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Predicting the Features of Structural Steel Welds with Internet Technology

by

Shunsuke Morinishi, B.Eng.

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

Master of Engineering

Ottawa-Carleton Institute for Mechanical and Aerospace Engineering

Department of Mechanical and Aerospace Engineering

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**PREDICTING THE FEATURES OF STRUCTURAL STEEL
WELDS WITH INTERNAT TECHNOLOGY**

submitted by

Shunsuke Morinishi, B.Eng.
in partial fulfilment of the requirements for
the degree of Master of Engineering

Thesis Co-Supervisor

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Chair, Dept. of Mechanical and Aerospace Engineering

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March 2000

Abstract

A computer system for predicting heat-affected zone (HAZ) hardness and weld features (size and shape of the weld bead), originally coded by Chan [1-9, 10] but herein re-coded for the world wide web, is described in this thesis. In fact the web version consists of two systems: a “passive” Java based system intended for remote processing, and an “active” neural network server system, coded with PHP (Personal Home Page Tools) and mySQL (Sequential Query Language), a data base management language intended for central processing.

The passive system is based on the regression algorithms of Yurioka [1-7, 8], Teresaki [1-5, 6] and Suzuki [1-4] for computing HAZ hardness and on the work of Chandel [2-6, 7] for computing weld features. In addition, a module based on fully trained neural networks for computing both HAZ hardness and weld features originated by Chan [1-9,10] has been re-coded for web implementation. Since the passive weld design tools are to be downloaded for remote processing by users, they have been coded with the Java language because it is relatively platform independent and therefore available to almost anyone familiar with the world wide web.

The active weld design tools consist of BPN (backpropagation network) modules designed for training on the server. Users are expected to submit training data in HTML format (via a web browser – Netscape or Microsoft Explorer) to the server which accepts and translates it for BPN processing. Among other things this permits “custom” training which is an important consideration because the welding process is not all that well

controlled and operator traditions often affect the outcome. After training the BPN model is then stored along with the training data in a server database. Users can recall the model for computing HAZ hardness or weld features as required.

One of the advantages of the active system is that user data and models are to be captured by the server. By so doing, it is anticipated that a large data base of weld sizes and shapes, and HAZ hardnesses, documented against operating parameters, can be assembled for the benefit of the entire welding engineering community. Central server processing to provide a data base of users, and weld data, is original insofar as this researcher knows. The research and methodology used to generate this system is described in this thesis.

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

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Nomenclature

FZ - fusion zone
HAZ - heat affected zone
IIW - the International Institute of Welding
GMAW - gas metal arc welding
SAW - submerged arc welding
GTAW - gas tungsten arc welding
 $t_{8/5}$ - 800 to 500°C cooling time (sec)
CTT – continuous cooling transformation
CHC - characteristics hardness curve
w/o - weight percent
CE - IIW carbon equivalent (w/o)
P_{cm} - Ito's carbon equivalent (w/o)
 $C_{eqI} \sim C_{eqIII}$ - Carbon equivalents (w/o) for Yurioka's first model
 $CE_I \sim CE_{III}$ – Carbon equivalents (w/o) for Yurioka's second model
B - boron content (w/o)
C - carbon content (w/o)
Cr - chromium content (w/o)
Cu - copper content (w/o)
Fe - iron content (w/o)
Mn - manganese content (w/o)
Mo - molybdenum content (w/o)
Ni - nickel content (w/o)
Nb - niobium content (w/o)
Si - silicon content (w/o)
V - vanadium content (w/o)
HV_{MAX} - maximum HAZ hardness (VHN)
 $t_{8/5}[3D]$ - thick plate cooling time from 800 to 500°C (sec)
 $t_{8/5}[2-D]$ - thin plate cooling time from 800 to 500°C (sec)
 $t_{8/5}[2.5-D]$ - intermediate plate cooling time from 800 to 500°C (sec)
 η_{proc} - welding process efficiency (%)
Q - heat input rate per unit length (J/s/mm)
 h_t - plate thickness (mm)
k - thermal conductivity (J/(s.mm.K))
C_p - volumetric specific heat (J/(mm³K))
T_o - plate initial temperature (°C)
Cr - ratio of cooling time on thick plate to that on finite plate
I_c - arc current (amperes)
V_o - arc voltage (volts)
S_p - wire travel speed (mm/s)
H_r - relative plate thickness
I – welding current (Amp) – weld feature model

V – arc voltage (volt) – weld feature model
 v – travel speed (mm/s) – weld feature model
 D – electrode diameter (mm) – weld feature model
 L – electric extension (mm) – weld feature model
 MR – melting rate (kg/h)
 BW – bead width (mm)
 BH – bead height (mm)
 Pene – penetration length (mm)
 A1 – deposited area (mm²)
 A2 – plate fusion zone (mm²)
 A – total fusion area (mm²)
 AI - artificial Intelligence
 ANN - artificial neural network
 BPN - backpropagation network
 I - input layer of backpropagation network
 H - hidden layer of backpropagation network
 O - Output layer of backpropagation network
 m - number of input nodes
 e - intermediate input node
 n - number of hidden nodes
 r - intermediate hidden node
 t - number of output nodes
 g - intermediate output node
 $W^{(I-H)}$ - weight between input and hidden layer
 $W^{(H-O)}$ - weight between hidden and output layer
 a,b - counter
 P_n - n-th data set
 p - total number of training data set
 $X_m^{P_n}$ - input of node I_m for data set P_n
 $Y_t^{P_n}$ - target output at node O_t for data set P_n
 F - transfer function
 S_r^H - summation of node H_r
 S_g^O - summation of node O_g
 E^P - error of the network
 G - a general function notation
 η - learning rate
 ΔW - change in weight
 δ - delta term
 RMS error - root mean squared error
 α - momentum coefficient
 SD - standard deviation
 PHP – personal home page
 SQL – Structured Query Language
 HTML – Hypertext Markup Language

Chapter One

Introduction

Fusion welding is an important and often underestimated industrial process. In fact 80% of all steel tonnage is welded in one form or another. Moreover, it is well understood that a joint (fastened by whatever means) is the critical area of a steel structure or device. In fact, almost all structural and device failures occur because of joint problems. The loss of money and/or life when a pipeline or an airliner fails can be devastating. The need for research to improve the integrity of joints designed for structures and devices is therefore evident.

In general, welded joints are considered better than the alternatives (bolting, brazing, etc.) because it is usually possible to match the strength of a weld to that of the base metal if the consumables are properly formulated and good welding technique is used. To a great extent a properly designed weld provides continuity across the joint which combines the workparts into one fully integrated system. The ideal joint is one where all mechanical properties are perfectly matched to those of the workpiece so that the weld is in fact, indistinguishable from the base metal.

1.1 Weld Problems

Real welded joints are usually far from ideal. In practical terms joint strength overmatches base metal strength which can cause non-uniform strain distributions when external service loads are applied. Moreover, triaxial residual stresses from the welding process are inevitably present even before the weld is put into service. But beyond

simple mechanical strength, it is not possible to match other important properties such as toughness; fatigue strength and corrosion resistance, which renders welded joints vulnerable to failure by several mechanisms, other than overload [1-1]. The heat-affected zone (HAZ), i.e., the base metal region adjacent to the weld that is inevitably adversely affected by the heat from the welding process, is generally recognized as the most difficult area to control. Often the toughness, fatigue and stress corrosion properties of this region are inferior to those of the unaffected base metal. Moreover, welding engineers are, more or less, hostage to the properties that appear in this region because the chemistry of the base material cannot be changed in general, although heat input adjustments, preheat and/or postheat provide some measure of control. Nonetheless, HAZ properties often limit the service performance of welded joints.

Notwithstanding what was said in the last paragraph, it is the formation of so called cold cracks (sometimes termed underbead or hydrogen induced cracks) in the HAZ that is the most serious limitation of the welding process. When the material next to the weld is heated, it is autenitized. When austenite cools it decomposes and if it cools relatively rapidly, as it does in many welding situations, the decomposition product is a hard and brittle phase called martensite. At the same time hydrogen and water vapor from the electrode coating and fluxes, and water vapor from the atmosphere breaks down chemically in the arc and nascent hydrogen is injected into the weld pool. From the weld pool some of the hydrogen diffuses into the HAZ. The combination of hard, brittle martensite, hydrogen from the arc and residual tensile stresses that form in the HAZ are conditions that favor the formation of cold cracks. They form spontaneously in the temperature range from about 250 °C to room temperature as the weld cools or in some

cases their formation may be delayed for anywhere up to five days after completion of the weld. This is a well known characteristic of hydrogen cracking under other circumstances (e.g. corrosion situations) and has led to the term "delayed cracking".

It is evident from the description above that cold cracks can form in the HAZ even before a weld is put into service. They are very dangerous, because when such a weld is loaded, high stress concentrations build up around such crack tips, which can cause them to propagate rapidly in a brittle manner to failure. In fact, pre-existing HAZ cold crack defects is a significant cause of weld failures [1-2].

Cold crack formation can be avoided if the welding conditions can be arranged to limit the HAZ hardness level. In practice a limit of about 320 VPN is imposed in most routine welding situations [1-3]. For highly loaded applications such as pipelines, a limit of 250VPN is often specified. As it turns out, in service stress corrosion cracking is also very sensitive to HAZ hardness and this also gives rise to the necessity of limiting the hardness in this region.

1.2 Weld Models

In view of the importance of HAZ hardness in engineering practice, several researchers have proposed regression based models for calculating the level that would be expected, given the welding parameters (current, voltage, welding speed, etc.) and workpiece chemical composition. Included in these are the models of Suzuki [1-4], Teresaki [1-5,6], and Yurioka [1-7,8]. These are the most recent and seemingly the best available, and are therefore the models that were included in the recent software system

generated by Chan for this purpose. A review of all hardness models may be found in Chan's work[1-9].

In addition to the regression based models, Chan [1-10, 11] proposed a neural network system for determining HAZ hardnesses. This system has the advantage that it can be custom "trained" to accommodate welding traditions and skills at one or another job shop or manufacturing facility. Universal systems such as regression models are at best only approximate because the welding process, even under well controlled automated manufacturing conditions, is somewhat variable. Characterizing such a system to ensure an unequivocal and accurate operating description is difficult and yet regression and physical modeling requires this to be the case. This is not to say that regression models are not useful; quite the contrary -- practitioners find them very useful, even though it is well understood that they may not be entirely accurate in one situation or another. However, with neural technology, the traditions of a job shop or a manufacturing operation can be captured implicitly by "training" with data relevant to the situation at hand. In this way the neural network system is expected to be flexible and sensitive to local welding tradition.

Chan recently generated a software system including both regression and neural network algorithms for predicting HAZ hardnesses [1-9,10], and for anticipating the size and shape of the weld fusion zone. Like HAZ hardness, the size and shape of a weld are important to the welding engineering community. However, in this case it is largely a productivity issue although weld properties are also integral with weld features. Welding is costly in fact it is one of the principal costs of metal manufacturing and fabrication. In general deep penetration, narrow welds are

considered to provide the highest productivity, but such welds are often difficult to arrange and their integrity can be problematic. If the penetration is too deep, burn through difficulties can arise, especially for thin plate situations. On the other hand insufficient penetration of the root region may occur when the heat input is small. Moreover, most joints are "prepared" before welding and there are a whole range of weld geometry issues that must be taken into account to optimize productivity on the one hand and weld properties (e.g. avoiding cold cracking, etc.) on the other.

The regression/neural network system generated by Chan has been well received. In particular, the neural network approach is thought to be the way to analyze process situations such as welding where physical modeling is very difficult and where there is uncertainty in the regression approach. However, this researcher hastens to add that physical modeling is very important. Even though the neural network approach is useful, it does not yield any understanding of the underlying physics and mechanisms involved. In the end physical modeling is the only way the welding process will be fully understood and controlled.

1.3 Web Based Weld Property Estimating Tool

A web based version of the Chan system is described in this thesis. The objective of generating a web based version of the system is to make it available to the world at large and, in particular, to those in the engineering community who would have an interest in it. While publishing the details of the system in contemporary journals has been done, it is a large step from there to working code. If the entire system were to be installed and housed on a web

server, anyone who wants to access and use it can do so without having to regenerate the code.

There are essentially three modules in the web based system. The first module is a re-coded Java based version of the regression module first established by Chan. By re-coding with the Java Internet language, it is made available to almost all Internet users since such a system is relatively platform independent. Users can download this module to their remote personal computers and use it in a straightforward manner, i.e., welding parameters are submitted and calculated HAZ hardnesses or weld features are returned. In some sense this can be viewed as a universal system for calculating HAZ hardness and weld features.

In addition, a second Java module, based on a pre-trained neural network is included in the web system. In practice using this module is similar to the way the regression module is used and it can be considered universal in the same sense. It serves as a second output for determining HAZ hardness or weld features which is useful considering the uncertainty in such calculations.

To permit "custom training" as discussed previously, an untrained neural network module has been made available to users as part of the web system. However, the neural network module is to be used only on the server via remote control from any web connected workstation, i.e., down loading will be prohibited. Users of the web based system will be asked to leave their names and affiliations, their training data, and their trained models. In this way it is anticipated that a worldwide database of researchers,

practitioners, welding data, and several trained models will be assembled for the benefit of the entire welding community.

While the system is not yet in practice (the issue of server maintenance has still to be decided), the equivalent of a manufacturing “pilot plant” has been generated for this thesis. The welding technology basis for the system is reviewed in the following section.

Chapter Two

Background

To understand fully the proposed web based system for predicting HAZ hardness and weld features, it is necessary to review the welding process itself (section 2.1), the metallurgical changes that give rise to the mechanical properties of a defect free weld, the occurrence of underbead cracks that so limit weld performance in service (section 2.2), and finally the HAZ hardness and weld shape algorithms that are to be incorporated into the system (section 2.3, 2.4, and 2.5).

2.1 Fusion Weld

While there are numerous welding techniques, the fusion process is by far the most common and therefore it is the focus of the proposed web based system. The SMAW fusion process is shown schematically in Figure 2.1. In this technique the joint between two

Figure 2.1: Schematic of DCEP (electrode positive) SMAW to demonstrate the fusion welding process.

pieces of steel is heated to the melting point by an electric arc (large luminous current flow) extending from the electrode to the workpiece. The arc is essentially an ionized gas (plasma) where electrons are accelerated to the positive electrode and heavy positive gaseous ions are accelerated to the

negatively charged workpiece. When electrons strike the electrode and ions strike the workpiece they lose kinetic energy which appears as heat. The intense heat of the arc causes a local molten pool to form under the arc which re-solidifies to fuse the joint which in turn, forms one continuous workpiece. The electrode not only serves as an essential electrical element for the arc, but it is also the source of filler material for the joint. Most joints are shaped to a V or K configuration for alignment purposes and to receive molten filler metal from the electrode. As the welding proceeds, the electrode is consumed and eventually has to be replaced.

As shown in Figure 2.1, a typical electrode is covered with a flux coating which, upon melting, forms a shielding gas and a slag layer on the molten pool. Both the shielding gas and the slag layer serve to protect the pool from atmospheric oxidation. If there were not some form of protection for the molten pool, oxide inclusions would otherwise seriously degenerate the mechanical properties of the joint.

The arrangement shown in Figure 2.1 above is known as the shielded metal arc (SMA) process or sometimes called manual welding. An automatic version of this is the gas metal arc (GMA) process where a continuous wire feed replaces discrete length electrodes so that continuous welding is possible. In addition, an inert gas, such as CO₂ or argon, replaces the flux that protects the molten pool. A review of other automatic welding processes such as the submerged arc, plasma arc, electron beam or laser processes may be found in reference [2-26].

While joints are prepared in most welding situations, the arrangement shown in Figure 2.1, where the weld is deposited on the surface of a workpiece, may be interpreted

as bead-on-plate (BOP). BOP welds are used to simulate joint welding situations for experimental purposes rather than for joining parts per se. The BOP procedure is relatively simple and technical errors are minimized with such an arrangement so that skill related parameters such as the heat input efficiency can be used with some confidence. Moreover, BOP welds have been used extensively by researchers to study the welding process in general and there is considerable experience with this configuration. For example, the heat flow morphology is relatively well understood for the BOP situation which is an important consideration. Yet the information gathered from such investigations can, in general, be adapted to other more common welding configurations and situations. In fact, the databases that form the basis for the web based HAZ hardness, and weld features system described in this thesis are derived primarily from GMA BOP weld experiments.

2.2 Weld Structure and Metallurgy

Figure 2.2: Three weld regions at a t-joint. (FZ, HAZ, and unaffected base metal, shown schematically for a T joint configuration. Also shown is an underbead crack which can form in some circumstances).

The intense heat source used in the fusion welding process induces crystal growth in the base metal adjacent to the joint. In fact, three distinctive regions form in a welded joint: the fusion zone (FZ), the heat affected zone (HAZ) and unaffected parent metal as shown schematically in Figure 2.2. The microstructure changes rather dramatically from one zone to

another and therefore the mechanical properties would be expected to vary with position accordingly.

A detailed cross section of a fusion welded joint (Figure 2.3) is shown together with part of the iron-carbon phase diagram to be used for explanation purposes. To understand the mechanisms that give rise to the microstructures and zones that appear adjacent to a fusion weld, it is first necessary to

Figure 2.3: Detailed cross section area of a fusion weld and iron-carbon (steel) phase diagram [2-2].

appreciate the thermal changes that accompany the process. Each fixed position adjacent to the weld centerline experiences a thermal cycle similar to that shown schematically in Figure 2.4.

