2.2. Models for determining $T_{8/5}$, the weld centre line 800°C to 500°C cooling time, have been developed by Adams [27,28]. The Adams model is selected by many practitioners because of its simplicity and convenience. In addition, it is accurate within 20% for most cases. Because the

HAZ is sensitive to cooling times over some three orders of magnitude for most steels, a 20% variation in cooling time can be tolerated.

Because of the difference in the behaviour of three-dimensional (3-D) and two-dimensional (2-D) heat conduction in a plate, the moving heat source on the workpiece is visualized as a point or a line respectively, as illustrated in Figure 2.3. According to the difference in penetration, two different weld bead shapes can be observed. If the ratio of energy input to plate thickness is small, the penetration is shallow and heat flows into the surrounding material radially. A hemispherical bead shape is generated as shown in Figure 2.4. Heat flows in three-dimensional semi-space and the equation describing the temperature-time profile is referred to as the 3D formulation or the thick plate equation:

$$T_{8/5}[3D] = \frac{1}{2\pi k} \frac{Q}{v} \left[\left(\frac{1}{500 - T_0} \right) - \left(\frac{1}{800 - T_0} \right) \right] \quad (1)$$

where

- $T_{8/5}[3D]$ = 3D cooling time from 800°C to 500°C (s)
- k = thermal conductivity (J/(s mm K))
- Q = heat input rate (J/s)
- v = welding speed (mm/s)
- T_0 = plate initial temperature (°C)

Figure 2.3 Schematic diagram of a point and a line welding heat source.

Figure 2.4 Schematic heat flow representation for the thick plate welding situation.

Figure 2.5 Schematic representation of heat flow in the thin plate.

On the other hand, if the ratio is large, heat spreads away laterally and the bead shape has a shape similar to that shown in Figure 2.5. Heat flows in two-dimensional space and the temperature-time profile equation is referred as the 2D formulation or thin plate equation :

$$T_{8/5}[2D] = \frac{1}{4\pi k C \rho} \left(\frac{Q}{vh} \right)^2 \left[\left(\frac{1}{500 - T_o} \right)^2 - \left(\frac{1}{800 - T_o} \right)^2 \right] \quad (2)$$

where

- $T_{8/5}[2D]$ = 2D cooling time from 800°C to 500°C (s)
- C = specific heat (J/(kg K))
- ρ = density of base metal (kg/mm³)
- h = plate thickness (mm)

In addition, a 2.5D equation is used to describe the transitional behaviour of heat flow in a range intermediate to the 2D and 3D situations. A schematic diagram showing the 2.5D zone is shown in Figure 2.6 and the heat flow of a typical weld in this range is illustrated schematically in Figure 2.7. The 2.5D equation is stated as:

$$T_{8/5}[2.5D] = \frac{1}{C_r} \frac{1}{2\pi k} \frac{Q}{v} \left[\left(\frac{1}{500 - T_o} \right) - \left(\frac{1}{800 - T_o} \right) \right] \quad (3)$$

Figure 2.6 Schematic diagram showing the cooling time - plate thickness relationship in the 2.5D heat flow range.

Figure 2.7 Heat flow in the intermediate - thickness range between the 2D and 3D morphology.

where

$$T_{8/5}[2.5D] = 800^{\circ}\text{C to } 500^{\circ}\text{C } 2.5D \text{ cooling time}$$

C_r is the ratio of the thick plate cooling time to that of the finite plate. The value of C_r can be obtained either from Figure 2.8 or Table 2.1. H_r in the Figure and Table is the relative thickness which is calculated from the following equation:

$$H_r = \frac{C_p h^2 (T - T_0)}{Q/v} \quad (4)$$

where

$$T = 650^{\circ}\text{C, i.e., average of } 800^{\circ}\text{C and } 500^{\circ}\text{C.}$$

Table 2.1
Tabulated Values of C_r Corresponding to H_r

H_r	C_r
0.3	0.30
0.4	0.43
0.5	0.63
0.6	0.76
0.7	0.85
0.8	0.94
0.9	0.94
1.0	0.97

Figure 2.8 Values of C_r corresponding to H_r for computing cooling times in the transitional 2.5D heat flow range.

Figure 2.9 Sensitivity of thermal properties of iron to temperature changes.

The relative thickness is not only used in determining C_r but also for assigning the appropriate cooling time equations, 2D, 3D or 2.5D. If H_r is greater than or equal to 1.0, the 3D cooling time equation is appropriate. The 2.5D equation is used when H_r is between 0.3 and 1.0. Otherwise the 2D equation is the most suitable. This is summarized in Table 2.2.

Table 2.2

Criteria for Selecting the Appropriate
Weld Cooling Time Equation

<u>Criteria</u>	<u>Equation</u>
$H_r \geq 1.0$	3-D
$1.0 > H_r > 0.3$	2.5-D
$0.3 \leq H_r$	2-D

The heat input rate, Q , is calculated as the product of welding current, arc voltage and process efficiency:

$$Q = \eta IV \quad (5)$$

where

η = welding process efficiency (%)

V = welding voltage (Volt)

I = arc current (Amperes)

The welding process efficiency is a measured quantity determined from the ratio of energy absorbed by the workpiece to the energy output of the welding unit. It varies from

process to process primarily determined by the intensity of the radiation losses. A summary of commonly accepted efficiencies for the different processes, from the experimental work of Christensen [34] and from the investigation of Yurioka [7] is listed in Table 2.3.

Table 2.3

Summary of Welding Process Efficiencies for
Commonly Used Welding Heat Sources.

<u>Process</u>	<u>Efficiency (%)</u>
SMAW	80
SAW	95
GMAW	70
GTAW	40
EBW	85

The thermal properties of steel, thermal conductivity (k) and volumetric specific heat (C_p), are quite sensitive to temperature as shown schematically in Figure 2.9. Mean values for these properties are used in the Adams approach. A thermal conductivity (k) for steel of $0.025 \text{ J}/(\text{mm s K})$ and a volumetric specific heat (C_p) of $0.006 \text{ J}/(\text{mm}^3\text{K})$ are considered appropriate. In the cooling time equations, several other assumptions are made. It is assumed that there are no heat losses through the surface by radiation or convection and that heat flows only by conduction in an infinite working medium.

Furthermore, the thermal properties of the base metal, the welding speed and thus the rate of energy input are assumed constant with time.

2.1.2 THE SUZUKI HAZ HARDNESS MODEL

Suzuki [1,2,3] assumed the HAZ hardness versus $T_{8/5}$ cooling time characteristic curve to be a backward logistic function as shown schematically in Figure 2.10. The backward logistic curve can be represented by equation 6, where K , a and Y are constants depending on the base metal chemical composition.

$$H_{\max} = H_{bm} + \frac{K}{1 + \exp(a(\log T_{8/5} - Y))} \quad (6)$$

where

$H_{\max}$ = maximum hardness in the HAZ (VHN)

H_{bm} = base metal hardness (VHN)

$T_{8/5}$ = weld centre line 800 to 500 °C cooling time (s)

From a stepwise multiple regression analysis (eleven alloying elements), the backward logistic constants are determined as follows:

$$K = 269 + 454C - 36Si - 79Mn - 57Cu - 12Ni - 53Cr - 122Mo - 169Nb - 7089B \quad (7)$$

$$H_{bm} = 884C + 287 - K \quad (8)$$

$$aK = 478 + 3364C - 256Si + 66Ni - 408Mo - 1321V - 1559Nb \quad (9)$$

Figure 2.10 Schematic characteristic hardness curve assumed by Suzuki (3).

Figure 2.11 Schematic characteristic hardness curve assumed by Arata (4).

$$Y = -0.035 + 2.07C + 0.495Mn + 0.655Cu + 0.122 Ni + 0.222Cr + 0.788Mo + 30B \quad (10)$$

All base metal chemical compositions are in weight percent (wt%). Since the hardness equation is semi-empirical, it is only valid for certain compositional ranges. The carbon limits are 0.017 wt% and 0.33 wt%.

2.1.3 THE ARATA HAZ HARDNESS MODEL (α FORMULATION)

T_{M100} and T_{M0} in Figure 2.11 indicate the critical cooling times ($T_{8/5}$) for one-hundred percent and zero percent martensite transformation at the weld line in the HAZ respectively. In order to approximate the HAZ hardness characteristic curve, Arata [4] assumed that the martensite hardness is a constant H_{VM100} when $T_{8/5}$ is less than T_{M100} . The hardness then decreases from point A through point B according to the fraction martensite formed at the weld line.

In the Arata formulation for predicting HAZ hardness, steels are classified into two main categories. The high strength (HT) steels and the conventional steels. The conventional steels contains alloying elements other than carbon, e.g. Si and Mn, of less than 0.1 wt%. All base metal chemical compositions are in weight percent (wt%).

The characteristic values for conventional steels:

Characteristic values at A, see Figure 2.11, i.e., 100% martensite:

$$H_{VTM100} = 835C + 287 \quad (11)$$

$$\log(T_{M100}) = 2.55 \left(C + \frac{Mn}{6.3} + \frac{Si}{3.6} \right) - 0.92 \quad (12)$$

Characteristic values at B, see Figure 2.11, i.e., 0% martensite:

$$H_{VTM0} = 273 \left(C + \frac{Mn}{13} + \frac{Si}{9.7} \right) + 133 \quad (13)$$

$$\log(T_{M0}) = -0.37 \left(C - \frac{Mn}{1.1} - \frac{Si}{0.44} \right) + 1.02 \quad (14)$$

For $T_{8/5}$ cooling times between T_{M100} and T_{M0} :

$$H_v = \frac{b}{e^{\log(T_{8/5} + a)}} + 150 \quad (15)$$

$$a = \frac{T_{M100} [\log^{-1}(\ln \frac{H_2}{H_1})] - T_{M100}}{1 - \log^{-1}(\ln \frac{H_2}{H_1})} \quad (16)$$

$$b = H_1 e^{\log(T_{M100} + s)} \quad (17)$$

$$\text{where } H_1 = H_{VTM100} - 150 \quad (18)$$

$$H_2 = H_{VTM0} - 150 \quad (19)$$

where

H_{VTM100} = hardness of 100% martensite (VHN)

H_{VTM0} = hardness of 0% martensite (VHN)

T_{M100} = 800 to 500°C cooling time for 100%
martensite transformation (s)

T_{M0} = 800 to 500°C cooling time for 0%
martensite transformation (s)

The characteristic values for high strength steels:

Characteristic values at A, see Figure 2.11, i.e., 100%
martensite:

$$H_{VTM100} = 835C + 287 \quad (20)$$

$$\log(T_{M100}) = 5.9 \left(C + \frac{Mn}{19} + \frac{Si}{14} + \frac{Ni}{37} + \frac{Cr}{19} + \frac{Mo}{9.1} - \frac{V}{49} + \frac{B}{0.31} \right) - 1.13 \quad (21)$$

Characteristic values at B, see Figure 2.11, i.e., 0%
martensite:

$$H_{VTMO} = 500 \left(C - \frac{Mn}{38} - \frac{Si}{68} - \frac{Ni}{45} + \frac{Cr}{9} + \frac{Mo}{9.9} + \frac{V}{2.1} + \frac{B}{0.48} \right) + 153 \quad (22)$$

$$\begin{aligned} \log T_{M0} = & -0.2 \left(C - \frac{Mn}{4.3} - \frac{Si}{0.4} - \frac{Ni}{0.58} + \frac{Cr}{0.45} - \frac{Mo}{0.49} + \frac{V}{240} - \frac{B}{0.0024} \right) \\ & + 1.60 \end{aligned} \quad (23)$$

For $T_{8/5}$ cooling times between T_{M100} and T_{M0} :

$$H_v = \frac{b}{e^{\log(T_{8/5} + a)}} + 160 \quad (24)$$

where

$$H_1 = H_{VTM100} - 160 \quad (25)$$

$$H_2 = H_{VTMO} - 160 \quad (26)$$

a and b can be determined from equations 16 and 17 respectively.

Values stated in Table 2.4 are limitations to the Arata equations in terms of base metal chemical composition.

Table 2.4

Chemical Composition Limits for
the Arata Relationships

Alloying Element -----	wt% range -----
C	0.07 - 0.53
Mn	0.0 - 1.50
Si	0.0 - 0.60
Ni	0.0 - 3.5
Cr	0.0 - 1.5
Mo	0.0 - 0.6
V	0.0 - 0.15
B	0.0 - 0.01

2.1.4 THE TERASAKI HAZ HARDNESS MODEL

Based on the same CHC principles, Terasaki [5,6] proposed similar equations to estimate the characteristic hardness curve.