As the heat source approaches a particular fixed position, the temperature first increases, reaches a maximum (peak temperature) and then decreases. It is intuitive that peak temperature decreases with distance from the weld centerline. Where the peak temperature exceeds the melting temperature (approximately 1500 °C), filler and base metal melt during heating and re-solidifies upon cooling to form the fusion zone (FZ) – region (a) in Figure 2.3. The grain morphology in this region is a coarse grained columnar structure containing a dendritic substructure that reflects the solidification mechanism. Adjacent to the FZ is the HAZ, which can be divided further into four

subsections; the grain growth zone (b), the recrystallized zone (c), the partially transformed zone (d) and a tempered zone (e). Rapid grain growth is experienced in the range from the melting temperature to about 1100°C . This leads to a relatively coarse grained equiaxed zone – region (b). The range of peak temperatures for the recrystallized zone (c) is from about 1100°C to the A_3 (austenite-ferrite phase boundary). The microstructure in this region is relatively fine-grained because the phase transformation causes recrystallization but there is limited time and temperature for grain growth to occur. Region (d) where the peak temperature is between A_3 and A_1 (eutectoid temperature) is called the partially transformed zone. Since the peak temperature does not reach A_3 in this region, there is only partial austenitization and mixed grains (original base metal ferrite/pearlite and decomposed austenite products) co-exist. Peak temperature below A_1 (approximately 720°C for carbon steel) but above about 580°C gives rise to the so-called tempered zone – region (e), there is some recrystallization if there has been prior cold work in this region; otherwise not much else happens. 580°C is approximately the lower limit of significant thermal activity in steels and therefore peak temperatures below this temperature leave the base metal virtually unaffected.

Figure 2.4 Schematic thermal cycle typical of a fixed position adjacent to a fusion weld [2-3]. (Note the 800°C to 500°C cooling time which is used to characterize a weld thermal cycle.)

While the above discussion explains the occurrence of the FZ, and the HAZ (together with sub-zones), it is not possible to rationalize the microstructures that might

occur in these regions from the equilibrium diagram in the same way. This is because the austenite decomposition products that are to be expected, depend on the rate of cooling. If the cooling rate is high, a high hardness, brittle decomposition product called martensite appears in the HAZ. On the other hand if the cooling rate is not as fast, less brittle products such as bainite or ferrite/pearlite form. The most sensitive product is martensite and as discussed in the introduction section, this is the phase that gives rise to underbead cold crack formation (Figure 2.2).

It has become customary to characterize the cooling behavior of a weld by its 800°C to 500°C cooling time $t_{8/5}$. Among other things, this is the transformation range (austenite decomposition) and as such it is considered to be the most sensitive region of the thermal cycle. While cooling times would reasonably be expected to vary across a weld, it turns out that the weld centerline cooling time does not differ substantially from the cooling time of the coarse grained HAZ [2-4], which as noted earlier is the most sensitive region of a weld. It is therefore, customary to speak of one single weld cooling time for a fusion weld. Cooling times range from about 1s for a very small weld to about 100s for a very large weld. HAZ martensite can be expected in the low cooling time (high cooling rate) range, whereas there is less tendency for the formation of martensite when the cooling time is high (slow cooling rate).

However, the tendency to form martensite in the HAZ depends not only on the cooling time but also on the “hardenability” of steel which, in turn, is a function of the grain size and chemical composition. The larger the austenite grain size, the greater the tendency for martensite formation. As it turns out, the effect of grain size on

hardenability is substantial - so much so that there is, in general, little concern for the HAZ other than the coarse grained region next to the FZ. Moreover, the "richer" the chemical composition, the higher the hardenability and the greater the tendency for martensite to form. It is well known that carbon has the greatest effect of all alloy additions on hardenability and therefore it is customary to express the hardenability of the HAZ of steel welds in terms of a so-called "carbon equivalent" (CE).

Finally, the hardness of the coarse grained HAZ depends not only on the tendency for martensite to form in that region but also on the inherent hardness of the martensite itself. To a first approximation, the hardness of martensite depends only on the carbon content. Therefore, low carbon martensites are relatively soft and less prone to cracking than higher carbon martensites. In this regard the carbon content of filler materials (electrode compositions) is normally kept intentionally low ($C < 0.05w/o$) compared with base compositions of $0.05w/o < C < 0.3w/o$ [2-5]. Because of this, the maximum hardness of a weld is usually found in the HAZ, with the exception of low carbon microalloy steels where the carbon content of the filler can exceed that of the base metal. To compensate for the loss of strength in the FZ, as a result of low carbon levels, the low alloy content (Mn, Si, Cr, Ni, Mo primarily) usually exceeds that of the base metal. This of course, leads to high hardenability and encourages the formation of martensite. However, the martensite so formed is usually of low hardness and less sensitive to cracking than the relatively higher hardness martensite of the coarse grained HAZ.

It is apparent from the foregoing discussion that HAZ hardness is a function of cooling time, low alloy content (i.e., hardenability) and carbon level (reflected by the inherent martensite

hardness) of the base metal. Therefore, these factors must be included in any models for predicting maximum HAZ hardness. HAZ hardness formulations are discussed in the following section.

2.3 Computational Models by Regression Analysis

To compute HAZ hardness from the regression expressions available for this purpose, it is first of all necessary to determine a cooling time from the welding parameters. An experimental value (measured by injecting a thermocouple into the weld pool) can be used but more often than not it is not available. If it is not available then it is necessary to calculate it from the welding parameters. The cooling time is then submitted along with the chemical composition of the base material to the hardness models (Suzuki, Yurioka (two models) and Teresaki (two models)) to determine HAZ hardness. The background necessary to calculate cooling times and subsequently HAZ hardness is given in 2.3.1 and 2.3.2 respectively. In 2.3.2, there are five subsections, one for each HAZ model implemented for web system. In addition, weld features modeling is described in 2.3.3 and the regression model of Chandel et al [2-6,7] for this purpose is documented in 2.3.3.1. The background necessary to understand the neural network technique used in this thesis for calculating HAZ hardness and for estimating weld features is given in 2.4.1, 2.4.2, and 2.4.3, and the proposed web based system is discussed in 2.5.

2.3.1 The 800 to 500 °C Cooling Time Model

As discussed in the last section, it is usually necessary to calculate an 800°C to 500 °C cooling time, $t_{8/5}$, from the input welding parameters (voltage, current, welding speed, preheat

or ambient temperature) before a HAZ hardness can be determined. The conventional theory of moving heat sources developed to model the welding process was originally put forward by Rosenthal [2-8, 9]. Subsequently Adams [2-4, 10] generated weld cooling rate relationships and from these he evolved cooling time formulations.

The Rosenthal/Adam's model is widely used because of its simplicity, although several simplifying assumptions are

Figure 2.5 : Weld heat flow morphology assumed in the Rosenthal/Adams analyses [2-10].

necessary: the weld is assumed to be a point (3D heat flow) or a line source (2D heat flow); the thermal properties (conductivity, heat capacity) are assumed constant even though they are well known to be temperature dependent; heat losses from the workpiece by convection or radiation are assumed to be small; and an arc efficiency is assumed to account for convection and radiation losses from the arc. Despite all of these assumptions it has been demonstrated that in general, cooling times can be calculated which agree with experimental measurements within about 20% for typical welding situations. Moreover, it has been shown that this level of cooling time accuracy is sufficient to predict reasonably reliable HAZ hardnesses in most cases [2-11]

Rosenthal and Adams demonstrated that it was necessary to consider two heat flow regimes when dealing with BOP welds - two dimensional (2D) for thin plate or deep penetration situations where heat flows away from the heat source parallel to the

plane of the workpiece (Figure 2.5) and three dimensional (3D) where the workpiece is thick and heat flows not only parallel to the plane of the workpiece but also in the through thickness direction. if the heat flow is intermediate, i.e., mixed 2D/3D, it is treated as a mixed morphology situation and is referred to as 2.SD heat flow. The Adams cooling time relationships for 3D, 2D and 2.SD situations are as follows:

Table 2-1 Summary of Welding Process Efficiencies for Commonly Used Welding Heat Sources

Process	SMAW	SAW	GMAW	GTAW	FCAW
Efficiency %	80	95	70	40	70

Table 2-2 Tabulated Values of Cr Corresponding to Hr

Hr	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Cr	0.30	0.43	0.63	0.76	0.85	0.94	0.94	0.97

$$t_{8/5}[3-D] = \frac{\eta_{proc} Q}{2 \pi k} \left[\left(\frac{1}{500 - T_o} \right) - \left(\frac{1}{800 - T_o} \right) \right] \quad \text{Equation 2-1}$$

$$t_{8/5}[2-D] = \frac{1}{2 \pi k C_p} \left(\frac{\eta_{proc} Q}{h_t} \right)^2 \left[\left(\frac{1}{500 - T_o} \right)^2 - \left(\frac{1}{800 - T_o} \right)^2 \right] \quad \text{Equation 2-2}$$

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

where Q is the welding process energy input rate per length in (J/mm):

$$Q = \frac{I_s \cdot V_o}{v} \quad \text{Equation 2-4}$$

η_{proc} is the welding process efficiency (Table 2-1), k is the thermal conductivity (0.025 J/(mm.s.K) is used), T_o is the initial plate temperature, C_p is the volumetric specific heat (0.006 J/(mm³.K) is used), h_t is the plate thickness in mm, C_r is a transition cooling time

parameter-- the ratio of the thick plate cooling time to that of the finite plate (discussed below) and I_c , V_0 , and S_p are arc current in amperes, voltage in volts, and wire travel speed in mm/s respectively.

The appropriate heat flow relationship to be used is determined by a relative thickness parameter (H_r) defined as:

$$H_r = \frac{C\rho \cdot h_i^2(650 - T_o)}{\eta_{proc}Q} \quad \text{Equation 2-5}$$

If H_r is greater than 1, the 3D relationship is used. If the H_r value is less than 0.3, the 2D cooling model is appropriate. In the H_r range between 0.3 and 1, the 2.5D model is applied. Values of the parameter, Cr , are obtained from Table 2-2 corresponding to the calculated value of H_r .

In the web based system described in this thesis, Equation 2-5 is computed to identify the heat flow regime. Then a cooling time is calculated with one of the relationships, equations 2-1 to 2-3, whichever is appropriate. The cooling time so calculated is then submitted to one of the models documented in the next section to calculate a HAZ hardness.

2.3.2 HAZ Hardness Regression Models

The HAZ hardness regression models originated by Suzuki [2-12], Teresaki [2-13, 14] and Yurioka [2-15,16] are incorporated in the web based software described in this thesis. While there are several other similar regression models in the literature, it is widely held that these models are the best available. For example it is well known that

these models are based on high quality databases and that they are well documented, i.e., the compositional limits are well defined in each case, among other things. In general these models predict relatively accurate HAZ hardnesses if the compositional limits are respected. At the same time the compositional limits incorporate a relatively wide range of low alloy and microalloy steels which are the materials of most interest to practitioners.

There is a case to be made for including all available models in the web system because they are regression based and therefore the accuracy and range of applicability is always open to question. It is the view of many researchers and practitioners that computations from a wide range of models would provide a better basis for making judgment. This was the philosophy used by Chan who reviewed all models and included them in his original work [2-17]. However, it was decided that for this investigation, including all models unnecessarily complicates the software. This is an important consideration when implementing the system on the web. Therefore in the end it was decided to implement only the Suzuki, Teresaki and Yurioka models. Other regression expressions can be added in future, if this is found to be a deficiency.

It is well understood in metallurgical science that a phase diagram such as that shown in Figure 2.3 is a fundamental and useful temperature/composition map of phases under equilibrium conditions. Yet the thermal situation during welding is certainly not equilibrium during cooling although it can reasonably be assumed when the joint is being heated. Transformation rates increase exponentially with temperature. Therefore during the heating part of the thermal cycle, phase changes take place quickly and it is widely

held that near equilibrium can be assumed. This is why the phase diagram is used to rationalize the extent of the HAZ as discussed in section 2.2 (Figure 2.3). However phase changes are much more sluggish in the cooling part of the cycle and in particular hardened phases including the bainites and martensite can form under relatively high cooling rate conditions.

In conventional heat treating, standard CCT diagrams (continuous cooling transformation diagrams) are used to predict the phases that would be expected in one situation or another. CCT diagrams generally reflect the material property known as hardenability, i.e., the greater the tendency to form hardenable products, the greater the hardenability. It is well known that the hardenability of a steel depends both on alloy content and austenite grain size. However, it is difficult to apply standard CCT diagrams to the welding situation because the austenitization temperature is high in the coarse grained HAZ region and the cooling time is short, quite unlike anything encountered in normal heat treating. Therefore special CCT diagrams are used for the welding situation where the cooling time from 800 °C to 500°C is the abscissa rather than heat treating time at temperature.

Figure 2.6 shows the HAZ hardness distribution that corresponds to the welding CCT diagram. Where the cooling time is short, the hardness is high because martensite is expected in this regime. As the cooling time increases, bainite and/or, ferrite and pearlite can form, and the hardness drops. The shape of the hardness/cooling time curve is characteristic and has been called the characteristic hardness curve (CHC). Models for predicting HAZ hardness are all based on the CHC. The problem reduces to predicting the CHC for a given chemistry and cooling time.

Figure 2-6 Heat-Affected Zone (HAZ) characteristic hardness curve (CHC) and corresponding welding continuous cooling transformation (CCT) diagram for a carbon-manganese steel designated as HS50 steel. (After Suzuki and Yurioka [2-16])

2.3.2.1 Suzuki Model

Suzuki [2-12] some time ago suggested a backward logistic function to simulate the CHC as follows:

$$H_{\max} = H_{bm} + \frac{K}{1 + \exp(a(\log t_{8.5} - Y))} \quad \text{Equation 2-6}$$

where:

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

H_{bm} = base metal hardness (VHN)

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

The constant K is the difference between the martensite hardness and base hardness as shown in the Figure 2-7.

Figure 2-7 : Schematic diagram to define the constant K in the Suzuki approach for calculating HAZ hardness.

K is a function of composition as follows:

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

Equation 2-7

The constants H_{bm} , a and Y are determined from the relationships:

$$H_{bm} = 884C + 287 - K$$

Equation 2-8

$$aK = 478 + 3364C - 256Si + 66Ni - 408Mo - 1321V - 1559Nb$$

Equation 2-9

$$Y = -0.085 + 2.07C + 0.495Mn + 0.655Cu + 0.122 Ni + 0.222 Cr \\ + 0.788 Mo + 30B$$

Equation 2-10

the appropriate weight percentage (w/o) is to be substituted where chemical symbols appear in these equations. The Suzuki relationship is valid for low alloy and microalloy compositions containing carbon in the range as show in Table 2-3.

Table 2-3 : Composition Limits for the Suzuki HAZ Hardness Model

Alloying Element	Wt% range
C	0.017 – 0.33
Si	0.05 – 0.65
Mn	0.45 – 2.06
Cu	0.00 – 0.47
Ni	0.00 – 2.09
Cr	0.00 – 1.06
Mo	0.00 – 0.66
V	0.00 – 0.07
Nb	0.00 – 0.06
Ti	0.00 – 0.02
B	0.00 – 0.0023

2.3.2.2 Terasaki Model I

Terasaki proposed two independent formulations [2-13, 2-14] to simulate the CHC. The first model formulation can be seen as following:

For $t_{8/5}$ less than or equal to t_M :

$$H_{\max} = 812C + 293 \quad \text{Equation 2-11}$$

For $t_{8/5}$ greater than t_M :

$$H_{\max} = H_{v0} + (H_{vM} - H_{v0}) \exp\left(-0.2\left(\frac{t_{8/5}}{t_M} - 1\right)\right) \quad \text{Equation 2-12}$$

where

$$H_{vM} = H_{\max} \quad \text{Equation 2-13}$$

$$H_{v0} = 164\left(C + \frac{Si}{2} + \frac{Cr}{7} + \frac{Mo}{2} + V + Nb + 7B\right) + 153 \quad \text{Equation 2-14}$$

$$\log t_M = 2.5C_{eq} - 1.27 \quad \text{Equation 2-15}$$

$$C_{eq} = C + \frac{Mn}{3} + \frac{Cu}{4} + \frac{Ni}{8} + \frac{Cr}{10} + \frac{Mo}{3} + 5B \quad \text{Equation 2-16}$$

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

This (Table 2-4) is the chemical composition limitation for Terasaki I model.