For $T_{8/5}$ less than or equal to T_M :

$$H_{\max} = 812C + 293 \quad (27)$$

For $T_{8/5}$ greater than T_M :

$$H_{\max} = H_{VJ} + (H_{VJ} - H_{VM}) \exp(-0.2 (\frac{T_{8/5}}{T_M} - 1)) \quad (28)$$

where

$$H_{VM} = H_{max} \quad (29)$$

$$H_{V0} = 164 \left(C + \frac{Si}{2} + \frac{Cr}{7} + \frac{Mo}{2} + V + Nb + 7B \right) + 153 \quad (30)$$

$$\log T_M = 2.5C_{eq} - 1.27 \quad (31)$$

$$C_{eq} = C + \frac{Mn}{3} + \frac{Cu}{4} + \frac{Ni}{8} + \frac{Cr}{10} + \frac{Mo}{3} + 5B \quad (32)$$

where

H_{VM} = hardness of 100% martensite (VHN)

H_{V0} = hardness of 0% martensite (VHN)

T_M = 800 to 500 °C cooling time for 100%
martensite transformation (s)

C_{eq} = carbon equivalent.

It is evident that the Terasaki relationships are somewhat less complex than the Arata system.

2.1.5 THE YURIOKA I HAZ HARDNESS MODEL

Yurioka et al [7] proposed an alternative formula for predicting the HAZ hardness. Instead of using the one carbon equivalent formulation of Terasaki, Yurioka proposed two carbon equivalents as follow:

$$H_v = 406 C + 164 C_{eqI} + 183 - (369 C - 149 C_{eqI} + 100) \cdot$$

$$\tan^{-1} \left(\frac{\log T_{8/5} - 2.822 C_{eqII} + 0.262}{0.526 - 0.195 C_{eqII}} \right) \quad (33)$$

where

$$C_{eqI} = C + \frac{Si}{24} + \frac{Mn}{6} + \frac{Cu}{15} + \frac{Ni}{40} + \frac{Mo}{4} + \frac{V}{5} + \frac{Nb}{5} + 10B \quad (34)$$

$$C_{eqII} = C - \frac{Si}{30} + \frac{Mn}{5} + \frac{Cu}{5} + \frac{Ni}{20} + \frac{Cr}{4} + \frac{Mo}{6} + 10B \quad (35)$$

The first carbon equivalent, C_{eqI} , determines the slow cooling hardness and the second carbon equivalent, C_{eqII} , is concerned with the critical cooling times for appearance of 100% and 0% martensite. This formulation can be applied to steels containing between 0.01 to 0.30 wt% carbon.

2.1.6 THE YURIOKA II HAZ HARDNESS MODEL

Beside the previous model, Yurioka et al [8] has also proposed a HAZ hardness relationship for so-called transformable higher alloy steels. The alloy limits are listed in Table 2.5.

Table 2.5
Alloy Limits for the Yurioka II Model

Alloying Element -----	Wt% Range -----
C	< 0.8
Si	< 1.2
Mn	< 2.0
Cu	< 0.9
Ni	< 10.0
Cr	< 10.0
Mo	< 2.0

$$H_{vmax} = 220 + 442C(1 - 0.3C^2) + 65 \tanh y +$$

$$[68 + 402C(1 - 0.3C^2) - 59 \tanh y] \tan^{-1} x \quad (36)$$

where

$$x = \frac{\log T_{8/5} - 2.3 CE_I - 1.35 CE_{III} + 0.882}{1.15 CE_I - 0.673 CE_{III} - 0.601} \quad (37)$$

$$y = 2.65 CE_{II} - 0.690 \quad (38)$$

$$CE_I = C_p + \frac{Si}{24} + \frac{Mn}{6} + \frac{Cu}{15} + \frac{Ni}{12} + \frac{Cr(1-0.16\sqrt{CE})}{8} + \frac{Mo}{4} + \Delta H \quad (39)$$

$$CE_{II} = C + \frac{Si}{24} + \frac{Mn}{5} + \frac{Cu}{10} + \frac{Ni}{18} + \frac{Cr}{5} + \frac{Mo}{2.5} + \frac{V}{5} + \frac{Nb}{3} \quad (40)$$

$$CE_{III} = C_p + \frac{Mn}{3.6} + \frac{Cu}{20} + \frac{Ni}{9} + \frac{Cr}{5} + \frac{Mo}{4} \quad (41)$$

where $CE_{I,II,III}$ = carbon equivalents

C_p = effective carbon

= C if $C \leq 0.3$ wt%

= $0.25 + C/6$ if $C > 0.3$ wt% (42)

ΔH = increase in hardenability due to boron

for $S \leq 0.016$ wt% and $O_2 \leq 60$ ppm ;

ΔH values are determined from Table 2.6

Table 2.6

 ΔH Values Corresponding to Boron Content

Boron content (ppm)	ΔH value
-----	-----
≤ 1	0
$= 2$	0.03 fn
$= 3$	0.06 fn
≥ 4	0.09 fn

where $fn = (0.02 - N)/0.02$ (43)
 N is the nitrogen content in percentage weight.

2.1.7 THE BECKERT HAZ HARDNESS MODEL

In some early work in Germany, Beckert [9] has also proposed a relationship for the characteristic hardness curve (CHC) as follows:

$$H_{max} = H_{v0} + (H_{VM} - H_{v0}) e^{-(bT_{8/5})^2} \quad (44)$$

$$H_{VM} = 939 C + 284 \quad (45)$$

$$H_{v0} = 167 C_{eq}^{2.42} + 137 \quad (46)$$

$$b = e^{-0.013 H_{v0} + 0.8} \quad (47)$$

$$C_{eq} = C + \frac{Si}{11} + \frac{Mn}{2.9} + \frac{Cu}{3.9} + \frac{Ni}{17} + \frac{Cr}{3.2} + \frac{Mo}{3.4} \quad (48)$$

where

H_{VM} = hardness at 100% martensite transformation

H_{V0} = hardness at 0% martensite transformation

C_{eq} = carbon equivalent.

2.1.8 THE DUEREN HAZ HARDNESS MODEL

The Dueren model [10] for predicting HAZ hardness is based on a large database of experimental results for welds on large diameter pipe steels. The Dueren relationship is as follows:

$$H_{Vmax} = 2019 [C(1 - 0.5 \log T_{5/5}) + 0.3(C_{eq} - C)] \\ + 66(1 - 0.8 \log T_{8/5}) \quad (49)$$

$$H_{VM} = 802C + 305 \quad (50)$$

$$H_{VB} = 350C_{eq} + 101 \quad (51)$$

$$C_{eq} = C + \frac{Si}{11} + \frac{Mn}{8} + \frac{Cu}{9} + \frac{Ni}{17} + \frac{Cr}{5} + \frac{Mo}{6} + \frac{V}{3} \quad (52)$$

where

H_{VM} = hardness of 100% martensite transformation

H_{VB} = hardness of 100% bainite transformation

ie. 0% martensite transformation

2.1.9 THE COTTRELL HAZ HARDNESS MODEL

Cottrell [11] noted that the hardening effect of nitrogen in steel is much stronger than that of carbon. Therefore, in his formulation for predicting HAZ hardness, the hardenability of nitrogen has been included even though the nitrogen content is often small. Cottrell's formulation is as follows:

$$H_v = 80 + 800 (C + 3N + 0.29) e^{-(0.025 r^{1.5 C_{eq}} + \frac{Ni}{Mn^2})^{-1}} \quad (53)$$

$$C_{eq} = C + \frac{Mn}{6} + \frac{Cr}{5} + \frac{Mo}{5} + \frac{V}{3} + \frac{Nb}{4} C + \frac{0.0001}{S} \quad (54)$$

where

r = 800 to 500 °C cooling rate (K/s)

$$= (800 - 500) / T_{8/5} \quad (55)$$

C_{eq} = carbon equivalent.

The alloy limits are listed in Table 2.7.

Table 2.7

Alloy Limits for the Cottrell Model

Alloying Element	wt% Range
C	0.06 - 0.23
Si	0.00 - 0.55
Mn	1.01 - 2.00
Ni	0.00 - 0.89
Cr	0.00 - 0.20
Mo	0.00 - 0.54
V	0.00 - 0.15
Nb	0.00 - 0.05
Cu	0.00 - 0.30
S	0.002 - 0.043
N	0.003 - 0.010

2.2 THE REHEAT HAZ HARDNESS MODEL

The application of supplementary heat to a joint before or after welding can be a very important part of a welding procedure. The application of heat to a joint that has been fully joined by welding is called post weld heat treatment (PWHT) or postheating. Post weld heat treatment may be applied to the entire weldment or to a localized portion of the workpiece in order to relieve residual stress, improve toughness, increase strength and reduce HAZ hardness. Usually reducing HAZ hardness is the principal concern since high

Figure 2.12 Schematic sketch of hardness versus postheat time for different postheat temperature (36).

hardness levels in the HAZ are associated with corrosion sensitivity and service cracking.

Often the HAZ of a weld cools so rapidly that the principal austenite decomposition product is hard martensite. During PWHT, minute crystals of carbides develop in the martensite. The hard martensite transforms to softer fine ferrite and carbide. The fine dispersion of carbide particles in the martensite hinders slip and thus the hardness is relatively high. As the carbide particles coarsen with time during reheating, the ability to hinder slip reduces and so does the hardness. These microstructure changes take place at about 550°C to 650°C. Figure 2.12 is a schematic sketch of the hardness versus time for different PWHT temperatures.

The semi-empirical model originally proposed by Yurioka et al [12] is the basis of the software used to predict the HAZ hardness after PWHT. The reheat software (RH) is based on this model. PWHT usually has the effect of reducing the as welded HAZ hardness, H_{VAM} , by an amount designated by ΔH_V . ΔH_V is assumed to be depended on the volumetric ratio of martensitic structure in the HAZ, M . The as-welded HAZ hardness of carbon and low alloy steels are given by the following equations:

$$H_V = \frac{(H_M + H_B)}{2} - \frac{(H_M + H_B) \tan^{-1} x}{2.20} \quad (56)$$

$$X = \frac{4 \log \frac{T_{8/5}}{T_M}}{\log \frac{T_B}{T_M}} - 2 \quad (57)$$

where $H_M = 884C + 294 \quad (58)$

= hardness of 100% martensite transformation

$$H_B = 197CE_{II} + 117 \quad (59)$$

= hardness of 0% martensite transformation

$$T_M = \exp (10.6CE_I - 4.8) \quad (60)$$

= critical 800 to 500 °C cooling time for
100% martensite transformation (s)

$$T_B = \exp (6.2CE_{II} - 0.74) \quad (61)$$

= critical 800 to 500°C cooling time for 0%
martensite transformation (s)

$$T_{8/5} = 800 \text{ to } 500^\circ\text{C cooling time calculated from}$$

Adams cooling time model (s).

The carbon equivalents C_{eqI} , C_{eqII} and C_{eqIII} are defined as follows:

$$CE_I = C + \frac{Si}{24} + \frac{Mn}{6} + \frac{Cu}{15} + \frac{Ni}{12} + \frac{Cr}{8} + \frac{Mo}{4} \quad (62)$$

$$CE_{II} = C + \frac{Si}{24} + \frac{Mn}{5} + \frac{Cu}{10} + \frac{Ni}{18} + \frac{Cr}{5} + \frac{Mo}{2.5} + \frac{V}{5} + \frac{Nb}{3} \quad (63)$$

$$CE_{III} = C + \frac{Mn}{3.6} + \frac{Cu}{20} + \frac{Ni}{9} + \frac{Cr}{5} + \frac{Mo}{4} \quad (64)$$

The PWHT HAZ hardness is determined by subtracting the as welded HAZ hardness from the reduction in HAZ hardness:

$$H_{VPWHT} = H_{VAW} - \Delta H_v \quad (65)$$

ΔH_v depends on both the volumetric ratio of martensite structure in HAZ, M , and the extent of the heat treatment which is expressed as a temper parameter, TP :

$$M = 0.5 - 0.455 \tan^{-1} x \quad (66)$$

$$TP = \frac{T(20 + \log t)}{10^3} \quad (67)$$

where T = reheat temperature in K
 $= 550^\circ\text{C} < T < 650^\circ\text{C}$
 t = duration of PWHT in hour
 $= 1 \text{ hr} < t < 10 \text{ hr.}$

ΔH_v is given as in the following equation:

$$H_a = 884C + 177 - 197CE_{II} + 16.5(TP - 21.5) \quad (68a)$$

$$H_b = [18(TP-18)^2 - 138] V^{1/2} \quad (68b)$$

$$H_c = [20(TP-18)^2 - 268] Nb^{1/2} \quad (68c)$$

$$H_d = [25(TP-17.3)^2 - 55] Mo^{1/2} \quad (68d)$$

$$\Delta H_v = H_a M + H_b + H_c + H_d - 7 CE_{II} + 26 \quad (68d)$$

Certain alloying elements are limited in this model. The limitations are listed in Table 2.8.