Table 2-4 Composition Limits for the Terasaki I HAZ Hardness Model

Alloying Element	wt% range
C	0.00 – 0.60
Si	0.00 – 0.35
Mn	0.00 – 1.90
Cu	0.00 – 0.50
Ni	0.00 – 2.00
Cr	0.00 – 1.60
Mo	0.00 – 0.60
V	0.00 – 0.08
S	0.00 – 0.05
B	0.00 – 0.006

2.3.2.3 Teresaki Model II

The Tereasaki HAZ hardness equation that approximates the CHC is as follows:

$$H_v = (H_{vm} - H_{vo}) \exp\{-0.05(t_{g/5} - t_{\mu})^A\} + H_{vo} \quad \text{Equation 2-17}$$

Where H_{vm} is the HAZ hardness corresponding to 100 w/o martensite:

$$H_{vm} = 812C + 293 \quad \text{Equation 2-18}$$

H_{vo} is the HAZ hardness corresponding to 0 w/o martensite:

$$H_{vo} = 293C + 47Mn + 48Si + 44Cr + 91Mo + 8Ni + 165V + Cu + 95Nb + 794B + 87$$

$$\quad \text{Equation 2-19}$$

The constants A and t_{μ} are evaluated as follows:

$$A = 5.1C + 1.7Si - 0.39Mn + 0.6Ni - 1.3Cr - 0.8Mo + 6.4V + 3Ni - 45B + 0.29$$

$$\quad \text{Equation 2-20}$$

$$\log(t_{\mu}) = 0.83 \arctan(8C) + 0.64Mn + 0.38Ni + 0.73Cr + 0.76Mo + 0.65Cu + 150B - 1.505$$

$$\quad \text{Equation 2-21}$$

The Teresaki II limits are shown in Table 2-5.

Table 2-5: Composition Limits for the Teresaki II HAZ Hardness Weld Model

Alloying Element	Wt% range
C	0.04 – 0.26
Si	0.00 – 0.60
Mn	0.35 – 1.60
Ni	0.00 – 2.00
Cr	0.00 – 1.30
Mo	0.00 – 0.50
Cu	0.00 – 0.4
V	0.00 – 0.14
B	0.00 – 0.003
Nb	0.00 – 0.05
Ti	0.00 – 0.03

2.3.2.4 Yurioka Model I

Yurioka proposed two relationships, one for low alloy materials and a second for higher alloy transformable steels [2-15,16]. At the same time Yurioka's formulations incorporated multiple carbon equivalents instead of the single carbon equivalent forms proposed by Teresaki and Suzuki. The Yurioka relationship for low alloy steels (sometimes called the Yurioka I formulation) is as follows:

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

$$\arctan\left(\frac{\log t_{8/5} - 2.822C_{eqII} + 0.262}{0.526 - 0.195C_{eqII}}\right) \quad \text{Equation 2-22}$$

where:

$$C_{eqI} = C + Si/24 + Mn/6 + Cu/15 + Ni/40 + Mo/4 + V/5 + Nb/5 + 10B + Cr/6$$

Equation 2-23

$$C_{eqII} = C - Si/30 + Mn/5 + Cu/5 + Ni/20 + Cr/4 + Mo/6 + 10B \quad \text{Equation 2-24}$$

The chemical composition limits for the Yurioka I model are shown in Table 2-6.

Table 2-6: Composition Limits for Yurioka I HAZ Hardness Weld Model

Alloying Element	wt% range
C	0.00 – 0.60
Si	0.00 – 0.35
Mn	0.00 – 1.90
Ni	0.00 – 2.00
Cr	0.00 – 1.60
Mo	0.00 – 0.60
Cu	0.00 – 0.50
V	0.00 – 0.08
B	0.00 – 0.006
S	0.00 – 0.05

The first carbon equivalent, C_{eqI} , is dominant where the cooling times are long, i.e., slow cooling HAZ hardness conditions while the second carbon equivalent, C_{eqII} , dominates in the transition region between the critical cooling times for 100% and 0% martensite. This formulation can be applied to steels containing between 0.01 to 0.30 wt% carbon.

2.3.2.5 Yurioka Model II

The second Yurioka model [2-16] was developed for higher alloy transformable steels as shown in Table 2-7 below. Although transformable higher alloy materials are quite different than the low alloy and microalloy materials considered in the Suzuki and Teresaki models, they are included here because this extends the range of applicability of the web system which will undoubtedly appeal to users.

Table 2-7 : Composition Limits for Yurioka II HAZ Hardness Weld Model

Alloying Element	wt% range
C	0.00 - 0.80
Si	0.00 - 1.20
Mn	0.00 - 2.00
Cu	0.00 - 0.90
Ni	0.00 - 10.00
Cr	0.00 - 10.00
Mo	0.00 - 2.00

The formulation for this model is as follows:

$$Hv_{max} = 220 + 442C(1-0.3C^2) + 65\tanh y + [68 + 402C(1-0.3C^2) - 59\tanh y] \arctan x \quad \text{Equation 2-25}$$

where:

$$x = \frac{\log t_{8.5} - 2.3CE_I - 1.35CE_{III} + 0.882}{1.15CE_I - 0.673CE_{III} - 0.601} \quad \text{Equation 2-26}$$

$$y = 2.65CE_{II} - 0.690 \quad \text{Equation 2-27}$$

$$CE_I = C_P + Si/24 + Mn/6 + Cu/15 + Ni/12 + \frac{Cr(1-0.16\sqrt{Cr})}{8} + Mo/4 + \Delta H \quad \text{Equation 2-28}$$

$$CE_{II} = C + Si/24 + Mn/5 + Cu/10 + Ni/18 + Cr/5 + Mo/2.5 + V/5 + Nb/3 \quad \text{Equation 2-29}$$

$$CE_{III} = C_P + Mn/3.6 + Cu/20 + Ni/9 + Cr/5 + Mo/4 \quad \text{Equation 2-30}$$

where

$CE_I, II, \text{ and } III$ = carbon equivalents

C_P = effective carbon

$$= C$$

$$\text{if } C \leq 0.3 \text{ wt\%}$$

$$=0.25 + C/6 \quad \text{if } C > 0.3 \text{ wt\%} \quad \text{Equation 2-31}$$

ΔH = increase in hardenability due to boron for $S \leq 0.016 \text{ wt\%}$ and $O_2 \leq 60 \text{ ppm}$;

ΔH values are determined from Table 2-8.

$$f_n = (0.02 - N)/0.02 \quad \text{Equation 2-32}$$

where: N is the nitrogen content in percentage weight.

Table 2-8: ΔH Values Corresponding to Boron Content

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

While these algorithms are straightforward in principle, it is necessary to code them for the web based system. As discussed previously the coding system selected was the Java applet technology. Java applets can be downloaded from a web server for remote use. Moreover, they are relatively platform independent and therefore can be accessed by a wide range of users.

2.3.3 Predicting Weld Features

In addition to HAZ hardness, a system for predicting weld shape and size has been incorporated into the web system. Weld size is an important feature for productivity and cost issues. It is also integrally related to heat-input, microstructure, hardness, strength and

toughness [section 2.1]. Therefore, a module for predicting weld size and shape should be helpful to practicing engineers in several ways.

Formulating a fundamental physics based model for predicting weld size and shape is not easily achieved since the welding process is very complex and not well understood. In particular the physics of the arc and its interaction with a workpiece is difficult to characterize. On the other hand, several semi-empirical models for determining weld size and shape based on regression techniques are available for the web system. A review of these models is given in some previous work by Chan [2-17]. Based on the Chan review and the need to use a model where the coding and computer requirements are reasonable, the model selected for implementation is that due to Chandel [2-6,7]. While there are models other than those of Chandel in the literature, this is the only model incorporated in the web system, primarily to keep the size and complexity of the applet system reasonable.

2.3.3.1 Chandel Weld Features Model

The Chandel model assumes that the features for GMAW welds can be described by a regression relationship of the form:

$$Feature = 10^K I^a V^b v^c D^d L^e \quad \text{Equation 2-33}$$

where 'Feature' is either bead width (BW) in mm, bead height (BH) in mm, penetration (Pene) in mm or total fusion area (A) in mm² and I, V, S, D, L are welding current (amperes), arc voltage (volts), wire speed (mm/s), electrode diameter (mm) and electrode extension (mm) respectively as shown in Figure 2.8.

Figure 2-8 Schematic diagram to identify the features in the Chandel weld features model.

The a, b, c, d, e and K in equation 2-33 are constants which depend on electrode polarity and the shielding gas composition. Weld size and shape are assumed independent of the chemical composition of the steel which is a reasonable first approximation. Weld efficiency is assumed to be constant and is implicitly incorporated in the relationships, so obtained. The a, b, c, d, e and K values for each feature are tabulated in Table 2-9. It should be noted that this regression analysis is really only valid for GMAW, BOP welds. However, the results of these computations form a useful basis for estimating weld size and shape for situations other than BOP.

With the coefficients from Table 2-9, all of the weld features referred to above can be calculated, with the exception of the deposit area and the fusion area. However, Chandel also generated a melting rate expression for calculating the deposit area:

$$MR = w \cdot I - x \cdot I \cdot V + y \cdot \frac{I^2 \cdot L}{D^2} + z \quad \text{Equation 2-34}$$

where:

I = welding current (Amp)

V = arc voltage (Volt)

D = electrode diameter (mm)

L = electrode extension (mm)

w , x , y , and z are given in Table 2-10

The deposit area A_1 can be calculated from the melting rate as follows:

$$A_1 = 35.47 \cdot (MR/v) \quad \text{Equation 2-35}$$

where:

A_1 = deposited area (mm^2)

MR = melting rate (kg/h)

v = travel speed (mm/s)

It follows that the plate fusion area can be determined as the difference between the total fused area (Table 2-12a) and the deposit area:

$$A_2 = A - A_1 \quad \text{Equation 2-36}$$

where:

A_2 = plate fusion area (mm^2)

A_1 = deposited area (mm^2)

A = total weld bead area (mm^2)

**Table 2-9a Coefficients for Chandel's Weld Bead Dimension Models
(C-25 Shielding Gas and +ve Electrode Polarity)**

Dimension	K	a	b	c	d	e
A	-2.350	1.689	0.260	-0.850	-0.630	0.2535
BW	-0.218	0.181	0.860	-0.614	0.567	0.0106
BH	-1.382	1.200	-0.690	-0.450	-1.360	0.3800
Pene	-4.030	2.050	0.142	-0.530	-0.860	-0.0630

**Table 2-9b Coefficients for Chandel's Weld Bead Dimension Models
(C-25 Shielding Gas and -ve Electrode Polarity)**

Dimension	K	a	b	c	d	e
A	-1.517	1.377	0.271	-0.905	-0.298	0.1900
BW	-1.500	0.520	0.272	-0.570	0.275	0.0001
BH	-0.460	0.690	-0.460	-0.360	-0.660	0.3370
Pene	-3.250	1.740	-0.093	-0.366	-0.460	-0.0630

**Table 2-9c Coefficients for Chandel's Weld Bead Dimension Models
(M-2 Shielding Gas and +ve Electrode Polarity)**

Dimension	K	a	b	c	d	e
A	-2.290	1.615	0.202	-0.835	-0.680	0.3400
BW	-1.004	0.534	0.660	-0.307	0.146	0.0258
BH	-1.440	1.070	-0.540	-0.450	-1.370	0.4900
Pene	-3.500	0.535	2.610	-0.340	-0.876	-0.6890

**Table 2-9d Coefficients for Chandel's Weld Bead Dimension Models
(M-2 Shielding Gas and -ve Electrode Polarity)**

Dimension	K	a	b	c	d	e
A	-0.544	1.123	-0.0378	-0.815	0.0320	0.166
BW	-0.900	1.030	-0.2300	-0.550	-0.0052	0.128
BH	-0.380	0.235	-0.0850	-0.320	-0.2070	0.120
Pene	14.420	1.246	1.8152	-0.183	-0.2360	-0.567

Table 2-10 Coefficient for Chandel's Wire Melting Rate Equation

Shielding Gas	Electrode Polarity	w	x	y	z
C-25	+ve	0.0230	0.000460	0.00000306	-0.50
C-25	-ve	0.0195	0.000158	0.00000100	0.39
M-2	+ve	0.0200	0.000540	0.00000100	-0.56
M-2	-ve	0.0268	0.000360	0.00000100	0.11

This completes the background necessary to implement a web based system for predicting weld features. The Chandel algorithm for determining size and shape is coded

in terms of the Java applet system which is housed on a server and down loaded by users for remote processing as needed.

2.4 Computational Models for (BPN) Processing

The database available for regression purposes and the number of parameters used in the analysis usually limits the applicability of the analysis. As a result, the final model can be limited if new sensitive parameters are found in later study. Since regression methods are essentially a curve fitting technique, it becomes difficult to modify the final model by adding or reducing parameters or by changing the limits of the data. Usually, modifying a regression expression requires restarting the analysis as a new problem. As a result, creating a model can be time consuming and the effective life cycle can be relatively short. In principle, the back propagation network (BPN) technique, does not suffer the limitations of regression analyses. BPN can identify and map both trends and relationships between input and output data with relative ease even when these relationships are relatively complex (i.e. when there are many factors involved).

This property is useful for modeling the welding process to predict HAZ hardness, or weld size and shape because, among other things, several input parameters (voltage, current, welding speed, plate thickness, and chemical composition, etc.) are necessary to provide an unequivocal characterization of the process. In addition input/output relationships may be non-linear and this too can create uncertainty in either regression or physical modeling. In principle the BPN mapping process can deal with multiple input/output parameters and non-linear relationships.

Figure 2-9 Basic ANN structure.

2.4.1 Backpropagation Network (BPN)

The basic concepts of the BPN method are captured from the mechanism that is thought to control the biological nervous system. In principle it seems to be a relatively simple mechanism that can be simulated by computer to solve complex physical problems. A general artificial neural network (ANN) consists of a series of weighted nodes connected together in a manner that simulates biological neurons. Usually, the nodes are arranged to have a layered structure. There are interlayer nodal connections but no nodal connections within layers. A typical structure consisting of an input layer, a hidden layer, and an output layer is shown in Figure 2-9. The input layer accepts information (e.g. welding parameters) while the output layer yields calculated results

such as HAZ hardness, t_{8-5} cooling time and/or weld features. Hidden nodes and layers constitute the internal representation of the network. Information is manipulated internally to identify and fix the trends and relationships that exist between the input and output data. Thus, the number of hidden layers and the number of nodes in each layer are adjusted to reflect the nature of the problem at hand. Basically the number of nodes and layers depends on the complexity of the problem.

Although a BPN network can achieve complex tasks with a combination of nodes, a single node has two simple functions: summation and transfer as shown in Figure 2.10. With summation all incoming weighted signals, that reflect nodal activity, are combined. Mathematically summation for the hidden nodes is expressed as follows:

Figure 2.10 Single node function.

$$S_i = \sum_{\text{for all } h} H_h \cdot W_{hi}$$

Equation 2-37

where:

S_i = sum at the i th node

H_h = incoming signal from the h^{th} node

w_{hi} = weight between the h^{th} node and i^{th} node

The outgoing signal depends on both the summation result (S) and the transfer function (F) used for this purpose. Any one of several transfer functions could be used -- such as a step function, a ramp function, a sigmoidal function, S-shaped curves, etc. The sigmoidal function was selected for this study because, among other things, both the function and its derivative are continuous, which is similar to the response of biological neurons. It has the form:

$$F(s) = \frac{1}{1 + e^{-s}} \quad \text{Equation 2-38}$$

With summation the weights are adjusted for each link and the input signals are thereby converted into output signals. In theory, there is a set of weights that custom tailors the system so that it will respond correctly in a specific domain for each problem.

The search for the correct set of weights (specific to each problem) is called network training or learning. It is necessary to have a training data set (usually experimental data) from which the network acquires knowledge. It is important to select the training data set so that it covers the entire domain of the problem. For example, maximum and minimum data should be included in the training selection.

In addition to the training data it is important to have a test data set which can be used to verify the integrity of the system. Usually, any experimental data that is not selected as training data set becomes test data. In this thesis, the experimental database consisted of HAZ hardness values or weld size and shape parameters, as the case may be against the corresponding welding parameters – voltage, current, welding speed, etc. In

each case, generally, about 20-30 measured HAZ hardnesses (or weld sizes and shapes) are selected from the database of up to 100 sets to train the system.

The training method used in this thesis is “error backpropagation” [2-18]. The principle is to optimize its weight set so that differences (errors) between the original experimental data set and the corresponding output data set from the BPN are minimized. In detail, the error (E) is found by making use of the least square method:

$$E_j = \frac{1}{2} (O'_j - O^n_j)^2 \quad \text{Equation 2- 39}$$

which basically reflects the difference between the network output signal (O^n) and the corresponding target output signal (O') from the training data set. Once this difference reaches an acceptable tolerance level by changing weights in the network, the learning is said to be complete.

Figure 2.11 A backpropagation network

The error backpropagation learning process can be seen in Figure 2.11. First, weights between the last hidden layer (next to the output layer) and the output layer are adjusted initially based on the error found from Equation 2-39. Then the weights in the next to the last hidden layer are adjusted and so on until the input layer is reached. In other words weld predictions are carried out in a forward direction, while weight adjustments are propagated back through the system (Figure 2.11). Bias nodes (B) [1-18, 19] are extra nodes that have been added to every layer except for the output layer as shown in Figure 2.11. The purpose of this is to stabilize the training process by providing an internal reference for each layer.

The weights connecting the output layer and the last hidden layer are adjusted in the following way:

$$\Delta W_{ij} = \eta I_i \delta_j + \alpha \Delta W_{ij}^{t-1} \quad \text{Equation 2-40}$$

where: η = the learning rate

I_i =hidden layer node

δ_j = delta term (amount to be changed based on the error obtained)

i = hidden layer node index

j = output layer node index

α = momentum coefficient (value between 0 and 1)

ΔW^{t-1} = weight adjustment term from previous path

The learning process is triggered by the delta term, which is based on the error detected according to:

$$\delta_j = F(S_j)(1 - F(S_j))(O' - O^n) \quad \text{Equation 2-41}$$

From Equation 2-40 and 41, those weights are adjusted based on the delta term (δ), the learning rate (η) and the momentum coefficient (α). The learning rate (η) can be viewed as the step size in the search for the optimum weight set, thus learning can be accelerated or decreased by adjusting the learning rate. However, the learning rate must be considered carefully because the desired weight set may be missed if the step size (i.e. leaning rate) is set too large. On the other hand the whole search process becomes slow if the learning rate parameter is set too low. Figure 2-12 shows a simplified weight-error relationship for training. From this figure, the learning rate has significant influence

on the size of the width, which is labeled as "change of weight". The momentum parameter is used so that the search is not trapped by a local minimum as shown in Figure 2-12. Because of the nature of the learning rate and the momentum coefficient, they should have positive values between 0 and 1 [2-18].

Figure 2-12 Simplified network weight - error relationship.

Errors are backpropagated to refine the weights connecting the input and hidden layers (ΔW_{hi}) as follows:

$$\Delta W_{hi} = \eta H_h \delta_i + \alpha \Delta W_{hi}^{t-1} \quad \text{Equation 2-42}$$

where:

$$\delta_i = F(S_i)(1-F(S_i)) \sum_{a=i}^j (\delta_a W_{ia}) \quad \text{Equation 2-43}$$

It should be noted that the delta equation, Equation 2-42, is different from the previous one, Equation 2-40. This is because the weight adjustments for an input-hidden layers involves a previous layer (hidden-out layer, in this case).

After the first pattern (set of data) has been submitted to the network, the weights are adjusted accordingly as documented above. Thereafter the 2nd, 3rd, and all other sets (up to the pth pattern) are submitted to the network and after each submission, the weights are adjusted. A complete set of patterns (data sets) submitted to the network during learning is said to be an "epoch". Usually many epochs are necessary for learning

to satisfy the specified tolerance. The tolerance level is measured by using the root mean square (RMS) method:

$$RMS\ error = \sqrt{\frac{\sum_{a=1}^p \sum_{b=1}^j (O_b^{ta} - O_b^{na})^2}{p \cdot j}} \quad \text{Equation 2-44}$$

where j = number of elements per data

p = total number of data set

O^t = target output from original data set

O^n = generated output by the network

When the RMS error reaches a specified tolerance, the learning is said to have converged, i.e. successful learning. A RMS error between 0.04 and 0.05 is customary in practice [2-19,20]. However, the number of epochs required to complete the convergence is not only dependent on tolerance. It also depends on the initial weights which are usually assigned randomly, the nature of the relationship between the input and output patterns, and the number of patterns.

2.4.1.1 Fahlman's Derivative

When the transfer function, $F(S)$ approaches one or zero in Equations 2-41 and 2-43, the derivative, $F'(S)$, goes to zero. This will be the case when the summation function, S (for both hidden and output nodes), is relatively large (>10) or small (<-10) as the sigmoid $F'(S)$, approaches zero, the weight adjustments diminish and no learning takes place.

Fahlman [2-21] proposed a slight adjustment to the derivative of the sigmoid function, Equation 2-38, by adding 0.1 to the equation:

$$F'(S)=0.1 + [1-F(S)]F(S) \quad \text{Equation 2-45}$$

The modified value, 0.1, is arbitrary selected, but it is important to keep the network learning. In the original code Fahlman's derivative was applied only to the hidden-output layer. However, Chan et al [2-22] suggest that the modified derivative should be applied to all layers.

2.4.1.2 Other Issues with the Backpropagation Network

In addition to the basic mathematics and enhancements of the backpropagation network, there are some other considerations for applying the network to real practical service. All input and output data are normalized between the upper and lower boundaries. The selection of limits is important for the serviceability of a production sized network. Since the transfer function is limited to the range between zero and one, the network output is also limited to this range. Because of this, extrapolation beyond the upper and lower limits is not possible. Therefore, it is necessary to do normalization before training starts. Moreover, if the range of the upper and lower limits is set too narrowly, the applicability of the network will be limited. On the other hand, if the range is set too wide, the network near the limits becomes unreliable. In this application, the output will be one or zero if the summation, S , approaches positive and negative infinity respectively for the sigmoid transfer function. Therefore, the maximum and minimum

data are normalized to 0.05 and 0.95 of the span respectively. Changing the range may also improve the learning time and accuracy of the network prediction.

2.4.2 BPN HAZ Hardness Model

The HAZ hardness BPN model used for the web system in this investigation was first established by Chan [2-22]. The input parameters for this system are the 800°C to 500°C cooling time, $t_{8/5}$, the carbon content (w/o) and the carbon equivalents (Pcm proposed by Ito and Bessyo[2-23], and CE attributed to Yurioka and Suzuki [2-24]):

$$CE(\%) = C + \frac{Mn}{6} + \frac{Cu + Ni}{15} + \frac{Cr + Mo + V}{5} \quad \text{Equation 2-46}$$

$$Pcm(\%) = C + \frac{Si}{30} + \frac{Mn + Cu + Cr}{20} + \frac{Ni}{60} + \frac{Mo}{15} + \frac{V}{10} + 5B \quad \text{Equation 2-47}$$

As discussed in Section 2.2, a carbon equivalent reflects the hardenability of a steel. In principle hardenability could be accounted for by considering each element individually as an input parameter. However, the complexity of the network increases considerably with each parameter added to the input nodes as the relationships in section 2.4.1 would indicate. In fact, with a relatively complete analysis for a typical low alloy steel of some 10-12 elements, the network complexity becomes unreasonable. Therefore some combination of elements is necessary to simplify this problem. Several carbon equivalents have been suggested in the literature but CE and Pcm are those most widely accepted with regard to cold cracking. Since there is a relationship between HAZ hardness and cold cracking, it is not unreasonable to use these same carbon equivalents for the web based hardness system. Indeed this was the philosophy used by Suzuki who proposed two HAZ hardness formulations NSC-S (CE) and NSC-S (Pcm) in an effort to

unify cold cracking and HAZ hardness technology[2-12]. Both carbon equivalents are included because it is said that Pcm is superior to CE when the cooling duration is relatively short, while CE is a better representation where cooling times are relatively long. Moreover, it is well known that Pcm correlates better with the cracking behavior of microalloy steels and low alloy steels with carbon content less than 0.17 w/o while CE correlates better for carbon levels in excess of 0.17 w/o [2-12]. By including both carbon equivalents, the BPN system uses them both during training to correlate input with output as appropriate.

Carbon content is also incorporated separately since it essentially determines the hardness of martensite as discussed in section 2.2, in addition to its hardenability role reflected through the carbon equivalent formulations. The cooling time reflects the welding parameters (i.e., arc current, voltage, travel speed, and plate thickness) and their effect on HAZ hardness. It is worth noting that the cooling time is determined by a separate neural network where the input parameters are the welding conditions.

By combining the two BPN models (one for $t_{8/5}$, and one for HAZ hardness), the HAZ hardness can be predicted in VHN. Chan found that the most successful BPN configuration for the HAZ hardness problem was two hidden layers with 5 and 3 nodes (including bias nodes) and a single hidden layer with 4 hidden nodes (including a bias node) for cooling time respectively. Therefore these same configurations were used for the web based model in this investigation.

2.4.3 BPN Weld Features Model

Chan [2-22] also developed a BPN system for predicting weld features which is incorporated into the web system. The input parameters are welding voltage, current, welding speed, plate thickness, process efficiency and gas cover (M-2 or C-25). The output parameters are bead width, bead height, penetration depth, bead area and plate fusion area, which is similar to the one for the Chandel weld feature model (section 2.3.3.1). In addition a new parameter was introduced, called bay length. The new parameter reflects the unique shape in the plate fusion area (Figure 2.13) for deep penetration welds. The region where the weld narrows is called the bay area. It has been found that, quite by accident, the natural bay angle seems to be about $\pi/8$ (22.5 degrees) and it is therefore only necessary to determine the length by BPN means [2-8].

Figure 2-13 Weld bead model cross section with bay length and angle definition.

A parabolic curve has been used to represent the deposited area from the predicted parameters, bead width (BW) and bead height (BH) :

$$y = -ax^2 + b$$

Equation 2-48

where:

$$a = \frac{4 \cdot BH}{BW^2} \quad \text{Equation 2-49}$$

$$b = BH \quad \text{Equation 2-50}$$

Two intersecting parabolic curves are used to represent the plate fusion shape in terms of the parameters, penetration, bead width and bay length. The bay length is used to fix the intersection of the two curves [2-22]. The top part of the shape is expressed in terms of one parabola as follows:

$$y^2 = c(x+d) \quad \text{Equation 2-51}$$

while the lower part takes the form of the other parabolic expression:

$$y = ex^2 - f \quad \text{Equation 2-52}$$

where:

$$c = \frac{y_1^2}{-x_1 + BW/2} \quad \text{Equation 2-53}$$

$$d = BW/2 \quad \text{Equation 2-54}$$

$$e = \frac{-y_1 + Pene}{x_1^2} \quad \text{Equation 2-55}$$

$$f = Pene \quad \text{Equation 2-56}$$

x_1, y_1 is the point of intersection of the two parabolas which is determined from the following:

$$x_1 = l \sin \theta \quad \text{Equation 2-57}$$

$$y_1 = l \cos \theta \quad \text{Equation 2-58}$$

where l = bay length (mm)

From these equations, a computer generated pictorial shape of a GMAW weld is possible. Chan found that the weld shape subsequently generated by BPN and presented in terms of parabolic curves represents the GMAW welding process quite well. Such a system is undoubtedly useful to welding engineers in practice. The next step in the development of computer tools for welding and manufacturing engineers is to make this software widely available by modifying it for use on the world wide web system as discussed previously.

2.5 A Web Based Internet “Weidsoft” System

As described above, Chan [2-17,22] developed a useful regression software system on the one hand, and a BPN software system on the other, for predicting cooling times $t_{8/5}$, HAZ hardnesses and weld features (size and shape) from the input welding parameters for the GMAW process. The Chan software system is one of the first comprehensive computer tool sets for engineers who must specify welding procedures and conditions in practice. It is easy to demonstrate that this system can save both time and money because, among other things, the weld size and shape parameters are productivity issues and HAZ hardness is a weld quality indicator.

The Chan system is known to be quite useful for those in the research community who read and follow such weld process developments. Moreover, a commercial version of the system is marketed by the American Welding Society, among others. Yet with rapidly increasing use of the Internet, it has been suggested that this would be a way of bringing this software to the attention of a greatly expanded audience of welding and fabrication engineers.

While everyone is aware of the Internet, it is worth a brief description of how it may be used in the context of the web system described above. It is well understood that the Internet may be viewed in its simplest form as a network of computers connected generally by telephone lines or by some other means of electronic communication. If the "weldsoft" system is made available on a "server", then in principle, anyone, anywhere with a computer connected to the Internet can access it. Moreover, since the software is hosted on a server, upgrading would be carried out centrally, and from a user point of view, he/she is always using the most updated version of the software. For example, such a system could be housed on the Cambridge University server available through the courtesy of Professor K. Bhadeshia, Department of Materials Science, for this purpose [2-25]. There are, however, significant computer issues that must be addressed before this can be realized.

The Internet world wide web (WWW) is a standardized method of publishing information on the Internet, using a computer language called the Hyper Text Markup Language (HTML). When the location of the desired information is known the address in the form of a Universal Resource Location (URL), is submitted to a browser (Netscape or Explorer), which in turn reaches out to access the server. Once the connection is established, information is returned in HTML form, and decoded by the browser.

Java is another computer language designed for Internet applications. This language has more functionality than HTML. It is capable of traditional computer processing such as calculations and graphics, while HTML is limited to text

enhancements of one sort or another. Moreover, so-called applets can be created with Java. Essentially the Java operating system is transmitted with the application in applet form to the user's computer. In this way the system is more or less platform independent and an applet can be customized with instructions to provide great flexibility.

In this thesis applets for calculating HAZ hardness and weld features are presented. The first system consists of applets based on the regression relationships detailed above. A second system is based on a BPN system first established by Chan. It consists of applets pre-trained to calculate HAZ hardness and weld features. This might seem like duplication especially since the accuracy and range of applicability of both systems is similar. However, there is considerable uncertainty when doing calculations which are regression or neural network based and the redundancy offered by the two systems is useful for the practitioner. It provides confidence if both systems are in reasonable agreement or a warning if they are not in agreement.

While the Java applet software tools for the welding process represents a considerable step forward, a third untrained BPN system is proposed. Like the previous BPN system it is designed to calculate HAZ hardness and weld features, but unlike the previous system processing is to take place on the server. Essentially it would permit "custom training" by users who would submit training data. As discussed previously welding practice is not entirely universal and there are differences in the industry based on traditions and experiences. Many of these can be captured with custom training and therefore providing an untrained web based system will undoubtedly be useful to the welding community.

But over and above the training issue, a server system would permit capturing user details and their training data. A database of users and training data would serve the welding and engineering communities well. Among other things it could well encourage “electronic” collaborations on a large scale by providing access to a large database of experience and software tools for processing. However, arranging for data capture and processing on a server gives rise to several as yet unanswered research issues. A description of the system and a discussion of the issues is included in the following sections.

Chapter Three

The Web Based Regression System

This section describes the details of three regression based modules for calculating weld cooling time, HAZ hardness and weld features (weld zone size and shape). given the welding parameters : voltage, current, welding speed, workpiece thickness and cover gas type, and the workpiece chemical composition. The mathematical basis for these algorithms is taken directly from the background material detailed in section 2.3. The programming language used to implement the algorithms is Java, used for reasons of Internet multi-platform operating capability as previously discussed.

3.1 The Regression Cooling

Time Module

The cooling time model is based on the relationships originally attributed to Rosenthal and Adams [3-1, 2, 3, 4] which are documented in section 2.3.1. A flow diagram for this module is shown in Figure 3.1.

Figure 3-1 Flow diagram for the regression cooling time module.

The welding parameters (voltage, current, travel speed, process efficiency, ambient temperature and workpiece thickness) are submitted to the cooling time module. The energy input is first calculated according to equation 2-4. The energy input is multiplied by a process efficiency to generate a heat input (J/mm) and this together with workpiece thickness is used to determine the heat flow regime (2D, 2.5D or 3D) according to equation 2-5 as discussed in section 2.3.1. With this decision in hand, the cooling time is then calculated with one of the 2D, 2.5D or 3D relationships (equations 2-1, 2-2 or 2-3), whichever is appropriate.

While the calculation is straightforward in principle, user convenience is an important consideration. In this regard a convenient user interface has also been generated using the Java program language as shown in Figure 3-2. It consists of three separate work areas. The welding parameters

Figure 3-2 User interface for the regression cooling time module

Input Parameters		
Voltage	25	V
Current	300	Amp.
Travel Speed	5	mm/s
Room Temp.	5	C
Thickness	10	mm
Weld Process	SMAW(80%)	
Calculate		
Cooling Time Model :		
2.5D		
18/5 Cooling Time :		
17.69	second(s)	

Figure 3-3 Input area for the regression cooling time.

are input through windows in area one (input area) as shown in Figure 3-3. This area also receives the output. As shown in the Figure, the output consists of the cooling time and the heat flow regime that is appropriate to the situation. This window also contains a “calculate” button to activate the computation.

Input Number	185 Cooling Time	s
Upper Limit: 40 V	48.89	s
Lower Limit: 20 V	11.47	s

Figure 3-4 Parametric study input area for regression cooling time module.

In addition to computing the cooling time for a specific welding situation, the system contains a graphic function to permit parametric study. This is considered to be an important contribution for busy welding engineers who have to specify welding conditions for one or another fabrication situation. The parameter to be studied and the parametric limits are input through work area

Figure 3-5 Parametric output (cooling time against voltage).

two (parametric study input area) as shown in Figure 3-4. A graph of cooling time vs. the parameter specified is displayed in the third work area (plot area) as shown in Figure 3-5.

The resulting graph based on the input parameters displayed is plotted

Figure 3-6 Message window for the regression cooling time module.

A messaging window designed to inform users of inappropriate input quantities or other “errors” with the system is also included in Figure 3-6.

3.1.1 Verification of the Regression Cooling Time Module

To test the validity of this module, calculated data have been compared with experimental data as shown in Figure 3-7. The experimental data used for this purpose were taken from the research of Kohno [3-5] - 25 submerged arc welds, the work of Yurioka [3-6] - 9 shielded metal arc welds, and the research of Signes [3-7] - 56 gas metal arc welds.

It is apparent that the calculated values for cooling time for the range between 0 to 60 seconds are reasonably accurate or at least in reasonable agreement with measured values. However, the calculated values drift considerably high when the measured values exceed this value (60-200 seconds). This is not a serious limitation because situations where the cooling times exceed 60 seconds are large welds where there is little HAZ hardening. Therefore crack formation due to HAZ hardening is not normally a problem in this range. Moreover, large pass welds using a technique like the submerged arc process are much less common than smaller multipass joints using a technique like the gas shielded metal arc process. Nonetheless, the experience of this investigation suggests that the web based cooling time software should be limited to cooling times of 60 seconds or less.