Table 2.8

Alloy Limits for the Reheat Model

Alloying Element	Wt% Range
-----	-----
C	0 - 0.3
Si	0 - 1.2
Mn	0 - 2.0
Cu	0 - 0.9
Ni	0 - 5.0
Cr	0 - 1.0
Mo	0 - 2.0
B	0 - 2 ppm

2.3 PREHEAT TEMPERATURE TO AVOID HAZ COLD CRACKING

The hardness and cracking susceptibility of a joint may also be decreased by preheating. In preheating, the entire part or, alternatively, the localized joint is heated immediately before welding. The preheat temperature depends on the welding conditions, the base metal chemical composition and the rigidity of the workpiece. Preheat temperatures are usually lower than reheat temperatures. The major advantage of preheat is to avoid cold cracking by alleviating the effects of hydrogen which enters the base metal HAZ. Furthermore, preheating the workpiece can minimize shrinkage and distortion, and reduce residual stresses during and after welding.

In order to determine the preheat temperature, surface thermometers or thermocouples, colored chalks that change color at known temperatures and pellets that melt at known temperatures are frequently employed [35,36]. The best method of preheating is to put the entire workpiece into a furnace and apply heat uniformly. However uniform preheat is confined to small workpieces. For the local preheat treatment, electrical resistance heating elements are often mounted around the joint.

Allowance must be made for cooling before welding. On the other hand, excessive preheat may be harmful and costly. Too much preheat may hinder the welder's ability to produce a sound

weld and may induce hot cracking by increasing the segregation of residual elements in the weld deposit.

In general, preheating the workpiece prolongs the cooling time. Preheating reduces the thermal conductivity and thermal gradients. As a result, heat from the weld zone spreads more slowly and this results in correspondingly slower cooling rates and longer cooling times. With the HAZ at a higher temperature for a longer period, the transformation of austenite to pearlite is encouraged and the amount of hard martensite is reduced.

The model used for determining the preheat temperature necessary to prevent the formation of HAZ cold cracking in this thesis was first proposed by Yurioka et al [13,14,15]. The cooling time from 1500°C to 100°C is incorporated in the Yurioka model for both uniform and local preheat situation. The Satoh and Matsui formulations [29] are used to make the cooling time computations under preheat conditions.

2.3.1 THE YURIOKA PREHEAT MODEL

In general, thermal shrinkage causes enormous elastic and plastic tensile stresses and strains after welding. These stresses encourage the formation of cold cracks. The hard martensitic HAZ microstructure limits slip while the workpiece is adjusting to thermal shrinkage. As a result, cold cracks are

usually found in the HAZ. Cold cracking is so named because it usually occurs at a temperature below 100°C. In addition, hydrogen plays a significant role in cold cracking. During welding, water vapour in the air decomposes to oxygen and hydrogen molecules. Hydrogen is absorbed into the weld pool. It penetrates the HAZ by high temperature diffusion. When the weld cools, the solubility of hydrogen decreases, some of the hydrogen escapes to the surface but the remainder stays in the base metal and forms microporosity. The microporosity acts as initiation sites for cold cracking. Cold cracking is sometimes also termed hydrogen cracking because of its close relationship with the hydrogen content in the weld. Cold cracking is also sensitive to stress level at the toe or root of a weld. At the same time, hydrogen cracks can appear well after the weld cooled. This is called delayed cracking and is viewed as a dangerous, insidious condition.

The Yurioka model relates the base metal chemical composition, welding conditions, stress level at the joint and the hydrogen content in the weld to predict a critical cooling time T_{cr} . The critical cooling time is the minimum required for the weld to cool from solidification, 1500°C, to 100°C to avoid cold cracking. The 1500°C to 100°C cooling time is selected because this is the time available for hydrogen to escape. If the measured or calculated weld cooling time, $T_{15/1}$, is less

than the critical cooling time T_{cr} , cold cracking is less likely to appear in the HAZ.

As in the HAZ hardness models described perviously, the chemical composition of the base metal reflects the hardenability of the HAZ. The richer the chemistry the higher the hardenability of the material and hence the greater the possibility of crack formation. A carbon equivalent, CE, is assigned in the calculation:

$$CE = C + [0.75 + 0.25 \tanh(20C - 0.12)] * \left(Si + \frac{Mn}{6} + \frac{Cu}{15} + \frac{Ni}{20} + \frac{Cr + Mo + Nb + V}{5} + 5B \right) \quad (69)$$

The weld stress level is given by a restraint intensity factor, R_f , which reflects the resistance of the workpiece to thermal shrinkage as the weld cools. R_f is calculated as follows:

$$R_f = 71 r_f \left[\tan^{-1}(0.017h) - \left(\frac{h}{400} \right)^2 \right] \quad (70)$$

$$\sigma_w = 0.05 R_f \quad \text{if } R_f \leq 20\sigma_y \quad (71)$$

$$\sigma_w = \sigma_y + 0.0025(R_f - 20\sigma_y) \quad \text{if } R_f > 20\sigma_y \quad (72)$$

where

r_f = restraint coefficient (N/mm^3)

h = thickness of the workpiece (mm)

σ_w = nominal tensile stress acting on the weld metal
(N/mm²)

σ_y = yield strength of the weld metal (N/mm²)

The restraint coefficient depends on the joint configuration. It has a value between 700 N/mm³ (complex joint configuration) and 400 N/mm³ (simple joint configuration). A series of values for r_f are given in Table 2.9. The stress level also depends on joint preparation. A group of effective joint preparation stress concentration factors, K_t , have been prepared by Yurioka and are tabulated in Table 2.10.

A cracking index, CI is calculated from σ_w , CE, K_t and hydrogen level (H_{JIS}). The hydrogen level (H_{JIS}) is the value determined by 'glycerin method':

$$CI = CE + 0.15 \log H_{JIS} + 0.3 \log (0.0017 K_t \sigma_w) \quad (73)$$

The hydrogen level determined by the 'mercury method', H_{IIW} is contained in Figure 2.13. Suzuki [37] suggests a conversion relationship from H_{IIW} to H_{JIS} :

$$H_{JIS} = 0.77 H_{IIW} - 0.47 \quad (\text{ml/100g}) \quad (74)$$

Finally the critical cooling time from 1500°C to 100°C, T_{cr} , is expressed as a function of cracking index, CI:

Table 2.9

Values of Coefficient of Restraint Intensity
for Various Joint Configurations [53].

Joint shape / Test	2D Restraint Coeff. $r(N/(mm \cdot mm))$
Tekken Test	690
Stout Test	490
H-slit Test	680
MRC Test	E/1
Ordinary Joints: e.g. bridges, steel frames, spherical vessels, ship hulls, fabricated joints, etc..	≤ 390

$E = 210 \text{ kN/mm}$ (Young's Modulus of steel).

l = length of restraint (mm).

Table 2.10

Stress Concentration Factors at Root and Toe Weld Positions in Various Weld Joints [13].

Groove type	K_t
y (root)	4
Double-Vee (root)	3.5
Y (root)	4~5
Single-bevel (root)	6~8
V (root)	1.5
y, x, Y, V, U (toe)	1.5

$$T_{cr} = e^{16.6CR^3 - 182CR^2 + 103.8(CR - 41)} \quad (75)$$

2.3.2 COOLING TIME EQUATIONS FOR THE PREHEAT MODEL

In order to obtain the required preheat temperature to avoid cold cracking, the weld cooling time, $T_{15/1}$, is compared with the critical cooling time T_{cr} . $T_{15/1}$ depends not only on the welding process but also the plate thickness and type of preheat treatment i.e., uniform preheat or local preheat. Satoh and Matsui [29] proposed the following equations to relate final temperature, T , after cooling time, t , with ambient temperature, T_o , and preheat temperature, T_{ph} :

For uniform preheat:

$$T = T_o + \left[\frac{Q\alpha}{kh} \frac{1}{\sqrt{4\pi\alpha t}} + (T_{ph} - T_o) \right] e^{-\frac{\alpha S}{kV_w} t} \quad (76)$$

where

$$Q = \text{energy input per unit length (J/mm)} \\ = \eta VI/v, \quad \eta = \text{welding process efficiency (\%)} \quad (77)$$

V = welding voltage (Volt)

I = arc current (Amp)

v = welding speed (mm/s)

α = thermal diffusivity (mm^2/s)

k = thermal conductivity (J/mm s K)

T_o = ambient temperature ($^{\circ}\text{C}$)

T_{ph} = preheat temperature ($^{\circ}\text{C}$)

t = cooling time (s)

S = total surface area of the workpiece (mm^2)

V_w = total volume of the workpiece (mm^3)

For local preheat:

$$T = T_o + \left\{ \frac{Q\alpha}{kh} \frac{1}{\sqrt{4\pi\alpha t}} + (T_{ph} - T_o) \right\} \left[\frac{F(\beta_1) - F(\beta_2)}{F(\beta_0)} \right] \left(\frac{2\alpha t}{kh} \right) \quad (78)$$

where

$$T_{ph} = T_o + \frac{qb}{4k} F(\beta_0) \quad (79)$$

$$F(\beta) = \frac{\text{erf}(\beta)}{2\beta^2} + \frac{e^{-\beta^2}}{\sqrt{\pi}\beta} - [1 - \text{erf}(\beta)] \quad (80)$$

and

$$\beta_0 = \frac{b}{\sqrt{4\alpha t_{ph}}} \quad (81)$$

$$\beta_1 = \frac{b}{\sqrt{4\alpha(t + t_{ph})}} \quad (82)$$

$$\beta_2 = \frac{b}{\sqrt{4\alpha t}} \quad (83)$$

erf = error function

b = heater width (mm)

q = heat input of the heater (J/s)

t_{ph} = preheating time (s)

The thermal properties of the base metal are the same as those used in the previous models. The preheat temperature in the locally preheated plate relationship depends on the power and the width of the heater and also the preheating time, t_{ph} . The calculation of the required preheat temperature or time is an iterative process. The iteration starts by setting cooling time (t) in the Satoh and Matsui equations equal to the critical cooling time (T_{cr}) - calculated from the Yurioka preheat model, and calculates the final temperature (T). Preheat is added until the final temperature is greater than or equal to 100°C .

2.4 WELD SHAPE

It has been suggested that weld fusion area can be used as a basis for predicting some HAZ mechanical properties [26]. Shultz and Jackson [26] have shown that there is a linear relationship between the weld metal deposit area and yield strength. Furthermore, a relationship between fusion area and HAZ hardness has been established [26]. The HAZ hardness decreases exponentially as the fusion area increases as shown in Figure 2.14.

Fusion zone size and shape are also important parameters in estimating the cost of welding during fabrication. For example, in order to increase productivity, the melting rate should be increased which can be achieved by increasing the

Figure 2.13 Hydrogen level HIIW in weld [37].

Figure 2.14 Schematic relationship of HAZ hardness and fusion nugget area [26].

welding current. However, if the current is increased, the energy input is also increased and hence the weld metal toughness may be affected. However, the weld speed may be increased to compensate for the negative effect of higher current. By increasing the welding speed, centre line cracking and incomplete penetration may be induced. On the other hand, melting rate can also be increased for fixed current and travel speed by using electrode negative polarity, longer electrode extension and smaller electrode diameter [26,35,36,38]. In view of the foregoing discussion it is apparent that modelling the weld features is important in establishing optimum processing for a minimum number of trials and thereby reducing the cost.

Variations in welding conditions modify the properties of weld deposits by their effect on the dilution, solidification and transformation processes for the weld metal. These complex processes are governed by the rapid weld thermal cycle. In addition, the nature and pattern of heat flow during solidification and surface tension of weld metal increases the complexity of the problem. As a result, a fundamental model for predicting weld size and shape is not easily achieved. On the other hand, semi-empirical modelling based on regression techniques is possible [17,18,19,39].

The chemical composition of the base material has little effect on the dimensions of weld bead for steels. The geometry

of the weld bead depends on the fusion temperature, surface tension and thermal conductivity which are relatively independent of alloying [40].

Chandel [19] has assembled an enormous database that relates the effect of welding conditions to the geometry of the weld fusion zone based for GMAW welding. From this he established regression relationships for computing the size and shape of the weld bead. The weld size and shape are defined in Figure 2.15. Both the plate and wire melted areas are considered. In general, the weld shape depends greatly on the heat input and the thermal cycle. Although process efficiency affects the weld shape, it is assumed constant for the GMAW process and is, therefore, eliminated in the model.