It is interesting to speculate why the calculated cooling times are higher than the measured values for larger welds. In fact Figure 3-7 (A) would suggest that at 200 seconds (measured), the calculated time is nearly three times that at about 600 seconds. The difficulty is almost certainly due to the importance of workpiece radiation and convective losses in the neighborhood of the joint when the heat input is high. The Adams relationships used

in this software assumes conductive heat transfer only, which seems valid for cooling times of 60 seconds or less. However it would seem that a model that includes radiation heat transfer would have to be used for cooling times greater than 60 seconds.

Figure 3-7 (A)

Figure 3-7 (B)

Figure 3-7 Comparison of calculated cooling times (Adams model cooling time estimation) with measured values: (A) 0 – 200 seconds range, (B) 0 – 60 seconds range)

3.2. The Regression HAZ Hardness Module

The HAZ hardness system is based on the five regression models described in section 2.3.2 for this purpose: Yurioka (two models) [3-8,9], Teresaki [3-10, 11] (two models) and Suzuki (one model) [3-12]. As discussed previously, five models are included in the system to provide the user with a calculated database of five values (in most cases). The advantage of this is that the user gets the benefit of the research and experience that is incorporated in all of these models rather than relying on any one exclusively. This is important

since there is considerable

uncertainty with HAZ hardness predictions. At the same time the compositional limits differ from model to model and having five models available extends the range of applicability. This is especially relevant with the Yurioka II model which applies to higher alloy heat treatable machine and tool steels as discussed and documented in section 2.3.2.

A flow diagram of the HAZ hardness calculation system is shown in Figure 3-8.

The input to the system consists of a cooling time, either from measurements if available

Figure 3-8 Flow chart for the regression HAZ hardness module.

or more commonly from the cooling time calculation module described in the last section, and the chemical composition of the workpiece steel. HAZ hardnesses are then generated from the equations documented in section 2.3.2: Suzuki (Equations 2-6 to 2-10); Teresaki I (Equations 2-11 to 2-16); Teresaki II (Equations 2-17 to 2-21); Yurioka I (Equations 2-22 to 2-24) and Yurioka II (Equations 2-25 to 2-32).

A user interface, similar to the one described for the cooling time module, is included in the system as shown in Figures 3-9a and 3-9b. It consists of three work areas: the first consists of windows to input

Figure 3-9a User interface for calculating HAZ hardness given the welding parameters and the chemical composition of the workpiece.

Figure 3-9b User interface for calculating HAZ hardness given a measured cooling time and the chemical composition of the workpiece.

(Figure 3-10a) or the cooling time (Figure 3-10b) and the chemical composition of the workpiece, together with a “calculate” button.

The second area (Figure 3-11a and 11b) receives the output, i.e. the five calculated hardness values are displayed, together with the cooling time and an indication of the heat flow regime (2D, 2.5D or 3D) relevant to the situation at hand. The third area (Figure 3-12) is reserved for parametric study. The axes, i.e., the x and y parameters are selected for study in this area.

When the model that is to be used for the parametric study is specified, it fixes the HAZ hardness relevant to the y axis. A welding parameter (e.g., current) or an alloy level (e.g., carbon content) can be selected for the x axis. Parameter limits for the x axis are then input where indicated. When the graphing button is activated, a parametric display is presented as shown in Figure 3-13. If the cooling time is specified as the x parameter, a log scale is used; otherwise the scales are linear. In fact the cooling time parametric curve is given the name

Weld Parameters

Current: 300 Amps Thickness: 5 mm

Voltage: 25 V Weld Speed: 5 mm/s

Room Temp: 5 °C Eky: SMAW(80%)

Calculate

Chemical Composition (Percent)

Steel: ASTMA299

C: 0.25	Cr: 0.15	Cu: 0.14
Mn: 0.37	Mo: 0.14	Nb: 0.00
Si: 0.27	V: 0.00	N: 0.00
Ni: 0.16	B: 0.00	S: 0.01

Figure 3-10a Input area from 3-9a.

Input Parameters

t8/5 time: 20 s

Steel: ASTMA299

C: 0.25	V: 0.00
Mn: 0.37	B: 0.00
Si: 0.27	Cu: 0.14
Ni: 0.16	Nb: 0.00
Cr: 0.15	N: 0.00
Mo: 0.14	S: 0.01

Calculate

Figure 3-10b Input area from 3-9b.

“Characteristic Hardness Curve” (CHC), a concept that was discussed in the background section 2.3.2.

With this system, welding parameters and workpiece chemical composition can be selected for any given welding situation. Thus, ultimately, it is possible to estimate the optimum combination of workpiece chemical composition and input welding parameters, or at the very least the software provides some reference data for specifying the welding conditions.

Hardness Prediction and Cooling Time			
Yutoka I	196.94 VHN	Terasaki I	231.13 VHN
Yutoka II	185.34 VHN	Terasaki II	211.36 VHN
Suzuki	204.92 VHN		
Cooling Time	76.4 S	Type of Cooling	2D

Figure 3-11a Results area from 3-9a.

Hardness Prediction in VHN		
Yutoka I	Terasaki I	Suzuki
251.91	234.96	245.82
Yutoka II	Terasaki II	
219.43	215.64	

Figure 3-11b Results area from 3-9b.

x,y-axis Definition	
x-axis :	Cooling time (t8/5)
y-axis :	Yutoka I Hardness
Cooling time Range Yutoka I Hardness	
Upper limit :	10 s 320.13 VHN
Lower limit :	0.1 s 528.03 VHN
Graph	

Figure 3-12 Parametric study input area for the regression HAZ hardness modules.

Figure 3-13 Plotting area for the regression HAZ hardness modules (a CHC is shown).

3.2.1 Verification of the Regression HAZ Hardness Module

To test the validity of the HAZ hardness module, calculated data have been compared with experimental data as shown in Figures 3-14. The experimental data used for this purpose were taken from an AMCA research report [3-13]. The chemical

compositions and welding conditions for three different microalloy steels are given in Appendix II. The carbon content of the microalloy steels ranged from 0.05 to 0.12 w/o, and the IIW and Ito's carbon equivalents ranged from 0.405 to 0.448 and 0.200 to 0.247 respectively. The correlation factors, the average value of absolute difference between measured and generated values, and standard deviations of the differences are all contained in Table 3-1. These three factors describe the characteristics of the data distribution. Generally, it is apparent from Figure 3-14 and Table 3-1 that there is reasonably good agreement between the measured and calculated values for all models for these particular steels.

Table 3-1 HAZ Hardness Comparison Result for Regression Models.

Model	Yurioka I	Yurioka II	Terasaki I	Terasaki II	Suzuki
Correlation Factor	0.95	0.97	0.96	0.95	0.96
Absolute Diff. Aveg.(VHN)	0.69	21.7	3.12	7.05	2.19
Standard Deviation	21.10	13.91	22.84	19.97	19.22

Figure 3-14(a)

Figure 3-14 (b)

Figure 3-14 (c)

Figure 3-14(d)

Figure 3-14 (e)

Figure 3-14 Comparison of measured (AMCA investigation) with calculated HAZ hardness : (a) Yurioka I, (b) Yurioka II, (c) Terasaki I (d) Terasaki II, (e) Suzuki.

3.3 The Regression Weld Features Module

In this system, weld features (bead width [BW], bead height [BH], penetration length [Pene], deposit area [A1], fusion area [A2], and total area [A]) are calculated according to the Chandel model described in section 2.3.3. A flow diagram of the calculations is given in Figure 3-15.

As shown in the flow chart, the welding parameters are submitted to the software, including voltage, current, travel speed, electrode diameter, electrode extension, polarity and gas cover. It is apparent that more parameters have to be specified to calculate weld features than to calculate HAZ hardness. In particular the

electrode details can have a considerable effect on the size and shape of the weld zone. On this basis the weld zone parameters cited in the previous paragraph are calculated based on equations 2-33 to 2-36 in section 2.3.3. In this module, a parametric study is not included as shown in the flow chart. The reason is that the module already is a large file and the inclusion of the parametric function would make it even larger. From this author's

Figure 3-15 Flow diagram for the regression weld features module

experience, an applet file of more than 30K bytes is problematic because among other things of the limitation of a 56K modem. Currently its file size reached 31K bytes, thus the parametric function has not been included.

The user interface for this module is shown in Figure 3-16. Similar to the other user interfaces described previously for managing the cooling time and HAZ hardness calculations, there are three work areas. The first consists of windows to input the welding parameters, together with a draw

Figure 3-16 User interface for the regression weld features module.

button (Figure 3-17). The second receives the calculated weld features (Figure 3-18) and the third is reserved for a presentation of the approximate shape of the weld based on the calculated parameters (Figure 3-19). The approximate shape is drawn by judiciously fitting a semi-ellipse for the upper-bead (deposited area) and a cosine curve for the lower-bead (fusion area) [3-15, 16, 17]. The validity of this has been shown in the work presented by Chan [3-14].

Figure 3-17 Input area for the regression weld features module.

Weld features calculations and pictorial presentations are expected to be useful for practicing welding engineers. Among other things, weld area can be a productivity parameter. Welding is usually one of the cost-effective joining methods and

Weld Geometry					
BH	3.79	mm	A1	31.04	mm ²
BW	14.09	mm	A2	20.19	mm ²
Pene	1.56	mm	A	51.24	mm ²

Figure 3-18 Output area for the regression weld features module.

Figure 3-19 Pictorial presentation of the regression weld features module.

the largest weld area possible would seem to be a logical objective. However, there are many considerations that limit this objective. For example the weld must be consistent with the joint size and preparation. In addition weld shape can sometimes give rise to serious stress concentration problems. There are many such considerations for which the weld features module can be helpful.

3.3.1 Verification of the Regression Weld Features Module

To test the validity of the weld features module, data provided from the experimental investigation conducted at Northern College [3-19] for C25 and M2 cover gases were selected. Calculated values are plotted against measured values for each weld feature in Figures 3-20 and 3-21 for C25 and M2 cover gas respectively.

It is apparent that there are significant differences between the calculated and measured values. In general the calculated deposit and fusion areas are considerably larger than the measured values. At the same time calculated bead width and penetration are considerably less than measured. At first glance this may seem surprising, but it is likely explained by the contention that the welding process is very difficult to control precisely enough to generate a universal regression expression for weld features. It is

postulated that differences in welding tradition and skill between the Chandel and the Northern College investigations could account for the differences observed. In this regard, the BPN system described in section 2.4 is likely a better method to use for determining weld features.

3.4 Computer Requirements for the Web Based Regression System

The primary computer consideration when creating a Java based system for the Internet is that users must have considerable workstation computational power. As discussed previously the primary advantage of a Java based system is that it is designed to run with several different operating systems (windows, unix, the apple system, etc.). This is only possible because a Java code interpreter, necessary to decode a program, is located in the user's Java-enabled browser. Because of this extra step, the client's machine must have enough additional computational power to execute the Java program. At this point in time, the minimum requirement for running the Internet software described in this thesis is a Pentium CPU processor with 32Mb RAM.

To run the web based system described in this thesis, the user machine must have a Java interpreter or a Java Virtual Machine (version 1.1.5 compatible), JVM, installed. MS Internet Explorer 4, Netscape 4 or later versions are the most commonly used Java 1.1.5 compatible JVM. Naturally, if the version of the Java program is more recent than the local Java interpreter (i.e. the user's JVM is outdated), it (the interpreter) is not able to convert the Java code for the operating system, which means that the program cannot be executed at the local site. Version compatibility can be easily checked; for example a menu called "Java Console" in Netscape contains the Java version numbers to be checked.

Figure 3-20 (a)

Figure 3-20 (b)

Figure 3-20 (c)

Figure 3-20 (d)

Figure 3-20 (e)

Figure 3-20 Comparison of calculated (Chandel model) with measured weld features (Northern College investigation – C25 gas cover): (a) bead height, (b) bead width, (c) penetration, (d) deposit area, (e) fusion area.

Figure 3-21 (a)

Figure 3-21 (b)

Figure 3-21 (c)

Figure 3-21 (d)

Figure 3-21 (e)

Figure 3-21 Comparison of calculated (Chandel model) with measured weld features (Northern College investigation – M2 gas cover): (a) bead height, (b) bead width, (c) penetration, (d) deposit area, (e) fusion area.

Chapter Four

The Web Based BPN System

In many ways this section parallels section 3. The implementation of web based software modules for computing the weld process modeling parameters - cooling time, HAZ hardness and weld features are described in sections 4.1, 4.2 and 4.3 respectively. However, the software modules developed in section 3 are regression based, whereas these same modules are BPN based in this section. Calculated values are compared with experimental quantities to evaluate the validity of the algorithms. In fact the same experimental data is used in section 4 as was used to evaluate the algorithms in section 3 so that the BPN methodology can be compared directly with regression technology for weld process modeling. Finally software and hardware issues with regard to BPN based applets are discussed briefly in section 4.4.

It should be noted that while a great deal has been said about the flexibility of BPN for custom training to suit the special needs of one or another user, the BPN modules described in this section are presented without a retraining capability. They are intended as “universal” models in the same sense that the “regression” models are intended to be general. In this way they are easy to use and therefore web “friendly”. At the same time they provide additional information for users over and above the regression computations for making process decisions in practice. Inasmuch as weld process computations are tenuous at best, redundant information in this regard is valuable for practitioners.

Web based BPN training is reserved for the investigation described in section 5.

4.1 The BPN Cooling Time Module

Two fully trained BPN cooling time modules were developed by Chan [4-1] for stand alone PC application. In this work these were modified and recoded as Java based applets for use on the web. The BPN methodology used to structure these modules is described fully in section 2-4. The configurations of each of these modules are respectively: 1 layer with 5 hidden nodes; and 2 layers with 5 hidden nodes in the first layer and 3 hidden nodes in the second layer. A bias node is included in each case. For the purposes of this thesis the first model is designated as the 1-5 module while the second model is designated as 2-5/3.

Figure 4-1 Flow diagram for the BPN cooling time module.

Figure 4-2 User interface of the BPN cooling time module.

A flow diagram of the cooling time system is shown in Figure 4-1. The welding parameters: voltage, current, travel speed, ambient temperature, workpiece thickness and

process efficiency are submitted to the software in the usual manner. Additionally, a BPN model described by its structure (1-5 or 2-5/3) is selected for parametric study. All of this information is essentially processed according to the methodology described in chapter 2

A user interface, similar to the one described in

section 3 for cooling time computations, has been generated for this BPN module as shown in Figure 4-2.

It consists of three work areas. The first work area (Figure 4-3) is arranged to accept the welding

parameters. In addition, two outputs for each BPN

model as well as the corresponding heat input based on

the welding parameters are displayed in this area when

the “calculate” button is activated. The second area is

reserved for parametric study (Figure 4-4). A welding

parameter is selected for the x-axis with parameter

limits while a BPN model is selected for the y-axis.

When the “graph “ button is activated, a graphics

display appears as shown in Figure 4-5. As mentioned previously, a parametric study capability is very useful in practice.

Input Parameters		
Current (Amp)	Voltage (V)	Travel Spd (mm/s)
530	36	11.92
Heat Input = 1.44		kJ/mm
Efficiency (%)	Thickness (mm)	Room Temp. (°C)
90	25	20
1 Hidden Layer (S)	2 Hidden Layer (S)	
5.31	5.99	
Calculate		

Figure 4-3 Input area for the BPN cooling time module.

X-axis Definition			
X axis variables	Current (Amp.)		
Model	2 Hidden Layer with 5/3		
Current (Amp)	Cooling time		
Upper Limit: 800	Atto.	8.85	S
Lower Limit: 150	Atto.	3.73	S
Graph			

Figure 4-4 Parametric study input area for the BPN.

Figure 4-5 Plot area for the BPN cooling time module.

4.1.1 Verification of the BPN Cooling Time Module

To test the validity of the system, calculated data have been compared with experimental data as shown in Figure 4-6. In fact the experimental data set selected for comparison is identical to the set selected to evaluate the regression cooling module (Figure 3-7 - section 3.1.1). In this way the BPN methodology can be compared directly with the regression technology for determining weld cooling times.

It should be noted that the Chan system was trained with cooling time data ranging from about 3 to 60 seconds. Therefore it would be expected to predict cooling times reasonably well in this range but would be suspect for cooling times outside this range. Indeed this is the case as shown in Figure 4-6. As suggested previously, noncompliance beyond 60 seconds is likely due to a change in the heat transfer mechanism for higher heat welds. As noted in section 3 it would seem that conduction is the primary mode of heat transfer where cooling times are less than 60 seconds. For cooling times in excess of 60 seconds radiation begins to play a part thereby accelerating the cooling. Beyond that, it would be expected based on conduction only.

Of course a change in mechanism such as this can be managed implicitly by retraining the BPN system with data extending to 200 seconds. However, HAZ hardening or cold cracking problems are rare where cooling times exceed 60 seconds. At the same time training to 200 seconds would have the effect of decreasing the sensitivity of the module in the 0 to 60 seconds range. Inasmuch as this module is to be used without custom training by users, i.e., it is seen to be a “universal” module, the decision

was made to use the Chan system trained only to 60 seconds. Obviously this software must then be limited to cooling times of less than 60 seconds in practice.

It is also apparent from the results (Table 4-1 and Figures 4-6) that the 2-5/3 BPN structure is somewhat more accurate than the 1-5 model. Intuitively a multi-layered structure would seem to be more flexible and therefore adapt better to the complexity of experimental results. However, the added complexity of multi-layered systems can cause computational difficulties and inaccuracies. Certainly, it would seem that the 2-5/3 is close to optimum.