The Chandel weld bead features relationship is a logarithm formulation as follows:

$$\text{Feature} = 10^K I^a V^b v^c D^d L^e \quad (84)$$

where I = welding current (Amp)
 V = arc voltage (Volt)
 v = travel speed (mm/s)
 D = electrode diameter (mm)
 L = electrode extension (mm)

and a, b, c, d, e and K are constants which depend on electrode polarity and the shielding gaseous composition. The weld

W = bead width

H = bead height

P = penetration

$A1$ = deposited area

$A2$ = plate fusion area

$C1$ = length of the reinforcement boundary

$C2$ = length of the fusion boundary

Figure 2.15 Definitions of weld shape.

features include fusion area, bead width, bead height, fusion boundary length, penetration and reinforce boundary length. The fusion area increases with current, voltage, electrode extension and heat input. This has the effect of increasing both the wire metal and plate metal melting rates. Higher wire melting rates can be obtained by increasing current, employing smaller diameter electrodes and fixing longer electrode extensions. In order to increase plate melting rates, higher current, voltages and heat input should be used. Bead height and length of the reinforcement boundary depend on the wire melting rate. Penetration and length of fusion boundary depend on the plate melting rate. The values of a , b , c , d , e and K are tabulated in Table 2.11 based on the multiple regression analysis of Chandel. It should be noted that these equation are strictly valid only for GMAW bead-on-plate welds but are nevertheless useful for other joint configurations. The melting rate equation has the form:

$$MR = wI - xIV + y \frac{I^2 L}{D^2} + z \quad (85)$$

where the values of w , x , y and z are given in Table 2.12 [19]. The deposited area, A_1 can be calculated from the equation :

$$A1 = 35.47 \cdot \frac{MR}{v} \quad (86)$$

where $A1$ = deposited area (mm^2)

MR = melting rate (kg/h)

v = travel speed (mm/s)

and the plate fusion area, $A2$, is calculated by subtracting the deposited area from the fusion area, A :

$$A2 = A - A1 \quad (87)$$

Table 2.11a
Coefficients for Weld Features Equation
(C-25 Shielding Gas and +ve Electrode Polarity)

Feature	K	a	b	c	d	e
A	-2.35	1.689	0.26	-0.85	-0.63	0.2535
BW	-0.218	0.181	0.86	-0.614	0.567	0.0106
BH	-1.382	1.2	-0.69	-0.45	-1.36	0.38
P	-4.03	2.05	0.142	-0.53	-0.86	-0.063
C1	-0.85	0.822	0.154	-0.55	-0.3	0.20
C2	-1.55	0.88	0.70	-0.456	0.112	-0.071

Table 2.11b
Coefficients for Weld Features Equation
(C-25 Shielding Gas and -ve Electrode Polarity)

Feature	K	a	b	c	d	e
A	-1.517	1.377	0.271	-0.905	-0.298	0.19
BW	-1.5	0.52	0.272	-0.57	0.275	-0.0001
BH	-0.46	0.69	-0.46	-0.36	-0.66	0.337
P	-3.25	1.74	-0.093	-0.366	-0.46	-0.063
C1	0.489	0.46	-0.12	-0.53	-0.025	0.164
C2	-0.52	0.71	0.31	-0.57	0.15	-0.052

Table 2.11c
Coefficients for Weld Features Equation
(M-2 Shielding Gas and +ve Electrode Polarity)

Feature	K	a	b	c	d	e
A	-2.29	1.615	0.202	-0.835	-0.68	0.34
BW	-1.004	0.534	0.66	-0.307	0.146	0.0258
BH	-1.44	1.07	-0.54	-0.45	-1.37	0.49
P	-3.5	0.535	2.61	-0.34	-0.876	-0.689
C1	-0.637	0.8	-0.036	-0.492	-0.456	0.246
C2	-1.28	0.60	0.82	-0.264	0.176	-0.029

Table 2.11d
Coefficients for Weld Features Equation
(M-2 Shielding Gas and -ve Electrode Polarity)

Feature	K	a	b	c	d	e
A	-0.544	1.123	-0.0378	-0.815	0.032	0.166
BW	-0.9	1.03	-0.23	-0.55	-0.0052	0.128
BH	0.33	0.235	-0.085	-0.32	-0.207	0.12
P	4.42	1.246	1.8152	-0.183	-0.236	-0.567
C1	0.28	0.57	-0.17	-0.523	-0.136	0.17
C2	-0.455	0.88	-0.128	-0.45	0.23	-0.074

Table 2.12

Coefficients for Melting Rate Equation

Shielding Gas	Electrode Polarity	w	x	y	z
C-25	+ve	0.023	0.00046	0.00000306	-0.50
C-25	-ve	0.0195	0.000158	0.000001	0.39
M-2	+ve	0.02	0.00054	0.000001	-0.56
M-2	-ve	0.0268	0.00036	0.000001	0.11

CHAPTER THREE

SOFTWARE DESIGN

3.1 SYSTEM REQUIREMENTS

The software is designed for IBM PC, XT, AT or compatible computers with a floppy or a hard disk system. The output device must be high resolution display unit. The software submitted with this thesis has been tested on Hercules, EGA and VGA video cards. To optimize the performance, an AT computer with a hard disk system is recommended.

There are a large variety of programming languages available. The most common languages used for engineering applications are BASIC, PASCAL and FORTRAN. BASIC is a simple programming language which has the ability to manipulate numbers and construct graphics output. In spite of its simplicity to use and learn, BASIC is too slow for our purposes. FORTRAN is extremely efficient in handling mathematical equations. However, the data management and user interaction of FORTRAN are limited. Pascal has been adopted as the programming language of choice because of excellent graphics capability and reasonable computation efficiency. The Pascal compiler used was Turbo Pascal 5.0 by Borland [41,42,43]. Pascal has been used as an academic computer

software language for some time. The popularity of Pascal means that it is fully supported. The compiled source code is a stand-alone executable file which can be carried on a floppy disk and transferred from system to system without violating copyright. Aside from Pascal, the language C satisfies these requirement, too, and C is gaining popularity in engineering applications recently.

Object-oriented programming (OOP) is a new approach to software design. The suitability of OOP for use in welding software is justified in Chapter 5. Expert systems software is the most exciting development in recent computer technology. In principal, expert system software is designed to emulate a human expert and gives advice rather than data. Furthermore, since the system holds knowledge in rule form rather than data, it learns from experience and thus the field of expertise grows [44,45].

3.2 SOFTWARE FEATURES

While the four software modules vary according to purpose, they have a common user-friendly interface, common graphics for data presentation and a common database system.

3.2.1 USER-FRIENDLY INTERFACE

Figure 3.1 is the general layout of the interface. Window 1 contains a help menu and is also the area reserved for the

graphics presentation (see Figure 3.1a). Numerical results are displayed in window 2 (Figure 3.1b). Window 3 is reserved for the input (welding parameters and the parameters editor (see Figure 3.1c)). When entering data, a whole cell is highlighted rather than only cursor positioning (see Figure 3.1c). The activated cell can be changed by pressing either the up and down arrow keys or the carriage return. Only real numbers are accepted. Special features are selected with the function keys (soft keys) e.g. <F1> for recalculate and <F10> for help menu. Details of the features vary from module to module and therefore the definitions of the other function keys are discussed separately as descriptions unfold. Any module session can be terminated by pressing <ESC>.

3.2.2 GRAPHICS PRESENTATION

The most powerful feature of these software modules is the graphics presentation of the computed results. This feature allows plotting of any input data range against the computed results with automatic scaling and labelling. Figure 3.2 shows the variation of HAZ hardness with carbon content predicted by the Suzuki model. In order to obtain a plot such as Figure 3.2 manually, it would take considerable calculation and plotting time. However, with the graphics presentation software of this thesis, the task can be accomplished within minutes and the

```

(ESC) QUIT
PARAMETER EDITING
(F9) -ENTER MELDING PARAMETERS/BASE CHEN
(DEL, F7) -TO ENTER
(F1) -RECALCULATE
(F10) (F7) DATABASE
PARAMETER EDITING
(F2) SET EXPERIMENTAL COOLING TIME
RESULTS
(F3) -SELECT Y-AXIS(HARDNESS,FM)
(F4) -SELECT X-AXIS(TEMP, etc)
(F5) -SET LIMITS (X-AXIS)
(F6) -PLOT
NOTE: FM = MAX MARTENSITE LEVEL AT WELD LINE

```

Figure 3.1a
Window 1, help menu.

```

ARATA = 0          BECKERT = 0
YURIYOKA I = 0      DUEREN = 0
COTTRELL = 0        YURIYOKA II = 0
SUZUKI = 0          FM ARATA = 0(%)
TERASAKI = 0        FM YURIYOKA II = 0(%)
T(R/S) = 0.00 (s)  PRESS (F10) FOR HELP

```

Figure 3.1b
Window 2, numerical results.

```

CURRENT      0.00 amps
VOLTAGE       0.00 U
INIT TEMP     0.00 C
THICKNESS     0.00 mm
FEED RATE     0.00 mm/s
EFFCY         0.00
SET T(R/S) PRESS (F2)
C : 0.00 %w
Mn : 0.00
Si : 0.00
Ni : 0.00
Cr : 0.00
Mo : 0.00
U : 0.00
B : 0.00
Cu : 0.00
Nb : 0.00
N : 0.00
S : 0.00

```

Figure 3.1c
Window 3,
parameter editor.

Figure 3.2 Graphics presentation of results.

possibility of human error is eliminated. For the HAZ hardness modules, WH and RH, it is useful to plot the 800°C to 500°C cooling time, $T_{8/5}$, on a log scale rather than on a linear scale to present the characteristic hardness curve (CHC). Such a graphical presentation is shown in Figure 3.3. The CHC can be plotted with a cooling time range of 0.1 sec. to 100 sec. on a log scale and the computed results (HAZ hardness) on a linear scale with a very few key strokes and step by step menu guidance.

Figure 3.3 Typical characteristic hardness curve generated by the as-welded hardness software (WH).

3.2.3 DATABASE

It was not the intent of this project to build a full scale database system for welding engineers. On the other hand, the limited database that is contained in these modules demonstrates the usefulness and convenience of applying this technology to software tools. The menu of the database system is activated by pressing a function key, as provided in the help menu. The database can store up to nine different steel compositions and nine sets of welding conditions. Data in the database can easily be retrieved, amended, added or deleted with the processing tools built into the system.

3.3 DESCRIPTION OF SOFTWARE

For graphics software such as this, most of the source code is for decorating the screen display. The descriptions of the algorithm implementation is explained by either simple flowcharts or pseudo code in order to avoid a lengthy description in the body of the thesis. On the other hand, since there are about twenty thousand lines of source code in total, the hard copy of the source code is not included in this thesis.

The general operation of the software requires only four instructions and perhaps three notes as follows:

- 1) Turn on the computer.

2) Type in the program name after the DOS prompt:

HAZ hardness	-	WH ;
PWHT HAZ hardness	-	RH ;
Preheat temperature	-	PH ;
Weld features	-	WF ;

3) The programmes are self descriptive and user-friendly.

4) Press <ESC> to terminate.

Notes :

- 1) Make sure that the floppy disk containing the programmes is not write protected.
- 2) In case of having any undesirable material on the screen, press <ESC> and restart the program.
- 3) The system may crash when the calculations are lengthy; turn off the computer and restart.

The rest of the operation is either self evident from the menus presented or from the help menu where required.

3.3.1 PROGRAM MODULE WH (as-welded HAZ hardness)

The software for this module contains Adams cooling time model and eight HAZ as-welded hardness models as described in chapter 2. A figure describing the general features of WH is shown in Figure 3.4. From the welding conditions and plate thickness, the computer automatically determines which cooling time equation is suitable from among the 2D, 2.5D and 3D

Figure 3.4 As-welded hardness software features at a glance.

formulation. From the welding parameters and steel chemical composition, the computer then calculates the 800°C to 500°C cooling time $T_{8/5}$ and HAZ hardness. The results are displayed in window 2 (Figure 3.2). Furthermore, a small pop-up window appears on the upper right hand corner to display the maximum, minimum and mean values of the results calculated for the eight hardness models. The mean hardness is calculated by averaging the six results with the maximum and minimum values eliminated. A simple algorithm flowchart, Figure 3.5, is presented to illustrate the general method of computation.

Instead of calculating $T_{8/5}$ from the welding conditions, an experimental $T_{8/5}$ can be entered with the <F2> soft-key, as shown in Figure 3.6. This is sometimes convenient where thermocouples have been plunged into the weld pool to determine $T_{8/5}$ - a procedure frequently used in experimental welding tests. In addition, by selecting a hardness model and the upper and lower $T_{8/5}$ limits, a cooling time versus HAZ hardness curve (characteristic hardness curve) can be obtained in seconds as shown previously in Figure 3.3.

Aside from entering data from the keyboard, both steel chemical composition and welding parameters can be retrieved from memory by selecting the database feature, <F7>. A menu as shown in Figure 3.7a prompts the user for action. After selecting either steel composition or welding parameters,

Figure 3.5 Flowchart describing the general computation scheme of the as-welded hardness software (WH).