Table 4-1 BPN Cooling Time Verification Result

BPN Structure	1 layer 5 Hidden Node	2 layers 5 and 3 Hidden Nodes
Correlation Factor (0-200)	0.82	0.88
Correlation Factor (0-60)	0.83	0.94

Figure 4-6 (a)

Figure 4-6 (b)

Figure 4-6 (c)

Figure 4-6 (d)

Figure 4-6 Comparison of measured cooling time with calculated values (a) 0 - 200s, 1-5 BPN structure, (b) 0 - 200s, 2-5/3 BPN structure, (c) 0 - 60s, 1-5 BPN structure, (d) 0 - 60s, 2-5/3 BPN structure.

4.2 The BPN HAZ Hardness Module

In addition to the cooling time system, two fully trained BPN models for predicting HAZ hardness were also developed by Chan [4-1]. It is well to be reminded that the Chan work was intended for stand alone PC implementation. In this work, the Chan models were modified and recoded as Java applets for web implementation.

A flow diagram for this module is showing in Figure 4-7.

A cooling time, either measured experimentally or calculated with the cooling time module, and the plate chemical composition are submitted to the software. The chemical composition is processed as a carbon content and two carbon equivalents (CE and/or Pcm). Based on the plate

chemical composition, those two carbon equivalents are obtained from equations 2-47

Figure 4-7 Flow diagram for the BPN HAZ hardness module.

Figure 4-8 User interface for the BPN HAZ hardness module.

and 2-48 respectively, as discussed in the background material for this thesis (section 2.4). It should be noted that both CE and Pcm are used in the BPN method. The intelligence

software decides which carbon equivalent is to be used, in one welding situation or another, as an intuitive decision, based on its training. The BPN algorithm necessary for processing the input information is fully described in section 2-4

The user interface for this module is shown in Figure 4-8. It has three work areas consistent with the structure all of the interfaces in this thesis. The first work area consists of windows for receiving the welding parameters and the two carbon equivalents. The output HAZ hardnesses from the two models (1-4 and 2-5/3) also appear in this area when the calculate button (Figure 4-9) is activated.

Input Parameters			
Carbon (Wt%)	Pcm	CE	2.5(%)
0.25	0.3	0.38	15
L1 Hardness (VHN)	L2 Hardness (VHN)		
281.09	287.55	Calculate	

Figure 4-9 Input area for the BPN HAZ hardness module.

X, Y-axis Definition			
X axis	Mn(wt%)		
Mn(wt%) Range		Hardness	
Upper Limit:	2.126 wt%	493.4	VHN
Lower Limit:	0.804 wt%	339.4	VHN
Y axis	1 hidden layer with 4 nodes		
Graph			

Figure 4-10 Parametric study input area for the BPN HAZ hardness.

Figure 4-11 Plot area for the BPN HAZ hardness module.

The second work area permits parametric study and graphical presentation, similar to the regression HAZ module described in section 3.2. It is shown in Figure 4-10. Windows are provided to input the parameter to be studied (x axis) and for fixing the limits. In addition the BPN model is specified (y axis --1-4 model or the 2-5/3 model, according to its structure). The draw button generates a graphical presentation such as that shown in Figure 4-11.

Chemical Composition			Equivalent
C	0.25	Cr	0.15
Mn	0.37	Mo	0.14
Si	0.27	V	0
		Ni	0.16
		B	0
		Cu	0.14

Figure 4-12 Chemical input area for the BPN HAZ hardness.

The third work area is used to calculate a carbon equivalent (CE and Pcm) values for the welding situation at hand (Figure 4-12). To an experienced welding engineer a carbon equivalent is a useful measure of weldability even in the absence of an other calculations. Therefore these calculations are set forth prominently in the interface.

4.2.1 Verification of the BPN HAZ Hardness Module

The experimental data used to evaluate the BPN HAZ module is taken from the AMCA study [4-2] consistent with the regression module study (section 3.2). In total there were 18 data sets used for the regression module evaluation.

The results of the HAZ BPN evaluation study are contained in Figures 4-13 and in Table 4-2. In general there does not seem to be much to choose between the two models (1-4 or 2-5/3). Both models provide similar accuracy. Similarly, the accuracy of the regression module can be compared with that of the BPN module. In general there seems to be little improvement in the BPN module, (e.g., compare with Table 3-1,

section 3.2 with Table 4-2). In this particular case the BPN computations consistently underestimated the AMCA measured hardnesses although the differences were not great. Since the system was trained with general data from a number of sources, this is not surprising. It may mean, for example, that the AMCA measurements were consistently low, although there could be any number of other reasons. As mentioned before in this thesis, one of the difficulties with BPN is that these kinds of discrepancies are obscured and an explanation in terms of the physical basis for observed differences is generally not possible. In principle, a custom model could be generated by training with AMCA data which would ensure agreement. However, there is not enough data available, and in any event the objective of the experiment, in this particular case, was to suggest a more universal BPN model. As mentioned previously redundant computations are useful in practice and therefore this module is expected to be well received by web users.

Table 4-2 BPN HAZ Hardness Correlation Factor Comparison

Model	1 layer 5 hidden nodes	2 layers 5 and 3 hidden nodes
Correlation Factor	0.973	0.972
Difference Factor	21.83	23.47
Difference Standard Deviation	14.13	15.28

Figure 4-13 (a)

Figure 4-13 (b)

Figure 4-13 Comparison of BPN Calculated HAZ hardness with measured values : (a) 1-4 BPN structure (b) 2-5/3 NPN structure.

4.3 The BPN Weld Features Module

In addition to cooling time and HAZ hardness modules, a BPN system for determining the size and shape of a weld (GMAW process) was originated by Chan, for use with a stand alone PC system. A Java applet version of the Chan system for implementation on the web is described in this section.

Figure 4-14 Flow diagram for the BPN weld features module.

A flow diagram for calculating weld size and shape is shown in Figure 4-14. In actual fact the BPN system for this purpose consists of six trained networks designed to calculate bead width, bead height, penetration depth, bay length, deposit area and fusion weld area. The welding parameters, voltage, current, travel speed, workpiece thickness and gas cover are submitted to the system. From these geometrical parameters a pictorial

of the weld cross section is generated and presented graphically. It should be noted that other variables such as the process efficiency (GMAW- 70%), polarity and electrode extension/diameter are fixed in this BPN module (electrode

polarity – positive; extension – 19 mm; diameter – 0.9 mm) unlike the regression model proposed by Chandel. Obviously then, the BPN module is only applicable where these parameters are consistent with the welding conditions. Similar to the regression weld shape module, this model does not have a parametric study function because of the file size (see section 3.3).

The user interface for this system is similar to the one used for determining weld shape from the regression system described in

section 3.3. An overview of the module is shown in Figure 4-15. Like all of the other user interfaces in this thesis, it consists of three working areas. The first area contains a number of windows to receive the welding parameters as shown in Figure 4-16.

Parameter	Value	Unit	Parameter	Value	Unit
BM	3.077	mm	A1	16.417	mm ²
BN	12.88	mm	A2	9.002	mm ²
Pens.	2.600	mm	A	25.42	mm ²
L-22.5	2.735	mm			

Figure 4-15 User interface for the BPN weld features module.

Figure 4-16 Input area for the BPN weld features module.

Weld Geometry					
BH	3.076	mm	A1	16.417	mm ²
BW	13.889	mm	A2	9.002	mm ²
Pene.	2.6	mm	A	25.419	mm ²
L-22.5	2.735	mm			

Figure 4-17 Result area for the BPN weld features module.

Figure 4-18 Plot area for the BPN weld features module.

The second work area receives the calculated size and shape parameters as shown in Figure 4-17 and the third area is for a graphical display of the approximate size and shape of the weld, based on these parameters (Figure 4-18). The shape is generated according to equations 2-48 to 2-58, following the system originally proposed by Chan [4-1]. In addition to the three work areas, there is a reset button and an error bar for indicating the status of the calculation.

4.3.1 Verification of the BPN Weld Features Module

Like the cooling time and HAZ hardness evaluations, the data set selected for evaluating the web based weld size and shape algorithm is the same as that selected to study the regression counterpart, i.e., the algorithm originally established by Chandel [4-3,4]. The data base consists of weld cross sectional measurements taken from a large number of GMAW bead-on-plate welds conducted a few years ago by Northern College for the Carleton welding process research program [4-5]. The data base consists of some 192 GMAW bead on plate welds ranging from 0.45 kJ/mm to 1.43 kJ/mm with C25 and M2 gas cover. All weld parameters were sectioned for the BPN model training and cross sectional measurements (bead width, bead height, penetration, deposit area and fused

area) were recorded for each weld. Some of these measurements were used by Chan for training while others were used for evaluation.

Calculated values for 36 welds from this database are plotted against measured values in Figure 4-19 and 4-20 for C25 and M2 gas cover respectively. Also Table 4-3 has a list of the correlation factors for each gas cover. The correlation factors for the bay length ($L_{22.5}$) is the most suspect for both gas covers. This might be expected but in addition there was some difficulty with domain. It is difficult to arrange for both the training and test domains to cover the same range when there are several independent parameters.

Despite the rather low correlation factor found for the bay length and to some extent the bead width, the BPN weld features module was considerably better than the regression model.

Table 4-3 Correlation Factor Comparison for the BPN Weld Feature Model

Shielding Gas	BH (mm)	BW (mm)	Pene (mm)	$L_{22.5}$ (mm)	A1 (mm^2)	A2 (mm^2)
C25	0.842	0.693	0.900	0.564	0.858	0.807
M2	0.718	0.671	0.813	0.523	0.698	0.760

Figures 4-19 and 4-20 can be compared with Figures 3-20 and 3-21 in section 3.3 respectively. It is apparent that the data points for the BPN module are more less distributed along a 45 degree line (i.e., reasonable correlation) whereas the regression data points are grouped and shifted far from the line (i.e., low correlation). This confirms the wisdom of using neural network analysis for processes such as welding where measurement and control of relevant parameters are difficult.

Figure 4-19 (a)

Figure 4-19 (b)

Figure 4-19 (c)

Figure 4-19 (d)

Figure 4-19 (e)

Figure 4-19 (f)

Figure 4-19 Comparison of with measured weld features (Northern College investigation – C25 gas cover): (a) bead height, (b) bead width, (c) penetration, (d) penetration, (e) deposit area, (f) fusion area.

Figure 4-20 (a)

Figure 4-20 (b)

Figure 4-20 (c)

Figure 4-20 (d)

Figure 4-20 (e)

Figure 4-20 (f)

Figure 4-20 Comparison of calculated BPN weld features with measured weld features (Northern College investigation – M2 gas cover): (a) bead height, (b) bead width, (c) penetration, (d) penetration, (e) deposit area, (f) fusion area.

4.4 Computer Requirements for the Web Based BPN System

The computer requirements for the BPN modules described in this section are basically the same as those described in the section 3 for the regression modules since both systems have been coded using the Java program language. However, this is only the case because there is no “training” for the BPN modules described in this section. It should be noted that as soon as there is training, the need for cpu resources increases enormously. This is the situation for the web system described in chapter 5 where training is assumed to take place in the web server. This is discussed at length in that section.

Chapter Five

Web BPN Server System for Modeling the Welding Process

This section describes the implementation of the back propagation network (BPN) weld process modeling system designed for the Internet. The objective that is unique to this work is to insist that BPN training take place on the server and thereby capture the identity of the user, his/her raw experimental data and his/her eventual trained network model or models as the case may be. The raw data that is to be captured consists of the welding parameters such as voltage, current, welding speed, preheat temperature, workpiece thickness, etc., and measured output quantities such as weld cooling times, HAZ hardnesses and eventually weld sizes and shapes. The models that are to be captured are trained neural networks that can return output calculated quantities such as cooling times, HAZ hardnesses, weld size and shape, given arbitrary input welding parameters voltage, current, welding speed, workpiece dimensions, etc. By capturing these data centrally, a really large data base can be accumulated from the contributions of many users which can be used for the benefit of the entire welding engineering community.

The methodology used for this section has been taken directly from the background material in section 2.4. The hardware and software used to generate the system is described in section 5.1. The BPN weld process modeling system essentially consists of five software modules implemented on a server which can be activated from a

user workstation. These five modules are designated as follows: a raw data submission module, a training module, a weight data submission module, a module for predicting weld characteristics given the input welding parameters and a data view module. These modules are described in section 5.2. The system was tested to evaluate its reliability by comparing calculated values for $t_{8/5}$ with measured values. The comparison is detailed in section 5.3.

5.1 Hardware and Installed Applications Software

The first issue that had to be dealt with was that of a suitable server. It seems that the computational demands of neural network training would be unreasonable for most servers that are set up for more general Internet traffic. Because of this, server administrators (at Carleton and elsewhere) were reluctant to permit BPN training and would not provide access. In the end it was decided that a server would eventually have to be dedicated to the BPN weld process modeling problem. But before committing to a fully implemented on-line Internet server, local experimentation to generate a workable network and sort out a number of potential problems was considered necessary. Therefore the system described in this chapter consists of two computers – one which functions as a server dedicated to welding process BPN modeling and the other a remote PC workstation which functions as a user machine.

The computer environment for the development of on-line weld process neural network modeling is shown schematically in Figure 5-1. The two computers used in this investigation will be referred to as the host and client machines. They were Pentium PCs, 200 Mhertz machines. Each computer had both a network card and was connected to the other in a network configuration. While this simple network consists of only a host and client for the purposes of development, there would be several client machines in a fully working on-line system in practice.

Communications and database applications software were installed on the host computer for recording information concerning the

Figure 5-1 Host - client computer configuration

users, raw experimental weld process data (welding parameters and measured weld characteristics) and calculated (trained) BPN weights. In addition, computational software for processing these data with BPN training was installed. Once the BPN network is trained for a given set of raw input data, the BPN network weights are recorded for future reference, and it (the network) is ready to accept arbitrary welding parameters and return calculated weld characteristics to the user. With this configuration, the only requirement of the client computer is a web browser to submit and access information from the host computer.

Linux was selected as the host operating system primarily because it is designed as network software, i.e., it is relatively easy to establish the host-client computer relationship with Linux. In view of recent Linux developments in the commercial world, this would seem to have been a good choice. Moreover, Linux is considerably more flexible for an application such as this, than alternatives such as Windows NT.

Following the installation of the operating system, a web server communications software application called “Apache”, was installed. Apache serves the host by receiving information from a network client or from the Internet generally. The database application MySQL was then installed to permit recording the raw welding data, user information and the nodal weights calculated from BPN training. It is convenient to think of the host machine as serving two environments, the web on the one hand and the database on the other. These will be referred to as the web server and the database server in the following discussion even though the hardware server is one single host machine.

Following the installation of the Apache communications software and the MySQL database application software, the development environment was established by installing the computational software PHP – personal home page. In many ways PHP is the server equivalent of the Java development software except that it (PHP) is designed for host processing whereas Java is designed for remote deployment. The primary function of PHP is to carry out the network mathematical calculations necessary for training. However, over and above this, PHP acts to interface the database server and the web server. For example, a database request from an Internet user is facilitated by the PHP software. The third function of the PHP software is to create html pages for the

system. The software is quite flexible in this regard and the content of the html pages, so generated, can be easily adapted to the needs of the user or the requirements of the system. For example, a raw data submission form can be easily changed to accommodate the number of input/output data elements in any given data set and the number of data records needed for training.

5.2 System Implementation

In its simplest form the server system for modeling the welding process consists of the following five steps for which there are corresponding software modules:

- raw data submission to the host computer;
- training data selection from the submitted data or from data otherwise stored in the host machine;
- network training;
- nodal weights stored in the host database;
- trained module ready for use – output weld characteristics computed from arbitrary input welding parameters (within the limits of the training).

All modules are self contained, and the results of each can be stored in the host database if necessary. Even though each module is independent, users must go through all modules if they are to generate a useful working model starting from raw experimental data. In addition to the five modules identified above there is a sixth module incorporated in the system – the “Data View Module”. It is somewhat supplementary to the five operational modules referred to above, but nonetheless very important. The significance of this module is detailed below. The following describes each module in more detail.

In the interests of clarity, the following data terminology (element, record, set) are hereby defined explicitly. An “element” is the term used to refer to one quantity of the data whether input or output, such as a voltage, a current, or a HAZ hardness. A “record” refers to the input welding parameters that fix a welding situation and the corresponding output quantities (cooling time, HAZ hardness, weld size and shape). For the HAZ

hardness problem, a record would consist of the combination of relevant input welding parameters – current, voltage, travel speed, plate thickness, and preheat, and the corresponding output quantity, HAZ hardness. In this case there are six input elements and one output element. A data “set” refers to the entire collection of records used for generating a BPN module. One training data set contains several records and each record contains several elements.

5.2.1 Raw Data Submission Module

The data submit module permits the submission of both general information regarding the data and user, and detailed information, i.e., the raw experimental data needed for training. The information flows from the client machine to the host computer. The process involved for this module is shown generally in the flow diagram, Figure 5-2. The general information includes the user’s identity and email address, a password for accessing the information, type of data (selected from a predefined list), a short description of the data set, the number of input/output elements, the total number of input data records in the set, and submission method. The client interface screen form for the submission of the general information is shown in the Figure 5-3. When all of the general information has been detailed on

Figure 5-2 Flow diagram for the raw data submission module.

screen, a confirmation screen is returned (Figure 5-4). Following confirmation, the next screen prompts for detailed welding parameter (voltage, current, etc.) input and corresponding output (cooling time, HAZ hardness, etc.) information (Figure 5-5).