<p><ESC> -QUIT</p> <p>CALCULATIONS</p> <p><F9> -ENTER WELDING PARAMETERS/BASE CHEM</p> <p><CR, I, T> -TO ENTER</p> <p><F1> -RECALCULATE</p> <p>STEELS <F7> -DATABASE</p> <p>SET T(8/5)</p> <p><F2> -SET EXPERIMENTAL COOLING TIME</p> <p>PLOTTING</p> <p><F3> -SELECT Y-AXIS(HARDNESS,FM)</p> <p><F4> -SELECT X-AXIS(VOGT,etc)</p> <p><F5> -SET LIMITS (X-AXIS)</p> <p><F6> -PLOT</p> <p>Note: FM = HAZ MARTENSITE LEVEL AT WELD LINE</p>		<p>ENTER COOLING TIME (s)</p> <p>0.00</p> <p>PRESS <CR> TO OK</p> <p>PRESS <F6> TO PLOT</p>																								
<p>ARATA = 308 BECKERT = 235</p> <p>YURIOKA I = 308 DIEREN = 315</p> <p>COTTRELL = 323 YURIOKA II = 282</p> <p>SUZUKI = 290 FM ARATA = 56(%)</p> <p>TERASAKI = 305 FM YUR II = 43(%)</p> <p>T(8/5) = 7.68 (s) PRESS <F10> FOR HELP</p>		<p>PRESS <F9> TO END</p> <table border="1"> <tr><td>C</td><td>0.12%</td></tr> <tr><td>Mn</td><td>1.20</td></tr> <tr><td>Si</td><td>0.26</td></tr> <tr><td>Ni</td><td>0.15</td></tr> <tr><td>Cr</td><td>0.15</td></tr> <tr><td>Mo</td><td>0.05</td></tr> <tr><td>V</td><td>0.10</td></tr> <tr><td>B</td><td>0.00</td></tr> <tr><td>Cu</td><td>0.01</td></tr> <tr><td>Nb</td><td>0.01</td></tr> <tr><td>N</td><td>0.01</td></tr> <tr><td>S</td><td>0.01</td></tr> </table>	C	0.12%	Mn	1.20	Si	0.26	Ni	0.15	Cr	0.15	Mo	0.05	V	0.10	B	0.00	Cu	0.01	Nb	0.01	N	0.01	S	0.01
C	0.12%																									
Mn	1.20																									
Si	0.26																									
Ni	0.15																									
Cr	0.15																									
Mo	0.05																									
V	0.10																									
B	0.00																									
Cu	0.01																									
Nb	0.01																									
N	0.01																									
S	0.01																									

Figure 3.6 Interface demonstrating the feature which allow the user to enter an experimental cooling time.

<p><ESC> -QUIT</p> <p>CALCULATIONS</p> <p><F9> -ENTER WELDING PARAMETERS/BASE CHEM</p> <p><CR, I, T> -TO ENTER</p> <p><F1> -RECALCULATE</p> <p>STEELS <F7> -DATABASE</p> <p>SET T(8/5)</p> <p><F2> -SET EXPERIMENTAL COOLING TIME</p> <p>PLOTTING</p> <p><F3> -SELECT Y-AXIS(HARDNESS,FM)</p> <p><F4> -SELECT X-AXIS(VOGT,etc)</p> <p><F5> -SET LIMITS (X-AXIS)</p> <p><F6> -PLOT</p> <p>Note: FM = HAZ MARTENSITE LEVEL AT WELD LINE</p>		<p>CURRENT 280.00 amps</p> <p>VOLTAGE 24.00 V</p> <p>INIT TEMP 4.00 C</p> <p>THICKNESS 35.00 mm</p> <p>FEED RATE 3.01 mm/s</p> <p>EFFCY 0.90</p>
<p>ARATA = 308 BECKERT = 235</p> <p>YURIOKA I = 308 DIEREN = 315</p> <p>COTTRELL = 323 YURIOKA II = 282</p> <p>SUZUKI = 290 FM ARATA = 56(%)</p> <p>TERASAKI = 305 FM YUR II = 43(%)</p> <p>T(8/5) = 7.68 (s) PRESS <F10> FOR HELP</p>		<p>DATABASE</p> <p>STEELS COMPOSITIONS</p> <p>WELDING PARAMETERS</p> <p>END</p> <p>PRESS <CR> TO SELECT</p>

Figure 3.7a The database system menu.

STEELS COMPOSITIONS

EDIT

RETRIEVE

RESET

END

PRESS <CR> TO SELECT

Figure 1.7b
Normal level edit menu screen.

STEEL

A710GrAC13

LloydsLT60

BS4360Gr50E

API X80

WES HW70

ASTM A299

JIS SM53B

A203D

A302B

PRESS <F9> TO END

<CR> TO SELECT

Figure 1.7c
Data set list.

STEELS COMPOSITIONS

AMEND

ADD

DELETE

END

PRESS <CR> TO SELECT

Figure 1.7d
Data level amend menu.

A710GrAC13

C	:	0.05 wt%
Mn	:	0.42
Si	:	0.23
Ni	:	1.03
Cr	:	0.73
Mo	:	0.21
U	:	0.00
B	:	0.00
Cu	:	1.06
Nb	:	0.04
N	:	0.01
S	:	0.01

PRESS <F9> TO END

Figure 1.7e
Add or amend feature of
the database system.

another function menu, Figure 3.7b, appears and the data in the database can be either edited or retrieved. The reset function sets all data in the editor to zero. The end function finishes this session and returns the user to the parameter editor. If the retrieve function is selected, a list of data set choices appears as shown in Figure 3.7c. Selection can be made by moving the cursor with the up and down arrow keys and activated with enter.

After a set of data has been selected, the data in the parameter editor will be automatically updated. With the 'edit' function, one can select 'amend', 'add' or 'delete' a set of data as shown in Figure 3.7d. Choosing 'delete' prompts the user with a listing similar to the 'retrieve' function but the choice selected is erased from the database file. The 'add' function allows the user to add a set of data to the database file (see Figure 3.7e). However, if there are already nine sets of data in the file, the last set of data will be automatically deleted. If 'amend' is selected, a list of choices to be amended appears. Both the name and the content of data set can be changed. All of the above procedure is self evident from the interface or if necessary from the help menu.

The plotting feature can be activated by selecting <F6>. Before activating <F6>, a choice among the HAZ hardness models is made with <F5> and a variable with x-axis title <F4>. Upper

and lower limits of variation are entered through <F5>. The choices of models and variable (x-axis) are indicated by a little left arrow sign on the right side of the name. Variable choices are made by activating the up and down arrow keys. The variable and x-axis title can be any welding parameter or steel chemical composition. A typical plot of arc voltage versus HAZ hardness predicted by the Suzuki model is shown in Figure 3.8. All of the above is self evident from the help menu.

3.3.2 PROGRAM MODULE RH (reheat HAZ hardness)

The general layout of the PWHT HAZ hardness software is shown in Figure 3.9. Window 1 is the help menu and presentation area. The as welded HAZ hardness and PWHT HAZ hardness and $T_{8/5}$ are displayed in window 2. Windows 3, 4 and 5 are reserved for input data, reheat parameters (temperature and time), welding conditions and base metal chemical composition, respectively.

The machine computes the 800°C to 500°C cooling time $T_{8/5}$ from the Adams cooling time equations. With $T_{8/5}$ and the base metal chemical composition, the as welded HAZ hardness is calculated with the Yurioka PWHT model (see Chapter 2). The PWHT HAZ hardness is reckoned by subtracting the change in hardness caused by reheat from the as welded hardness. The change in hardness is determined from the PWHT parameters and

Figure 3.8 Typical plot generated by the air welded hardness software (WH).

Figure 3.9 Revised layout of the air welded hardness software (WH).

Figure 3.10 Flowchart describing the algorithm implementation of the reheat software RH.

the base metal chemical composition. A detailed flowchart for algorithm implementation is included in Figure 3.10.

The operation of RH is similar to that of WH. Both the PWHT and the as welded HAZ hardness can be plotted as shown in Figure 3.11. The cooling time $T_{8/5}$ can be entered directly from keyboard instead of using a calculated value from the Adams equations. The operation is similar to that of WH.

As previously noted, the database feature is activated with the soft-key <F7>. A set of welding parameters or a base metal chemical composition can be retrieved, amended, added or deleted. The procedure is the same as that previously described for the as-welded hardness module WH.

The plot function differs a little from that of WH. Since only one hardness model is presented, the step of choosing a y-axis title (among models) is eliminated. The x-axis variables are selected with <F3>. Limits are entered with <F4>. Finally <F6> generates a graph. If welding parameters or base metal chemical composition are selected as the x-axis variable, two curves are produced, both the as welded and PWHT hardness, as shown in Figure 3.11. On the other hand, if a reheat parameter (reheat temperature or time) is selected as the axis variable, only the PWHT HAZ hardness is presented, as shown in Figure 3.12, since the as welded hardness is a constant. All of this

2 of/de 2

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

Figure 3.11 Typical plot generated by the reheat software (RH) with both the as-welded and the PWHT hardness.

Figure 3.12 Plot with only PWHT HAZ hardness generated by the reheat software.

is self evident as the computation and presentation proceed. If necessary the help menu is activated for additional guidance.

3.3.3 PROGRAM MODULE PH (preheat temperature to avoid underbead cracking)

The preheat temperature calculations are much more complicated than the hardness computations discussed in the previous modules. The cooling time $T_{15/1}$ formula involves an error function (erf) and the preheat temperature computations require iteration. The description of the algorithm is presented in pseudo code shown in Figure 3.13 and 3.14.

Because of the complexity of the calculations involved, the run time for this program is considerably longer than it is for other modules, especially when using the plot function with the locally preheated plate model. The general layout of the software is shown in Figure 3.15. Windows 3a&b, are reserved for the preheat parameters of the uniformly preheated and locally preheated models respectively. Windows 4a,b & 5, contain the welding parameters, cracking index parameters and base metal chemical composition respectively.

When the cursor is moved into window 4b, special information pops up in window 2. H_{JIS} or H_{IIW} can be selected if the cursor is located in the 'HYDROGEN' cell, as shown in Figure 3.16a. If 'HIIW' is selected, some typical hydrogen

```

determine Rf, Ceq, CI, etc. ;
calculate critical cooling time ;
IF uniform plate THEN
    BEGIN
        upper preheat temperature = 800°C ;
        lower preheat temperature = 0°C ;
        determine total surface area and volume ;
        estimate preheat temperature = room temperature ;
        calculate weld pool temperature with estimated
            preheat temperature ;
        IF calculated weld pool temperature <= 100°C THEN
            BEGIN
                Repeat
                    estimated preheat temperature =
                        (upper - lower) / 2 ;
                    calculate weld pool temperature ;
                    IF calculated weld pool temperature > 100°C THEN
                        upper = estimated preheat temperature
                    ELSE
                        lower = estimate preheat temperature
                Until (Upper - Lower < 2°C)
                    OR (calculated weld pool temperature between
                        100°C and 102°C)
            END
        END
        required preheat temp = estimated preheat temp
    
```

Figure 3.13 Pseudo code for implementing the uniform preheat temperature calculation.

```

determine Rf, Ceq, CI, etc. ;
calculate critical cooling time ;
IF local preheat THEN
  BEGIN
    set upper preheat time = 8000 sec ;
    set lower preheat time = 0 sec ;
    REPEAT
      estimated preheat time :=
        (upper preheat time + lower preheat
         time)/2;
      determine  $\beta_0$ ,  $\beta_1$  and  $\beta_2$  ;
      calculate preheat temperature ;
      calculate weld pool temperature with the
        estimated preheat time, critical
        cooling time, etc. ;
      IF weld pool temperature > 100°C THEN
        upper = estimated preheat time
      ELSE
        lower = estimated preheat time ;
    UNTIL (upper preheat time - lower preheat
           time) <= 3 sec)
      OR (calculated weld pool temperature between
          101°C and 99.8°C)
      OR (preheat time < 10 sec)
      OR (preheat time > 7950 sec) ;
    IF preheat time >= 7950 sec THEN
      BEGIN
        upper = 30000 sec ;
        lower = estimated preheat time ;
        REPEAT
          ....
        UNTIL (upper - lower <= 10 sec)
          OR (calculated weld pool
              temperature between 99.5°C and
              103°C)
      END
    END ;
  END ;

```

Figure 3.14 Pseudo code for implementing local preheat time and temperature calculation.

<ESC>:-QUIT CALCULATIONS <F9>:-ENTER WELDING PARAMETERS/BASE CHEM. PREHEAT PARAMETERS <F2>:-SELECT UNIFORMLY PREHEATED <F3>:-SELECT LOCALLY PREHEATED <CR,1,7>:-TO ENTER <F1>:-RECALCULATE VIEWS <F7>:-DATABASE ROUTING <F4>:-SELECT X-AXIS(Volt,ETC) <F5>:-SET LIMITS (X-AXIS) <F6>:-PLOT		CURRENT : 0.00 amps VOLTAGE : 0.00 V THICKNESS : 0.00 mm AMBI TEMP : 0.00 C FEED RATE : 0.00 mm/s EFFCY : 0.00 HYDROGEN : 0.00 rf : 0.00 YIELD ST : 0.00 Kt : 0.00 C : 0.00 %w Si : 0.00 Mn : 0.00 Cu : 0.00 Ni : 0.00 Cr : 0.00 Mo : 0.00 Nb : 0.00 U : 0.00 B : 0.00
T(1500/100) (s) = 0 PREHEAT TEMP (C) = 0 PREHEAT TIME (s) = 0 PRESS <F10> FOR HELP	UNIFORMLY PREHEATED LENGTH : 0.00 WIDTH : 0.00 LOCALLY PREHEATED HEAT INT. : 0.00 WIDTH : 0.00	

Figure 3.15 General layout of the preheat software.

HYDROGEN CONTENT (100ml/gm) HJIS HIIW PRESS <CR> TO SELECT PRESS <F10> FOR HELP
--

Figure 3.16a
Selection of HJIS or HIIW.

HIIW RUTILE COATED : 25 FLUX-CORED CO2 : 22 SUBMERGED-ARC : 15 BASIC COATED : 13 GAS SHIELDED : 7 PRESS <F10> FOR HELP
--

Figure 3.16b
Typical HIIW values.

2-D Restraint Coefficient : Tekken Test : 690 Stout Test : 490 H-slit Test : 680 ARC Test : E/1 Ordinary Joints : <=390 PRESS <F10> FOR HELP
--

Figure 3.17
Typical restraint coefficients (rf).

Stress Conc. Factor : y Groove : 4 Double-U : 3.5 Y Groove : 4-5 Single-Bevel : 6-8 U or TOE : 1.5 PRESS <F10> FOR HELP

Figure 3.18
Typical stress concentration factors.

content values are shown in window 2 (Figure 16b). When the cursor is at ' r_f ', some values are shown (Figure 3.17). Stress concentration factors are displayed if the cursor has moved to the ' K_t ' cell (Figure 3.18). Uniformly or locally preheated models can be selected and high-lighted by pressing <F2> or <F3> respectively.

The database feature is the same as previously described for the WH and RH modules. The plot feature is similar to the RH module plot feature. The variable x-axis title can be selected by pressing <F4> and the limits are entered with <F5>. Once again this is apparent from the help menu and does not need further explanation. For the uniformly preheat model, the critical cooling time T_{cr} or preheat temperature can be selected for y-axis with <F6>. With the locally preheated model, y-axis can be T_{cr} , preheat temperature or preheat time. Typical plots are shown in Figure 3.19a & b.

3.3.4 PROGRAM MODULE WF (weld features)

The calculations involved in the weld features model are much simpler than those for the previous modules. The upper half of the weld shape is assumed to be a semi-ellipse and the lower half is similar to a peak to peak sine-wave i.e., the bead width is equal to the period of a sine function. Curve fitting techniques have been used to generate mathematical

Figure 3.19a Graph of critical cooling time vs carbon content generated by the preheat temperature software (PH).

Figure 3.19b Graph of required preheat temperature vs carbon content generated by the preheat temperature software (PH).

equations but none provide a satisfactory and consistent shape, e.g. third and fourth degree polynomials.

The operation is very similar to that of WH (as-welded hardness). The electrode polarity and shielding gas employed can be changed by selecting <F2> and <F3> respectively, as shown in Figure 3.20. Whenever <F1>, the recalculate key, is activated, the weld shape appears in the lower right corner window along with a set of numerical results in the lower left window, as shown in Figure 3.21. If <shift F1> is selected after pressing <F1>, a set of four weld shapes of different electrode polarities and shielding gases are displayed to scale in the upper left corner window (Figure 3.22). This provides a visual reference on the effect of electrode polarity and shielding gas. All of this is evident as the session proceeds or if necessary with the aid of the help window.

The database feature can be activated by activating <F8>. Only the choice of welding parameters is available. Therefore, whenever <F8> is selected, the database feature functions menu appears. They are 'retrieve', 'amend', 'delete' and 'add'. The operation of the database system is similar to that described previously for software module WH.

Similar to WH, the feature selected for study (y-axis) and variable x-axis titles should be selected before plotting by activating <F4> and <F5> respectively. The limits are entered

<p><ESC> -QUIT</p> <p>CALCULATIONS</p> <p><F9> -ENTER WELDING PARAMETERS</p> <p><CR, I, T> -TO ENTER</p> <p><F2> -SELECT POLARITY</p> <p><F3> -SELECT SHIELDING GAS</p> <p><F1> -RECALCULATE</p> <p><Shift F1> -COMPARE POLAR & GAS</p> <p>PROCESS <F8> -PROCESS DATABASE</p> <p>PLOTTING</p> <p><F4> -SELECT Y-AXIS(FEATURES)</p> <p><F5> -SELECT X-AXIS(VOLT, etc)</p> <p><F6> -SET LIMITS (X-AXIS)</p> <p><F7> -PLOT / <Shift F7> -DRAW</p>		<p>CURRENT 0.00 amps</p> <p>VOLTAGE 0.00 V</p> <p>SPEED 0.00 mm/s</p> <p>E DIA 0.00 mm</p> <p>E EXT 0.00 mm</p>
<p>F AREA = 0.00 mm² B WIDTH = 0.00 mm</p> <p>De AREA = 0.00 mm² R B LENGTH = 0.00 mm</p> <p>B HEIGHT = 0.00 mm F B LENGTH = 0.00 mm</p> <p>PENET = 0.00 mm MELT RATE = 0.00 kg/h</p>		<p>ELECTRODE POLARITY</p> <p>NEGATIVE</p> <p>POSITIVE</p>
<p>PRESS <F10> FOR HELP</p>		<p>SHIELDING GAS</p> <p>Ar</p> <p>C 25</p>

Figure 3.20 General layout of the weld features software (WF).

<p><ESC> -QUIT</p> <p>CALCULATIONS</p> <p><F9> -ENTER WELDING PARAMETERS</p> <p><CR, I, T> -TO ENTER</p> <p><F2> -SELECT POLARITY</p> <p><F3> -SELECT SHIELDING GAS</p> <p><F1> -RECALCULATE</p> <p><Shift F1> -COMPARE POLAR & GAS</p> <p>PROCESS <F8> -PROCESS DATABASE</p> <p>PLOTTING</p> <p><F4> -SELECT Y-AXIS(FEATURES)</p> <p><F5> -SELECT X-AXIS(VOLT, etc)</p> <p><F6> -SET LIMITS (X-AXIS)</p> <p><F7> -PLOT / <Shift F7> -DRAW</p>		<p>CURRENT 200.00 amps</p> <p>VOLTAGE 32.00 V</p> <p>SPEED 4.23 mm/s</p> <p>E DIA 1.59 mm</p> <p>E EXT 31.75 mm</p>
<p>F AREA = 38.09 mm² B WIDTH = 12.42 mm</p> <p>De AREA = 4.08 mm² R B LENGTH = 13.15 mm</p> <p>B HEIGHT = 2.44 mm F B LENGTH = 14.50 mm</p> <p>PENET = 3.90 mm MELT RATE = 0.49 kg/h</p>		<p>ELECTRODE POLARITY</p> <p>NEGATIVE</p> <p>POSITIVE</p>
<p>PRESS <F10> FOR HELP</p>		<p>SHIELDING GAS</p> <p>Ar</p> <p>C 25</p>

Figure 3.21 Numerical results along with the estimated weld shape generated by the weld features software (WF).

Figure 3.22 Weld shape dependence on shielding gas and electrode polarity.

Figure 3.23 Typical plot generated by the weld features software (WF).

with <F6>. <F7> activates automatic plotting as shown in Figure 3.23. The variation of shape with designated welding parameter is activated by <shift F7> (Figure 3.24). Once again all of this is evident as the session progresses or with the aid of the help menu.

Figure 3.24 Weld shape variation due to welding speed.

CHAPTER FOUR

DISCUSSION

The software systems described in this thesis can be used by several professionals - welding engineers either consultants or specialists associated with large fabrication facilities, mechanical design engineers or material engineers. It is often necessary to specify welding parameters for a given job at the design stage or in consultation with fabrication specialists. At the moment specifications are based either on long experience or on the basis of trial and error activities. The software presented in this thesis provides some guidance in anticipating the as-welded HAZ hardness, PWHT HAZ hardness, preheat temperature to avoid underbead cracking and weld shape and size for GMAW. Taken together, a welding, fabrication or design professional is provided with considerable information about the quality of a given weld before final specifications are required. Of course, faith in this software should not preclude experimental verification but it no doubt limits the extent of the trial and error often necessary to arrive at optimum welding conditions.

It has been said that the regression limits should be incorporated into the system. However, it is often interesting and useful to extrapolate by computations beyond the valid limits.

At the same time, the limits are well documented in this thesis for reference. It is left to user to use the software wisely.

In a general sense, the interface, automatic plotting and database facilities are tools that are appropriate not only for the computations proposed in this thesis but for many other engineering applications. Wherever research has suggested algorithms that would be potentially useful in practice, they can be substituted for the HAZ hardness models. With little modification the interface, graphics and database software can remain almost intact.

Useful software depends both on the ease of use and the accuracy of the mathematical models being implemented. A user-friendly interface guarantees ease of use. The accuracy of each of the modules implemented in this thesis is evaluated in the following sections.

4.1 CALCULATED AND MEASURED 800°C TO 500°C COOLING TIME COMPARISON

The following is a comparison of measured 800°C to 500°C cooling times from an investigation at the AMCA research laboratory [30] with computed values. In each case, submerged arc bead-on-plate welds were deposited with a range of heat inputs to achieve a range of cooling conditions. The cooling times were measured by injecting a thermocouple into the weld pool just behind the heat source. The calculated and measured

Figure 4.1 The graph showing the measured and calculated cooling times.

cooling times are shown in Figure 4.1. It is apparent that the calculated values for cooling time are somewhat less than their measured counterpart values. Better agreement would be achieved if an efficiency of somewhat higher than 90% was applied, since it is well known that losses from the submerged arc process are low. However, a value of 90% is based on many years of experience and extensive data. The limited number of measurements in this investigation is not sufficient to suggest a change. The difference may well be a consistent measurement error although none is known.

4.2 COMPUTED AND MEASURED AS-WELDED CHC CURVES

The following is a comparison of the experimentally measured characteristic hardness curves (CHC) for three microalloy steels (Table 4.1) with CHC curves computed with the software system for the eight models involved. The data are again taken from the AMCA study [30]. Submerged arc bead-on-plate welds were deposited with a range of heat inputs for the three steels as documented in section 4.1. The cooling times measurements are also documented in section 4.1. The hardness measurements were VPN with a 10 kg load. To provide the best possible experience base, it was decided to provide all CHC curves for a total of 24, in Figures 4.2, 4.3 & 4.4. In general sense it is apparent that there are several models that

(i) Arata

(ii) Yurioka I

(iii) Cottrell

(iv) Suzuki

(v) Terasaki

(vi) Beckert

(vii) Dueren

(viii) Yurioka II

Figure 4.2 Characteristic hardness curves computed for steel A (+ measured values).

(i) Arata

(ii) Yurioka I

(iii) Cottrell

(iv) Suzuki

(v) Terasaki

(vi) Beckert

(vii) Dueren

(viii) Yurioka II

Figure 4.3 Characteristic hardness curves computed for steel B (+ measured values).

(i) Arata

(ii) Yurioka I

(iii) Cottrell

(iv) Suzuki

(v) Terasaki

(vi) Beckert

(vii) Dueren

(viii) Yurioka II

Figure 4.4 Characteristic hardness curves computed for steel C (+ measured values).

anticipate the HAZ hardness relatively well for steels A and B. The Arata, Teresaki, Yurioka I and Suzuki models seem to provide quite reliable data for these particular steels. It would seem that there is considerably less agreement with the Beckert model. The Beckert model is an early HAZ computational method and the experimental database used to generate it was probably somewhat limited.

One of the most interesting developments of this investigation is the absence of reasonable agreement between the computed and measured values for steel C. Steel C is a low carbon (0.05 wt%), copper bearing (1.06 wt%) material. This may not be too surprising, however because 1.06 wt% Cu is beyond the compositional limits of all models except the Yurioka II method. It is apparent that this model provides better agreement than any of the others. The experience with steel C suggests that the regression limits must be respected as might be expected.

4.3 COMPUTED AND MEASURED PWHT CHC CURVES

In the same AMCA investigation HAZ hardnesses after post weld heat treatment are documented. The reheat temperature and time of 620°C and 2 hours respectively was used. The CHC curves of the three steels are included in Figures 4.5, 4.6 & 4.7, with both the as-welded and PWHT hardness.

Table 4.1
Chemical Compositions of the
Three Experimental Steels (in wt%).

STEEL	C	Mn	Si	Cr	Mo	V	Ni
A	.16	1.42	.30	.02	<.01	<.01	.03
B	.12	1.29	.26	.15	.05	.10	.15
C	.05	.42	.23	.73	.21	.002	1.03

	Cu	P	S	Nb	Al	N	
A	.07	.012	.011	.02	.03	.006	
B	.006	.01	.006	.01	.03	.006	
C	1.06	.01	.009	.042	.023	.010

Figure 4.5 Characteristic hardness curve computed for steel A after PWHT.