BPN Training Data Set Input Form

For Weld Application

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[Information](#)

Your email address:

Type of Training Data:

Training data description:

Password: You may enter any password here. This password allows you to come back and modify your submitted training report at a later date.

Number of input elements:

Number of Output elements:

Methods of upload

Number of Training data sets:

Figure 5-3 General data submission form for the raw data submission module.

The detailed information includes input/output name, and the numerical value of each element. For example, in the case of the cooling time problem, plate thickness, heat input and preheat temperature are submitted as input elements while $t_{8/5}$ is the output element. Several cooling time records (input/output) are detailed on the screen which forms the raw data set. When all of the records in the data base have been detailed on screen and

submitted, a confirmation page appears (Figure 5-6) which permits the user the opportunity of checking before registering the contents in the host database. When the user confirms these data, all user information data and weld process records are stored in the host computer (Figure 5-7).

Back to
Home

BPN data Input Page - Data Comfirm

For Weld Application

You submitted the data set at 1999-11-24 10:07:19.

Please make sure the following is the information you put in.

Your email address	smorris@chat.carleton.ca
Type of training data	Cooling time (t85) problem
Training data description	Demonstration
Password :	1234AB
Number of input element	3
Number of output element	1
Number of training data set	20
Method used to transfer	Manual

Confirm

Information

Figure 5-4 General data confirmation screen for the raw data submission module.

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BPN data Input Manually

[Information](#)

For Weld Application

This is the 3rd page of the BPN data input

You submit the data set at 1999-11-24 10:07:45.

Name of Input / Output Elements

Input Name 1	Input Name 2	Input Name 3
Thickness	Heat In	Preheat
Output Name 1		
t8/5		

Data Set Manual Input

Data No.	Input 1	Input 2	Input 3	Output 1
1	40	3.71	100	39.5
2	31.8	1.06	20	3.6
3	25.4	2.13	20	9.3
4	31.8	2.13	155	23.2

Data No.	Input 1	Input 2	Input 3	Output 1
20	28.7	4.13	220	26.3

[Continue](#)

[Reset](#)

Figure 5-5 Detailed data submission form for the raw data submission module.

Back to Home **BPN data Input Page 4 (5 pages)** Information

For Weld Application

If there need to have a modification, please push *Back*.

Name of Input / Output Elements

Input Name 1 Input Name 2 Input Name 3
 Thickness Heat In Preheat
 Output Name 1
 t8/5

Data Set Manual Input

Data No.	Input 1	Input 2	Input 3	Output 1
1	40	3.71	100	39.5
2	31.8	1.06	20	3.6
3	25.4	2.13	20	9.3
4	31.8	2.13	155	23.2
...				
20	12.7	4.13	20	96.8

Figure 5-6 Detailed data submission screen for the raw data submission module.

Figure 5-7 Raw data submission completion screen.

5.2.2 Selecting Training Data

The training data select module allows users to select training data from all of the raw data that resides in the host computer. A flow diagram for this module is shown in Figure 5-8. For one reason or another a user may not have any raw experimental data to work with or may not choose to draw training data from that submitted to the host. In this case, the user can initiate a search of the host computer for data that is appropriate to his/her situation by using keywords in the data description or an email address that is associated with a given set of data, or by simply listing all available raw data sets (Figure 5-9). In this Figure, the keyword used for this presentation was “demo”.

Figure 5-8 Flow diagram for the selecting training data module.

When the search is complete, the list of the raw data sets will be displayed with submission date, email addresses of those who submitted data, type of data, description of the data and the raw data ID index number (Figure 5-10). The data ID is an index number for the data set, and clicking the link under the data ID number brings forward more information regarding the data set selection as shown in Figure 5-11. The input/output elements are identified, and the set records are listed together with check boxes. Those records that are needed for training are checked and are then registered in the database as training data (Figure 5-12).

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BPN Training Data Selection

Information

For Weld Application

Kind of data in:

Search in:

Show the list

☒ Raw data Training type: Any

☐ Email address Key word of: demo

☐ Description

Feature/Change requests must be explicitly selected to be shown

Figure 5-9 Desired data condition input screen for the selecting training data module.

Back to Home

Dataset Selection For Training

Information

For Weld Application

2 entries

Submission Date	Email Address	Type of Raw Data	Description	Data ID
1999-11-24 09:50:35	smorinis@chat.carleton.ca ...	Other	Demonstration ...	Data Set 7
1999-11-24 10:07:45	smorinis@chat.carleton.ca ...	Cooling time (t85) problem	Demonstration ...	Data Set 8

Figure 5-10 List of raw data set for the selecting training data module.

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Detail Raw Data Set

For Weld Application

Information

Detail of data ID of 8

Name of Input / Output Elements

Input Name 1: Input Name 2: Input Name 3:

Thickness Heat In Preheat

Output Name 1:

t8/5

Data Set Input Submitted by Manual

Data No.	Thickness	Heat In	Preheat	t8/5	Check for train data selection
1	40.0000	3.7100	100.0000	39.5000	☒
2	31.8000	1.0600	20.0000	3.6000	☒
3	25.4000	2.1300	20.0000	9.3000	☒
4	31.8000	2.1300	155.0000	23.2000	☒
●					
●					
●					
Data No.	Thickness	Heat In	Preheat	t8/5	Check for train data selection
20	12.7000	4.1300	20.0000	96.8000	☒

Submit Training Data

Please push *Back* to go back to raw data list page.

Figure 5-11 Detailed selectable raw data set screen for the selecting training module.

Back to Home

Training Data Selection

For Weld Application

Information

Thank you for selecting . . data for training and training number is 21
Please use this number for the further use in training.

Figure 5-12 Data selection completion screen for the selecting training data module.

5.2.3 Training Module

A BPN model is then generated by submitting the training data to the training module. The flow diagram for this module is shown in Figure (5-13). The first step in this process requires the user to specify the general training conditions (Figure 5-14). The general training information includes the user's email address, the basic BPN structure that is to be used, the model accuracy required, a training limit, and the training enhancements that have been suggested by various researchers to help the process converge.

The basic BPN structure includes specifying the number of nodes, excluding a bias node which is always included in the configuration, and the number of nodal layers. The model accuracy is determined by comparing calculated model output with the

training data input. The comparison takes the

form of a RMS – root mean square comparison (see equation 2-44, chapter 2). The

process is limited by setting a maximum number of training cycles per session. A total

training limit is imposed on the process because there is not always convergence and this

could lead to endless training. If the training time reaches the limit, the user has the option

Figure 5-13 Flow diagram for the training module.

of restarting or aborting the run. The available training enhancements are controlled by the momentum and through the use of Fahlman's derivative formulation. These are detailed in chapter 2, specifically equations 2-42 and 2-45 respectively.

When all of the information has been provided to the module and the system is prompted to move forward, a list of the training data is returned to the client computer (Figure 5-15). The list contains information about each data set, such as the submission date, type of data, number of input/output elements, and number of records in the data set. A training data set is selected from among those available and a confirmation of submission appears as shown in Figure 5-16. The screen also contains a summary of the training session parameters -- information regarding the BPN structure, detailed information about the training data set and the initial weights for training, which are assigned randomly between 0.5 and -0.5. When all of this information is confirmed it is submitted to the training module and training begins.

The training may be terminated in one of two ways. If the RMS value specified in the conditions for training is reached the training stops and a screen like that shown in Figure 5-17 appears. Basically, the screen contains the nodal weights determined from the training. On the other hand, if the training does not reach RMS value within the specified training period, the user is given the option of terminating or restarting the training (Figure 5-18). If the user elects to continue, the training resumes where it left off; otherwise, the incomplete weight set is stored to the host computer if the user so decides (Figure 5-19).

Back to Home	<h1>BPN Calc. Training Function</h1>	Information
For Weld Application		
<u>User Information</u>		
Your email address: <input type="text" value="smorinis@chat.carleton.ca"/>		
<u>BPN Structure Information</u>		
Number of hidden layer: <input type="text" value="1"/>		
Number of nodes in the first hidden layer: <input type="text" value="5"/>		
Number of nodes in the second hidden layer: <input type="text" value="0"/>		
<u>BPN Calculation Option</u>		
Target RMS value for training: <input type="text" value="0.1"/>		
Learning rate : <input type="text" value="0.7"/>		
Moment value: <input type="text" value="0.2"/>		
Maximum epoch to be executed per one training: <input type="text" value="100000"/>		
Frequency to be shown: <input type="text" value="2000"/>		
Calculating method enhancement: ☐ no enhancement(but bias) ☐ Momentum ☒ Fahlman's derivative (with bias and momentum)		
<input type="button" value="Go next"/>		
<input type="button" value="Reset train information"/>		

Figure 5-14 General training condition submission form for the training module.

Back to Home

Available Training Data List

Information

For Weld Application

10 entries (out of 22 total)

Submission Time	Type of Data	Number of Input	Number of Output	Number of Data Set	Data ID
1999-11-25 10:07:28	Cooling time (t85) ...	3	1	20	Data Set 22
1999-11-25 00:24:56	Cooling time (t85) ...	3	1	14	Data Set 21
1999-11-24 21:48:38	Cooling time (t85) ...	3	1	15	Data Set 20
		•			
		•			
		•			
		•			
1999-11-21 08:24:23	Cooling time (t85) ...	2	1	6	Data Set 13

All Records

Next 10 records

Go next step

Figure 5-15 List of train data set for the training module.

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BPN Train Condition Confirmation

Information

For Weld Application

You submitted the data set at 1999-11-25 10:09:17.

Number of hidden layer	1
Number of nodes in hidden layer	5
Number of input element	3
Number of output element	1
Number of training data set	20

Input and Output Values				
	Thickness	Heat_In	Preheat	t8/5
Set 1	40.000	3.710	100.000	39.500
Set 2	31.800	1.060	20.000	3.600
Set 3	25.400	2.130	20.000	9.300
Set 4	31.800	2.130	155.000	23.200
● ● ●				
Set 19	12.700	2.130	20.000	24.400
Set 20	12.700	4.130	20.000	96.800

Weights From Input to Hidden Layer					
	Hidden Node 1	Hidden Node 2	Hidden Node 3	Hidden Node 4	Hidden Node 5
Bias	0.320	0.500	0.010	-0.370	-0.470
Input node 1	0.500	0.130	-0.440	-0.090	-0.370
Input node 2	0.490	0.340	0.470	-0.280	-0.060
Input node 3	-0.160	0.210	-0.470	-0.130	-0.080

Weights From Hidden to Output layer	
	Output Node 1
Bias	0.090
Hidden node 1	-0.190
Hidden node 2	0.410
Hidden node 3	0.210
Hidden node 4	-0.040
Hidden node 5	0.040

Please "Submit" button to proceed

Figure 5-16 Training condition summary screen for the training module.

Back to Home	<h2 style="text-align: center;">BPN Training data Page</h2>	Information
For Weld Application		
RMS error is 0.30022 at the counter of 0		
Training is done and the rms value is 0.09996 and the target RMS value is 0.1 with counter of 176		
Please press "Continue" button to proceed		
<input type="button" value="Continue"/>		

Figure S-17 Training completion screen for the training module.

Back to Home	<h2 style="text-align: center;">BPN Training data Page</h2>	Information
For Weld Application		
RMS error is 0.29679 at the counter of 0		
RMS error is 0.29322 at the counter of 2		
RMS error is 0.29179 at the counter of 4		
Training maynot done due to counter		
and the rms value is 0.29108 and the target RMS value is 0.04 with counter of 6		
The calculation has not been reached the specified RMS value.		
DO you want to continue training ?		
<input type="button" value="YES"/>		
<input type="button" value="NO"/>		

Figure S-18 Training incomplete screen for the training module.

Back to Home

BPN Training Result

Information

For Weld Application

Thanks for training the data set.

The weight set will be maintained in the weight data base

You submitted the data set at 1999-11-25 10:18:50.

Number of hidden layer	1
Number of nodes in hidden layer	5
Number of input element	3
Number of output element	1
Number of training data set	20

Weights From Input to Hidden layer					
	Hidden Node 1	Hidden Node 2	Hidden Node 3	Hidden Node 4	Hidden Node 5
Bias	0.990	-0.359	-0.549	0.847	-0.724
Input node 1	2.935	-1.318	-1.969	2.039	-0.090
Input node 2	-3.409	2.778	2.334	-4.134	-1.337
Input node 3	-0.792	0.472	-0.206	-0.584	-0.321

Weights From Hidden to Output layer	
	Output Node 1
Bias	0.367
Hidden node 1	-2.856
Hidden node 2	2.533
Hidden node 3	2.337
Hidden node 4	-2.948
Hidden node 5	-0.677

Please "Submit" button to proceed

Figure 5-19 Weight set summary screen for the training module.

Figure 5-20 Weight set submission complete screen for the training module.

5.2.4 Weight Data Submission Module

This is the module designed for submitting the weight data set submission to database in the host computer. The process involved for this module is shown in a flow diagram (Figure 5-21). The process here is similar to that used to submit raw data to the database. The information is of two types, general information and detailed weight data. The first interface requires the input of the general information (Figure 5-22). The general information includes the user's identity and email address, a short description of the data set, the number of input/output nodes (elements) and the submission method. When the general information is sent to the database a screen

Figure 5-21 Flow diagram for the weight submission module.

arises calling for the detailed information (Figure 5-24) after the general information is confirmed (Figure 5-23). The detailed information includes input/output name, each input/output range and the numerical weight data. For example, in the case of the cooling

time problem, plate thickness, heat input to the process, and preheat temperature are submitted as input names, while $t_{8/5}$ is used for the output name together with the corresponding training ranges. The user then submits weight numbers from the training (previous module) as shown in the Figure. When these data are documented on the screen, a confirmation page is displayed (Figure 5-25) for checking purposes before registering the contents to the database. If the user confirms the content all the records are stored in the host computer data base (Figure 5-26).

BPN Trained Weight Data Set Input Form

For Weld Application

[Back to Home](#)
[Information](#)

Your email address:

Type of Training Data:

Training data description:

Password:
You may enter any password here. This password allows you to come back and modify your submitted training report at a later date.

RMS Error:

Number of hidden layer:

Number of nodes in the first hidden layer:

Number of nodes in the second hidden layer:

Number of input elements:

Number of Output elements:

Methods of upload

Number of Training data sets:

Figure 5-22 General information submission form for the weight data submission module.

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BPN Weight data Input

Page - Data Comfirm

For Weld Application

You submitted the data set at 1999-12-01 01:21:28.

Please make sure the following is the information you put in.

Your email address	smorris@chat.carleton.ca
Type of training data	Cooling time (t85) problem
Training data description	Billy's Data
Password :	1234Abcd
RMS error :	0.04
Number of hidden layer	1
Number of nodes in hidden layer	4
Number of input element	3
Number of output element	1
Number of training data set	20
Method used to transfer	Manual

Figure 5-23 General information confirmation screen for the weight data set submission module.

Back to Home

BPN Weight Data Input

Information

For Weld Application

You submit the data set at 1999-12-01 01:21:58.

Name of Input / Output Elements

Input Name 1: Input Name 2: Input Name 3:

Thk (mm) Q (kJ/mm) PT (C)

Output Name 1:

$t_{8/5}$ (s)

Input Max - Min Range

	Maximum Value	Minimum Value
Input1	<input type="text"/> 69.287	<input type="text"/> 6.412
Input2	<input type="text"/> 10.840	<input type="text"/> -0.663
Input3	<input type="text"/> 172.5	<input type="text"/> -2.500

Output Max - Min Range

	Maximum Value	Minimum Value
Output1	<input type="text"/> 108.513	<input type="text"/> -8.613

Weight Set Input From Input to Hidden Layer

	H-1	H-2	H-3	H-4
Bias	<input type="text"/> 2.0179	<input type="text"/> -0.8899	<input type="text"/> -2.9159	<input type="text"/> -0.2342
1	<input type="text"/> 0.0343	<input type="text"/> -0.6645	<input type="text"/> -7.3858	<input type="text"/> -1.9222
2	<input type="text"/> -2.7766	<input type="text"/> -0.8637	<input type="text"/> 7.5618	<input type="text"/> -4.7141
3	<input type="text"/> -2.8057	<input type="text"/> -0.1840	<input type="text"/> 0.908	<input type="text"/> 1.9218

Weight Set Input From Hidden Layer To Output Layer

Out-1

Bias	<input type="text"/> 0.7092
H-1	<input type="text"/> -2.8975
H-2	<input type="text"/> -0.2957
H-3	<input type="text"/> 7.6563
H-4	<input type="text"/> -3.3045

Continue Reset

Figure S-24 Detailed information submission form for the weight submission module.

Back to
Home

BPN Weight Data Input (Confirmation)

For Weld Application

If there need to have a modification, please push *Back*.