Figure 4.6 Characteristic hardness curve computed for steel C after PWHT.

Figure 4.7 Characteristic hardness curve computed for steel B after PWHT.

In a general sense, the Yurioka reheat model predicts the PWHT HAZ hardness relatively well for steels A and B. However, for steel C, the mathematical model predicts hardening in the HAZ despite an increase in 800°C to 500°C cooling time. The measurements show that the post weld heat treatment has little effect on the HAZ hardness. Further experiment and computations are required to sort this contradiction out.

4.4 DIFFERENT METHODS FOR DETERMINING THE REQUIRED PREHEAT TEMPERATURE TO AVOID UNDERBEAD CRACKING

Since there is limited experimental work available for evaluating the software module PH, other methods for determining the required preheat temperature to avoid underbead cracking are used for comparison purposes. Several methods for calculating the preheat temperature are available in the literature. However, it is not the purpose of this thesis to examine these. Therefore, only two simple methods were selected for comparison purposes.

(A) Linnert Method [35,36]

In this method the preheat temperature required to avoid underbead cracking is determined from the equivalent carbon content C_{eq} (see table 4.2):

$$C_{eq} = C + \frac{Mn}{6} + \frac{Ni}{15} + \frac{Cr}{5} + \frac{Cu}{13} + \frac{Mo}{4} \quad (88)$$

Table 4.2	
Calculation of Preheat Temperature	
Ceq ---	Preheat Temperature -----
up to 0.45%	optional
0.45% to 0.60%	200°F - 400°F
above 0.60%	400°F - 700°F

The formula given above is intended for carbon and alloy steels containing not more than 0.5% C, 1.5% Mn, 3.5% Ni, 1% Cr, 1% Cu and 0.5% Mo.

(B) Seferian Method [31]

Seferian also made use of this same carbon equivalent formulation. The required preheat temperature is given as follows:

$$T_p = 350\sqrt{C_{eq} - 0.25} \quad (^\circ\text{C}) \quad (89)$$

Figure 4.8 Preheat temperature predicted by the Yurioka and Seferian models for uniform preheat.

Figure 4.9 Preheat temperature predicted by the Yurioka and Seferian models for local preheat.

$$C_{eq} = C_c (1 + 0.005 h) \quad (90)$$

$$C_c = C + \frac{Mn + Cr}{9} + \frac{Ni}{18} + \frac{7 Mo}{90} \quad (91)$$

where T_p = preheat temperature in °C
 C_{eq} = total carbon equivalent
 C_c = chemical carbon equivalent
 h = plate thickness in mm

The method is quite simple. Although the plate geometry, cooling condition and metal properties are not taken into consideration, the method provides a reasonable preheat temperature estimate. As shown in Figures 4.8 & 4.9, in most cases, the Seferian method is conservative, i.e. the preheat temperature predicted by the Seferian method is higher than that predicted by the Yurioka preheat model. It should be noted that Figures 4.8 & 4.9 are generated by the software PH with a little modification to take into account the Seferian method.

4.5 ACCURACY OF SOFTWARE WF

Certainly the software is faithful to the mathematical relationships in the original publication of Chandel [17,18,19]. This have been verified by independent computation.

Beyond this it is not the purpose of this thesis to evaluate the authenticity of the algorithm. Reference is made to the original work of Chandel for that evaluation.

Since the weld shape is estimated by combining a semi-ellipse on the top and a cosine curve at the bottom, only the bead height, bead width and penetration match the values generated by Chandel model. Although the shape is just an estimate, it is in good agreement with the fusion area, reinforced boundary length and fusion boundary length calculated from the Chandel model, see Figures 4.10, 4.11, 4.12 & 4.13. The estimated fusion area is calculated by adding the area of a semi-ellipse [46] and the area under the cosine curve.

$$\text{semi-ellipse area} = \frac{\pi * \text{bead height} * \text{bead width}}{4} \quad (92)$$

$$\text{cosine curve area} = \frac{\text{penetration} * \text{bead width}}{2} \quad (93)$$

$$\text{Total estimated fusion area} = \text{semi-ellipse area} + \text{cosine area} \quad (94)$$

The reinforced boundary length, which is equal to half the perimeter of an ellipse, is estimated as follow:

$$\text{half ellipse perimeter} = \pi \sqrt{\frac{1}{2} \left(\frac{\text{bead width}^2}{2} + \text{bead height}^2 \right)} \quad (94)$$

The fusion boundary length is estimated by calculating the length of cosine curve within one period, equation 96. The length of the cosine curve is estimated by fragmenting the curve into ten pieces of straight lines. The total length of the cosine curve is approximately equal to the sum of the length of the ten straight lines.

$$\text{cosine curve} = \frac{\text{penetration}}{2} \cos \left(\frac{2\pi x}{\text{bead width}} \right) \quad (96)$$

where x = horizontal distance from the far left hand corner of the weld bead in mm.

Line integration can be used to determine the length of the cosine curve. However, the line integral is more time consuming and complex. On the other hand, the approximation suggested here is quite accurate and easier to implement and integrate into the existing software. Note that Figures 4.10, 4.11, 4.12 & 4.13 are also generated by the software WF with some modification.

The question is often raised regarding the applicability of bead-on-plate measurements and computations for realistic

joining situations where there is joint preparation. While joint preparation undoubtedly has an effect, bead-on-plate computations still provide relative guidance. Combined with experience this can be valuable and in any event alternatives are limited. The effect of joint preparation on weld size has been studied to some extent but it is not sufficiently well understood at this point to treat it explicitly.

Figure 4.10 Comparison of the Chandel and estimated fusion area.

Figure 4.11 Comparison of the Chandel and estimated deposited area.

Figure 4.12 Comparison of the Chandel and estimated reinforced boundary length.

Figure 4.13 Comparison of the Chandel and estimated fusion boundary length.

CHAPTER FIVE **OBJECT-ORIENTED (OOP)** **VERSUS** **PROCEDURAL PROGRAMMING**

Object-oriented (OOP) languages have three characteristics that distinguish them from traditional procedural languages: encapsulation, polymorphism, and inheritance. In OOP, objects are protected from outside access by encapsulation, i.e. no object can be accessed by another. Polymorphism is the ability of having different kinds of objects respond to the same message in different ways. Inheritance denotes the ability of an object to derive its data, automatically from another object based on a hierarchy of descendants [30,47,48,49].

Smalltalk is a pure OOP language, built with objects divided into classes according to their states and behaviours. From the point of view of software programming, a state is defined from the meaning and values of an object's variables. The object's response to external stimuli such as instructions or questions is behaviour. Objects communicate by message passing. By limiting communication to message passing, objects are only known by their behaviour in response to messages, i.e. OOP is a revolutionary approach to data abstraction. Methods

are the algorithms performed by an object in response to receiving a message. They also may be viewed as the internal detailed implementation of an object. Objects are organized into a hierarchy of classes. Every object inherits the methods and behaviour of objects above it in the hierarchy (superclass), i.e. the subclasses of the superclass have similar behaviour. This character enhances code sharing which in turn reduces programming time and probability of error.

Smalltalk is an OOP environment. Classes and fragments of code can be created and compiled inside the Smalltalk environment. Smalltalk contains a rich set of classes to provide a host of functions such as menus, pop-up windows and mouse control which are standard objects.

5.1 SMALLTALK VERSION SYSTEM DESCRIPTION

In order to compare OOP and procedural programming from the weld software modules generated, the Suzuki model for computing HAZ hardness [1,2,3] was implemented using Smalltalk. Figure 5.1 is the Smalltalk interface which contains the 'system transcript'. Code fragments are implemented by highlighting the statements and selecting 'show it' or 'do it' from the 'system menu'. Figure 5.2 is the general layout of the hardness module interface which contains a main menu, help menu, welding parameters window and results window. In the

Figure 5.1 Smalltalk interface.

welding parameters window, the base metal chemical composition and the welding conditions are displayed in sequence. The calculated 800°C to 500°C cooling times and predicted HAZ hardnesses are shown in the results window. The feature required is selected from the main menu by mouse technology.

If the 'composition' or 'condition' feature is selected from the main menu, a database of chemical compositions or welding conditions can be edited. Selecting 'calculate' activates the hardness computation and the results are displayed in the results window. A characteristic hardness curve (CHC) can be generated if the feature 'CHC' is selected from the main menu as shown in Figure 5.3.

By selecting 'plot', a second menu is prompted for examining the effect of either composition or welding condition on HAZ hardness. After selecting the parameter to be plotted and entering the upper and lower limits, a graph as shown in Figure 5.4 is generated.

5.2 ADVANTAGES OF OOP

Figure 5.3 and 5.4 generated and displayed with Smalltalk can be compared with the plots (Figure 5.5 a&b) obtained with Turbo Pascal programming. There are almost no significant differences. However Smalltalk contains much better pop-up menu window and mouse features for the convenience of the users.

Custom Transcript		C (wt%)	0.120
exit		Mn	1.290
composition		Si	0.260
condition		Ni	0.150
calculate		Cr	0.150
CHC		Mo	0.050
plot		V	0.100
help		B	0.000
		Cu	0.010
		Nb	0.010
		N	0.010
		S	0.010
exit	:-	CURRENT (amp)	200.00
	quit / go back to pervious menu	VOLT. (V)	24.00
composition :-		TEMP. (C)	4.00
	edit metal chemical composition	THICK. (mm)	35.00
condition :-		SPEED (mm/s)	3.81
	edit welding condition	EFFCY	0.90
calculate :-			
	calculate / recalculate HAZ hardness		
CHC :-			
	Characteristic Hardness Curve (t8/5 vs UHN)		
plot :-			
	plot different parameter vs hardness		
help :-			
	help menu		

Suzuki Hardness (UHN)	
800 C to 500 C cooling time	= 7.68 sec
Maximum HAZ hardness	= 290.70 UHN

Figure 5.2 General layout of object-oriented programming (OOP) module interface for computing as welded HAZ hardness.

Figure 5.3 Characteristic hardness curve generated by OOP Smalltalk.

Figure 5.4 Carbon content versus Suzuki hardness generated with Smalltalk to demonstrate parameter study.

Figure 5.5a Characteristic hardness curve generated with Pascal.

Figure 5.5b Carbon content versus Suzuki hardness generated with Pascal to demonstrate parameter study.

There is no doubt that the same problem can be solved in either language (OOP or procedural). The question is how efficient is the process. More efficient programming implies less time and hence lower cost.

The major benefit of OOP is the reusability of the software. OOP improves software systems because it facilitates better factoring of functionality and related data than traditional procedural programming techniques. OOP languages add features that allow the efficient implementation of well-factored, minimally coupled systems which promotes high cohesion through inheritance and polymorphism, allowing more general, more modular code. OOP improves code reuse by using less complex, loosely coupled, highly cohesive components [48].

However the benefits of OOP are not free. A new language requires retraining - both language syntax and class library and this takes time. The major advantage of investing this time in Smalltalk is the possibility reusable components (classes of objects). The most time-consuming part of the OOP learning curve involves acquiring a familiarity with the class libraries which come with the Smalltalk environment: the basic library includes several hundreds classes and thousands of methods.

5.3 AN EVALUATION OF SMALLTALK VS PASCAL

Perhaps the best way of communicating a Smalltalk / Pascal comparison is a question - if the software system presented in this thesis was to be rewritten what language should be used. The question should be considered in two ways:

- 1) if the software is to be marketed or transferred from one computer to another, i.e. the system is to be distributed and used in industry;
- 2) if the software is for personal use only, i.e. the system is not to be distributed.

If the software system is to be distributed, the Pascal version is the choice, since an executable file can be marketed without violating copyright. Furthermore, the performance of the Pascal version on either a XT or AT machine with or without math-coprocessor is quite acceptable. The software can also be adapted to different graphics adaptors from hercules to VGA. However, a math-coprocessor is necessary for Smalltalk, in order to manipulate floating point calculations with reasonable performance. Once the Smalltalk environment is installed for a certain graphics adaptor, it performs only on that particular graphics adaptor. Therefore, transportability and portability are limited.

On the other hand, if the software is for personal use only, Smalltalk might well be the language of choice. Smalltalk

has the advantage of reusable components (classes of objects). Once a method is implemented, it can be reused anytime. Moreover, the compile time is much faster. The whole system grows in a self tailored manner as more classes and methods are added. The Smalltalk environment takes full advantage of pop-up menus and mouse interface technology. Recently a new version of Smalltalk has been released by Digitalk Inc. by which a compiled version of the source code is possible. When this is evaluated, the question of the choice of languages may be different.

5.4 FINAL WORDS (OOP)

OOP languages do not make poor programmers into good ones but do help with the construction of software. For a new OOP user, it is useful to implement the object-oriented technique within a traditional procedural language. By so doing it helps to understand the inner workings of OOP languages, and it also provides a transition state for changing from a procedural world to an object-oriented world [48].

CHAPTER SIX

CONCLUSIONS AND CONTRIBUTIONS

- (1) Software systems for computing the as-welded hardness of the heat-affected zone (HAZ), post weld heat treated HAZ hardness, required preheat temperature to avoid underbead cracking, and the size and shape of gas metal arc welds have been presented.
- (2) The role of creative interface design, graphics (bit map diagrammatic and line plotting) and database technology to provide a user friendly system has been emphasized. Of particular importance is the premise that the system had to be very simple to use - one page of instructions or less.
- (3) The application of these software tools to other engineering situations was discussed at length.
- (4) Computed values have been compared to experimentally measured values to evaluate the system and there was found to be general agreement.
- (5) Originating these tools with OOP Smalltalk language was compared to the same tools originated with procedural Pascal programming.

CHAPTER SEVEN

FUTURE WORK

- 1) The Pascal version of the software system can be improved by:
 - a) adding a printer driver to the system - at this stage in order to obtain a hard copy of the graphics output, the user must have screen dump programmes (e.g. SCRNDU.COM by HARDWOOD SOFTWARE ASSOCIATES or GRAB.COM by WORDPERFECT CORP.). By adding a printer driver the system can be made fully self-contained.
 - b) adding a mouse interface as a result of the experience of mouse control in the Smalltalk version, there is no doubt that a mouse interface in the Pascal version will significantly add convenience to the software.
 - c) improving the error handling procedure in the calculation functions.
 - d) adding pop-up windows to indicate the limitations of chemical composition for each hardness prediction model.
 - e) integrating all four modules into one environment and adding a menu to select between modules. Provisions should be left for future modules.

- f) investigating accuracy and significance of the preheat temperature model and perhaps new module should be written if a better procedure for calculating preheat temperature can be found.
- g) building new module for predicting weld features for submerge arc welds.

Nb: As mentioned at the very beginning, the graphics, database and user-friendly interface tools developed in this thesis can be applied to all sorts of engineering problem that can be described by mathematical models, i.e. the system can be expanded well beyond welding or materials engineering problems to more general mechanical problems.

- 2) As discussed perviously, OOP tools are worth future development, several things can be done to the Smalltalk version:
 - a) improve the input welding parameters procedure.
 - b) expand the system to include all the hardness prediction models both as welded and PWHT, the preheat temperature model, and the weld features models.
 - c) investigate the possibility of creating a stand-alone executable file of the Smalltalk version.

- 3) The next major development of this work should be to investigate the use of expert system with graphics output to assist both design and production engineers in welding process specification and design.

REFERENCES

- 1) Suzuki H., Carbon Equivalent and Maximum Hardness, Trans. Jap. Weld. Soc., Vol. 15, No. 1, 1984.
- 2) Suzuki H., Root Cracking and Maximum Hardness in High-Strength Steel Welds, Trans. Jap. Weld. Soc., Vol. 15, No. 1, 1984.
- 3) Suzuki H., A New Formula for Estimating HAZ Hardness in Welded Steels, Trans. Jap. Weld. Soc., Vol. 16, No. 2, pp 25-33, 1985.
- 4) Arata Y., Nishiguchi K., Ohji T. Kohsai N., Weldability Concept on Hardness Prediction, Transaction of Journal of Japanese Welding Research Institute, Vol. 8, No. 1, pp 43, 1979.
- 5) Satoh K., Terasaki T., Estimation of HAZ Hardness, Jap. Weld. Soci. General Meeting, Vol. 25, pp 98, 1979.
- 6) Terasaki T., Study of Predictive Equations of Thermal Factor and Hardness Related with Weld Cold Cracking, Iron and Steel, Vol. 16, pp 145, Japan, 1981.
- 7) Yurioka N., Ohshita S., Tanehiro H., Study on Carbon Equivalent to Assess Cold Cracking Tendency and Hardness in Steel Welding, Proc. Conf. on Pipeline Welding in the 80's, Melbourne, March 1981.
- 8) Yurioka N., Okumura M., Kasuya T., Prediction of HAZ Hardness of Transformable Steel, Metal Construction, April, 1987, pg217R.
- 9) Beckert M., Hoz R., Use of Carbon equivalent and Prediction of the Weld HAZ Hardness, Schw. Tech., Vol. 23, No. 8, pp 344, 1973.
- 10) Dueren C., Equation for the Prediction of Cold Cracking Resistance in Field Welding Large Diameter Pipes, IIW Doc IX-1 356-85 "3R international", 24 Jahrgang, Heft, 1985.
- 11) Cottrell C.L.M., Hardness Equivalent May Lead to a More Critical Measure of Weldability, Metal Construction, Dec. 1984.

References

- 12) Okumura M., Yurioka N., Kasuya T., Cotton H.J.V., Prediction of HAZ Hardness after PWHT, IIW International Conference on Residual Stress and Stress Relieving, Sofia, Bulgaria, July 6-7, 1987, pp61-68.
- 13) Yurioka N., Suzuki H., Ohshita S., Saito S., Determination of Necessary Preheat Temperature in Steel Welding, Welding Journal, Vol. 62, No. 6, 1983, pg147s.
- 14) Yurioka N., Okumura M., Ohshita S., Saito S., On the Methods Determining Preheat Temperature Necessary to Avoid Cold Cracking in Steel Welding, IIW Doc. XII-E-10-81, April 1981.
- 15) Suzuki H., Yurioka N., Weldability of Line-Pipe Steels and Prevention of Cracking in Field Welding, IIW Doc IX-1458-87.
- 16) Mehrotra V., Bibby M., Goldak J., Moore J., A Microcomputer Method for predicting Preheating Temperature, published in "Welding for Challenging Environments", edited by the Welding Institute of Canada, Pergamon Press, New York, 1986, pp233-244.
- 17) Chandel R.S., Mathematical Modelling of Gas Metal Arc Weld Features, Modeling and Control of Casting and Welding Processes IV. The Minerals, Metals and Materials Society, 1988, pg109s.
- 18) Chandel R.S., Wire Melting Rate in Mild Steel MIG Welding, Metal Construction, May 1988.
- 19) Chandel R.S., An Investigation into the Electrode and Plate Melting Efficiencies of SAW and GMAW Processes, Metal Technology Laboratories Report: 89-10(J).
- 20) Chandel R.S., Oddy A.S., Goldak J., Computer Prediction of Weld Bead Shapes, Paper 9, second International Conference on Computer Technology in Welding, Welding Institute, Abington, Cambridge, June 8-9, 1988.
- 21) Wayman C.M., Stout R.D., A Study of Factors Affecting the Strength and Ductility of Weld Metal, Welding Journal, May 1958, pg193s.

References

- 22) Easterling K.E., Introduction to Physical Metallurgy of Welding, Butterworths & Co. (Publishers) Ltd., London, 1983.
- 23) Hanson A., Parr J.G., The Engineer's Guide to Steel, Addison-Wesley Publishing Company Inc., 1965.
- 24) Yurioka N., Impact of Welding Research on Steel Composition Development, Materials and Design, Vol. VI, No. 4, 1985.
- 25) Shigley J.E., Mitchell L.O., Mechanical Engineering Design, 4th edition, McGraw-Hill Book Company, 1983, pg175-176.
- 26) Shultz B.L., Jackson C.E., Influence of Weld Bead Area on Weld Metal Mechanical Properties, Welding Journal, January 1973, pg26s.
- 27) Adams C.M.Jr., Cooling Rates and Peak Temperatures in Fusion Welding, Welding Journal AWS, Vol 37, No 5, pp 210, 1958.
- 28) Jhaveri P., Moffat W.G., Adams C.M.Jr., The Effect of Plate Thickness and Radiation on Heat Flow in Welding and Cutting, Welding Journal, Vol. 41, No. 1, pp 12, 1962.
- 29) Satoh K., Matsui S., Determination of Preheating Condition to Avoid Weld Cracking in Steel Constructions, Journal of JWES, Vol. 40, No. 11, 1971, pg1117 (in Japanese).
- 30) Pond S., An Investigation into the Weldability of Two Canadidate Steels, AMCA Internation Limited Research and Technology Center, Internal Report, December 1983.
- 31) Seferian D., The Metallurgy of Welding, John wiley & Sons Inc., New York, 1962.
- 32) Rosenthal D., Mathematical Theory of Heat Distribution during Welding and Cutting, Supplement to Journal of American Welding Society, May 1941.
- 33) Rosenthal D., The Theory of Moving Sources of Heat and Its Application to Metal Treatments, Transaction of the ASME, Nov. 1946, pg849.

References

- 34) Christensen N., Davies V. de L., Gjermundsen K., Distribution of Temperature in Arc Welding, British Welding Journal, Feb. 1965, pg54.
- 35) Linner G.E., Welding Metallurgy Vol 1 Fundamentals, 3rd edition, American Welding Society, New York, USA, 1967.
- 36) Linner G.E., Welding Metallurgy Vol 2 Technology, 3rd edition, American Welding Society, New York, USA, 1967.
- 37) Suzuki H., Cold Cracking and its Prevention in Steel Welding - Report 1, Trans. JWS, 9, 1978, pg140-149.
- 38) Eagar T.W., Physics of Arc Welding, AIP Conference Proceedings, American Institute of Physics, 1982.
- 39) Shinoda, Masumoto, Prediction of Weld Geometries for Co2 Butt Welded Joints, Materials Science and Technology, March 1989, Vol. 5, pg293.
- 40) Clark J.N., Manual Metal Arc Weld Modelling: Part 1 Effect of Process Parameters on Dimensions of Weld Bead and Heat-Affected Zone, Materials Science and Technology, December 1985, Vol. 1, pg1069.
- 41) Turbo Pascal 5.0 Reference Guide & User Guide, Borland International, USA, 1989.
- 42) O'Brien S.K., Turbo Pascal 5.5: the Complete Reference, Borland Osborne / McGraw Hill Programming Series, USA, 1989.
- 43) Weiskamp K., Heiny L., Shammass N., Power Graphics Using Turbo Pascal, John Wiley & Sons, Inc., USA, 1989.
- 44) Lucas W., Microcomputer Systems, Software and Expert Systems for Welding Engineering, Welding Journal, April 1987, pg19.
- 45) Kuhne A.H., Cary H.B., Prinz F.B., An Expert System for Robotic Arc Welding, Welding Journal, November 1987, pg21s.
- 46) Fogiel M., Handbook of Mathematic, Scientific, and Engineering Formulas, Tables, Functions, Graphs, Transforms, Research and Education Association, NJ, 1984.

- 47) Smalltalk/V Tutorial and Programming Handbook, Digitalk Inc., USA, 1986.
- 48) Duff C., Howard B., Object Lessons: Migration Patterns, Byte, October 1990, pg223s.
- 49) Goldak J., Northover S., Chi X., WEE : An Engineering Frame Work for Computer Aided Design, Analysis and Production of Welds, CASCADE Report No. 870801, Department of Mechanical and Aerospace Engineering, Carleton University, Ottawa, 1987.
- 50) Graville B.A., The Principles of Cold Cracking Control in Welds, Dominion Bridge Company, Montreal, April 1975.
- 51) Flinn R.A., Trojan P.K., Engineering Materials and Their Application, 2nd edition, Houghton Mifflin Company, Boston, 1981.
- 52) Van Vlack L.H., Elements of Materials Science and Engineering, 5th edition, Addison-Wesley Publishing Company, USA, 1985.
- 53) Shing G.Y.Y., Microprocessor Model for Predicting Weld Heat-Affected Zone and Fusion Zone Hardnesses, M. Eng. Thesis, Department of Mechanical and Aeronautical Engineering, Carleton University, Ottawa, February 1985.
- 54) Moore J., A Comparison of the Calculation Schemes for Computing Welding Cooling, M. Eng. Thesis, Department of Mechanical and Aeronautical Engineering, Carleton University, Ottawa, April 1985.
- 55) Mehrotra V., A Microprocessor Method for Predicting Preheat Temperatures to Avoid Cold Cracking in Steel Welds, M. Eng. Thesis, Department of Mechanical and Aeronautical Engineering, Carleton University, Ottawa, August 1984.
- 56) Graville B.A., Weld Cooling Rates and Heat-Affected Zone Hardness in a Carbon Steel, Welding Journal, September 1973, pg377s.
- 57) Degarmo E.P., A Theory for Preheating of Plain, Low-Carbon Steels, Welding Journal, March 1958, pg93s.

References

- 58) Toyooka T., Terai K., On the Effects of Postweld Heat Treatment, Welding Journal, June 1973, pg247s.
- 59) Kyte W.S., Chew B., Postweld Heat Treatment for Hydrogen Removal, Welding Journal, February 1979, pg54s.
- 60) Evans G.M., Christensen N., Correlation of Microstructure with HAZ Embrittlement, IIW Doc IX 823-73.
- 61) Bibby M.J., The Principles of Manufacturing Engineering, Carleton University, Ottawa, Sept. 1982.
- 62) Goldak J., Materials Engineering, Carleton University, Ottawa, 1976.

END

03·03·92

FIN