Information

Names of Input / Output Elements

Input Name 1	Input Name 2	Input Name 3
Thk(mm)	Q(kJ/mm)	PT(C)
Output Name 1		
t8/5(s)		

Weight Data Set Input Max/Min Number

Max/Min	Maximum Number	Minimum Number
Input 1	69.287	6.412
Input 2	10.840	-0.663
Input 3	172.5	2.500
Output 1	108.513	-8.613

Weight from Input to Hidden Layer

In -> Hid	H-1	H-2	H-3
Bios	2.0179	-0.8899	2.9159
1	0.8243	-0.6645	-7.3858
2	-2.7066	-0.8637	7.5618
3	-2.8057	-0.1840	0.908

Weight from Hidden to Output Layer

Hid -> Out	Out-1
Bios	0.7092
1	-2.8975
2	-0.2957
3	7.6563
4	-3.3045

Continue submission

Figure 5-25 Detail information confirmation screen for the weight submission module.

Back to Home	<h2 style="text-align: center;">Last step for BPN weight data submission</h2> <p style="text-align: center;">For Weld Application</p> <p style="text-align: center;">Thank you for the <u>weight data</u> submission.</p> <p style="text-align: center;">Please click <u>here</u> to go back to the main menu.</p>	Information
-----------------	--	-------------

Figure 5-26 Weight data submission complete screen for the weight data set submission module.

5.2.5 BPN Calculation Module

When the training is complete the nodal weights can be used to generate a weld process model, custom generated to match the choice of the training data. As mentioned several times in this thesis, custom training is important because it implicitly takes into account variables that arise from operator skill and elsewhere that cannot otherwise be quantified. If the model is generated with training data from the user's job shop or manufacturing operation, then the model implicitly incorporates operator tradition and other effects unique to that operation. This is not possible when universal models (regression, physical modeling) that have been generated elsewhere are used.

Figure 5-27 Flow diagram for the BPN calculation module.

The BPN calculation module is essentially the weld process model arising from the training. Users can submit arbitrary welding parameters (within the limits of the training) and calculated output quantities are returned. The flow diagram for this module is shown in Figure 5-27. The first step in this process is selecting a set of weights. A list of available BPN models (i.e. list of weight sets) in the host computer is displayed on the screen as shown in Figure 5-28. Listed in the display are training submission date, email address of the trainer, the type of training data, data description, and training ID (an index number for each set of weights). From this information users can decide which set of weights are consistent with their needs. In many cases the user will also have been the “trainer” in which case he/she will use the set of weights that was determined during the training session. However in other cases, potential users may not have training data and in that case they can still select from among those models (training weights) that are contained in the data base.

A weight set is selected by clicking the training ID index number on the screen, which among other things, brings forward a screen that lists the limits of each of the input data elements (Figure 5-29). For example, if the training covers the welding current range 150-300 amps, then calculations are only valid within this current range. When the welding parameters have been submitted, the calculate button is activated and output quantities (cooling time, HAZ hardness, etc.) are displayed on the screen (Figure 5-30).

[Back to Home](#)

Weight Database Inside List For Calculation

[Information](#)

For Weld Application

10 entries (out of 322 total)

<u>Submission Time</u>	<u>Eamil Address</u>	<u>Type of Training Data</u>	<u>Description</u>	<u>Train ID</u>
1999-11-25 00:14:15		Cooling	Trained_on_line.	Weight Set 322
1999-11-20 16:20:25	shun@	Other	Trained_on_line.	Weight Set 321
1999-11-20 04:44:13	shun@	Other	Trained_on_line.	Weight Set 320
1999-11-20 04:34:44	shun@	Other	test on Nov20	Weight Set 319
1999-11-19 16:00:28	HAZ@NOV18	Hardness	Trained_on_line.	Weight Set 318

Figure 5-28 List of weight data set for the BPN calculation module.

Back to Home		Detail Weight Data Set					Information
For Weld Application							
Input				Output			
Name of Input	Input Max	Input Min	Input Value	Name of Output	Output Max	Output Min	Output Value
Thickness	63.000	12.700	<input type="text" value="20"/>	t8/5	96.800	3.600	<input type="text"/>
Heat_In	9.690	0.820	<input type="text" value="5"/>				
Preheat	155.000	15.000	<input type="text" value="100"/>				
<input type="button" value="Calculate"/>	<input type="button" value="Reset"/>						
Please push <i>Back</i> to go back to raw data list page.							

Figure 5-29 Input data submission form for the BPN calculation module.

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Detail Weight Data Set

Information

For Weld Application

The result has been shown in the output window.
To proceed, please change input content and push calculate button again.

Input				Output			
Name of Input	Input Max	Input Min	Input Value	Name of Output	Output Max	Output Min	Output Value
Thickness	63.000	12.700	20	t8/5	96.800	3.600	44.498
Heat_In	9.690	0.820	5				
Preheat	155.000	15.000	100				

Please push *Back* to go back to raw data list page.

Figure 5-30 Calculation result for the BPN calculation module.

5.2.6 Data View Module

The data view module allows users to see both raw experimental data and the weight data sets in the host computer. It is necessary to view the data in this way when trying to decide the applicability of one or another model in practice. Therefore, this is a very useful module in the system. The flow diagram for this module is shown in Figure 5-31. A search facility is available in the module that will list the data sets requested as shown in Figure 5-32. The search returns a list containing the data submission date, the email address of the trainer, the type of data, a description of the data and a data ID index number. With that information a user can display the raw input experimental data or weight data set by activating the data ID index number as shown in Figure 5-33.

These data can also be displayed in "text format", as shown in Figure 5-34. By saving the information to a client local hard drive, the file can be used with the NNWorks software.

It may be recalled that the NNWorks software is the PC stand alone version of the BPN contained in this thesis. It was authored by Dr. B. Chan (5-1). The downloaded raw data can be used to train NNWorks for one application or another while the weight data can be used to generate a fully working NNWorks model directly. This is a very important contribution it essentially is

another way of using the Internet to assist the welding community in exchanging useful research data and weld process modeling information. It has been found that training on an Internet server is limited. The difficulty is that the PHP generated software for BPN training consumes considerable computing resources and may occupy a server for long periods of time which is not very good in a practical sense. By downloading the raw data and using NNworks the training is carried out locally with efficient software and then there is little problem with computing resources; yet useful data has been exchanged and the user enjoys virtually all the benefits of the server training system. Moreover, if the server is occupied with training, it is not accessible to other users and this will lead to frustration and problems in practice. This or

Figure 5-31 Flow diagram of the data view module

some variation of the downloading philosophy is likely an attractive alternative in the end. It should be more fully investigated in future research.

Back to Home
Information

BPN Data Set View Form

For Weld Application

Kind of data in: ☒ Raw data ☐ Weight data set

Search in: ☐ Email address ☒ Description

Display

Training type:

Key word of:

Feature/Change requests must be explicitly selected to be shown

Figure 5-32 Desired data conditions for the data view module.

Back to Home
Information

Dataset Database Inside List Sorted by Description

For Weld Application

2 entries

<u>Submission Date</u>	<u>Email Address</u>	<u>Type of Raw Data</u>	<u>Description</u>	<u>Data ID</u>
1999-11-24 09:50:35	smorinis@chat.carleton.ca ...	Other	Demonstration ...	Data Set 7
1999-11-24 10:07:45	smorinis@chat.carleton.ca ...	Cooling time (t85) problem	Demonstration ...	Data Set 8

Figure 5-33 List of data for the data view module.

Back to Home

Detail Raw Data Set

Information

For Weld Application

Detail of data ID of **8**

Name of Input / Output Elements

Input Name 1: Input Name 2: Input Name 3:

Thickness Heat_In Preheat

Output Name 1:

t8/5

Data Set Input Submitted by Manual

Data No.	Thickness	Heat_In	Preheat	t8/5
1	40.0000	3.7100	100.0000	39.5000
2	31.8000	1.0600	20.0000	3.6000
3	25.4000	2.1300	20.0000	9.3000
4	31.8000	2.1300	155.0000	23.2000
...				
20	12.7000	4.1300	20.0000	96.8000

[Display Text Format](#)

Please push *Back* to go back to raw data list page.

Figure 5-34 Detailed data (Html format) for the data view module.

```

NN RAW DATA FILE 20 Thickness*Heat_In*Preheat*t8/5* 40.0000 3.7100
100.0000 39.5000 31.8000 1.0600 20.0000 3.6000 25.4000 2.1300 20.0000 9.3000
31.8000 2.1300 155.0000 23.2000 19.0000 1.0600 20.0000 3.5000 37.5000 3.1000
20.0000 12.9000 50.8000 1.0600 20.0000 4.0000 38.1000 0.8200 20.0000 5.1000
63.0000 0.4900 22.0000 3.1000 63.0000 2.2100 22.0000 13.8000 63.0000 9.6900
22.0000 62.0000 40.0000 5.5700 100.0000 66.0000 15.9000 1.0600 20.0000
3.9000 31.8000 4.1300 20.0000 20.9000 22.2000 2.1300 15.0000 24.0000 19.0000
2.1300 140.0000 30.6000 15.9000 4.1300 20.0000 71.9000 12.7000 2.1300
150.0000 59.2000 12.7000 2.1300 20.0000 24.4000 12.7000 4.1300 20.0000
96.8000

```

Figure 5-35 Detailed data (text format) for the data view module.

5.3 BPN Training Module Verification

Verification of the Internet weld process modeling system included both testing the performance of the BPN training module and measuring the accuracy of the output quantities calculated with a trained model. Performance was tested because there were difficulties with the training process. It seems that server training is time consuming, much more so than stand alone PC training. There may be many reasons for this, the efficiency of the PHP application software compared with C++, the complexity of the server system, etc. The exclusive-or (XOR) problem is one that is widely used to test neural network systems and therefore it was incorporated in this study to examine performance. Since the cooling time and the HAZ hardness problems were used by Chan to test his system when he generated NNWorks, the stand alone version of the server system described in this thesis, they also formed part of the test study. The complexity of the test networks ranged from simple (an exclusive-or, XOR, problem), to medium (the cooling time problem) to complex (the HAZ hardness problem).

For all performance tests, the network initial weights were set randomly between +0.5 and -0.5 [5-2], and all input and output parameters were normalized between 0.95 and 0.05 (see chapter 2-4-1-1). The learning process was not limited in this case but continued until the RMS limit was reached. When the training was completed, the number of learning cycles otherwise called epochs was recorded. Four separate learning trials were carried out for each problem, except for the HAZ hardness problem where the training time became unreasonably long. In that case the term “unreasonably long time” became the result of the test.

5.3.1 The XOR Problem

The XOR problem is a linearly non-separable problem. Graphically it is shown in Figure 5-36, and it is noteworthy that white spots in this diagram cannot be separated by a straight line graphically, i.e., it is a non-linear problem. Because it is one of the simplest non-linear problems possible, it is frequently used as a BPN bench-mark test problem. The XOR

Figure 5-36 Graphical representation of XOR problem.

problem has two input values (zero and one) and one output value (either zero or one). The XOR truth table is shown in Table 5-I. The BPN structure that was tested in this case consisted with one hidden layer which contained two hidden nodes with a bias node, i.e., a 1-3 configuration; the input layer has two input nodes, while the output layer consisted of simply one output node. Four training patterns were used, which are listed in the truth table. The initial learning rate was set at 0.70 and the momentum coefficient set at 0.20 when it was used in the study. A relatively tight RMS error tolerance level of 0.04 was selected. Since performance was the object of this study, the basic BPN structure was tested and compared with the structure including the enhancements, momentum and Fahlman's derivative (see section 4-1-1). The results of these tests are shown in Table 5-2.

Table 5-1 XOR Truth Table

Input 1	Input 2	Output
0	0	0
1	0	1
0	1	1
1	1	0

Table 5-2 Performance of Different Learning Enhancement Algorithm for the XOR Problem

	Basic (No enhancement) (epoch) (min)	Momentum ($\alpha=0.20$) (epoch) (min)	Momentum with Fahlman's derivative (epoch) (min)
Trial 1	1633 (4)	2097 (5)	1266 (3)
Trial 2	2306 (6)	1471 (3)	1325 (3)
Trial 3	2431 (6)	1934 (4)	1361 (3)
Trail 4	2173 (5)	1894 (4)	1705 (4)
Average	2136 (5)	1849 (4)	1414 (3)

As the table shows both enhancements improve the performance of the learning process, especially the combination of the Fahlman's derivative and momentum. In this case the average learning time was decreased some 30%. This is strong evidence that the extra complexity of including both momentum and Fahlman's derivative is certainly worth while.

5.3.2 The Cooling Time Problem

The cooling time problem is considered to be more complex than the XOR problem because it includes some noisy data (scatter in the results) and there are more data records per set available for training. The experiment reported in this work paralleled the work of Chan's [5-1] who used three input elements (heat input, plate thickness, and ambient temperature) and one output element ($t_{8/5}$ cooling time) with one hidden layer which had 5 nodes including a bias node. Chan used this arrangement to

test the performance of the stand alone PC BPN system incorporated in NNWorks and it seemed like a good idea to use the same configuration for comparison purposes. Twenty data records [5-4, 5, 6, 7] were used in the training which are listed in the Appendix 1. The results are tabulated in Table 5-3. The results demonstrate conclusively that the combination of the two enhancements is most effective in reducing the training time. Once again, using the enhancement combination provided the best overall epoch reduction.

As expected, the training time is considerably longer for the cooling time problem than it is for the XOR problem (compare Table 5-2 with 5-3). It seems reasonable to suppose that this is because there is more data for training in the cooling time problem and then again the added complexity that there is with this problem also likely contributes to the increase in training time. In effect, training the cooling time network takes about twice as long as the XOR problem. Moreover, the training for this problem with the Internet server system took about 20 times as long as the same test with NNWorks as documented by Chan [5-1]. There may be many reasons for this but it is likely due to differences in Server generated PHP software rather than the more efficient C++ software used by Chan.

Table 5-3 Performance of Different Learning Enhancement Algorithms for the Cooling Time Problem

	Basic (No enhancements) (epoch number) (min)	Momentum ($\alpha = 0.20$) (epoch number) (min)	Momentum with Fahlman's Derivative (epoch number) (min)
Trial 1	4090 (57)	2966(41)	2061(28)
Trial 2	5626(78)	2360(33)	1768(24)
Trial 3	4051(56)	3781(52)	1526(21)
Trial 4	3999(56)	3038(42)	1914(26)
Average	4441(62)	3036(42)	1817(25)

Table 5-4 Model Accuracy Result For The Cooling Time Problem

	Trial 1	Trial 2	Trial 3	Trial 4
Correlation Factor	0.96	0.97	0.97	0.97
Average Diff	4.73	4.55	4.57	4.70
Standard Deviation	3.70	3.37	3.37	3.46

However, the correlation factor and the standard deviation of the difference between measured and calculated values would indicate that it is a fairly accurate system - certainly this kind of accuracy would be welcomed by the welding community.

5.3.3 The HAZ Hardness Problem

The HAZ hardness problem selected for testing was taken directly from the study of Yurioka [5-3], which consists of four inputs elements (cooling time, two carbon equivalents, and a carbon content) and one output element (HAZ hardness). Thirty data records were used to train this model, the details of which are documented in Appendix II. Because the problem is much more complex than the XOR and cooling time problems, the BPN structure consisted of 8 nodes in a single hidden layer, four nodes for the input and a single output node. The combination of Fahlman's derivative and momentum enhancements were used for this experiment.

The calculation time for the hardness problem was much longer than that for the cooling time problem. Though both enhancements were incorporated the time to convergence was considered unreasonably long (greater than one day) and the test was aborted. It is not reasonable to tie up a server with training for days at a time. Moreover, training times this long can lead to numerical difficulties such as round-off errors and basic reliability can become a problem. The time consuming difficulty is likely software

efficiency as mentioned above with regard to the cooling time problem. This is certainly an issue for future research and development before the system can be deployed.

While BPN server weld process modeling has been demonstrated and all the necessary elements are in place, there is considerably more work to be done.

Nonetheless, the principle of server training and model deployment, together with accumulating user identities and raw data has been established. It is for future thesis researchers to sort out some of the difficulties that have been identified in this thesis and to bring the system into practice.

Chapter Six

General Discussion

The general objective of this thesis was to bring the weld process modeling software, that was initially generated by Chan [6-1], to the Internet for the benefit of the welding engineering community at large. While the Chan software is in the marketplace under the name of Weldsoft (regression based software) and NNworks (neural network based software), it is not used to the extent that might be expected, and yet it has been said that this software is very useful for practicing engineers in the welding and fabrication industries. The basic premise of this thesis is that Internet availability would address this problem. In this regard, Internet Java applet versions of both Weldsoft and NNworks have been presented in this thesis which in effect addresses the objective directly.

In addition to the Java applets, a server based BPN weld process modeling facility has been demonstrated which adds an important dimension to the issue of availability. In this system, Internet users submit raw experimental data to a dedicated weld process server, whereupon BPN training takes place. At the same time the raw experimental training data and information concerning the user is captured by the server and made available to the welding engineering community as a whole. Moreover, the trained model is captured by the server and also made available to users at large. The potential of this system for capturing and assembling a really large database is considered to be an important contribution for the benefit of entire welding community.

Java applets perform well, especially the applet for computing cooling time (800 to 500 °C) and from this the applet for calculating HAZ hardness. The software applets reside in a central Internet server and are downloaded to a user on demand. A convenient user interface form has been incorporated in the HAZ hardness model containing windows for all input quantities. Welding parameters (voltage, current, welding speed, arc efficiency and workpiece thickness), and the workpiece chemical composition are input through the interface form. Calculated HAZ hardnesses are returned. Parametric study is possible whereby HAZ hardness as a function of any of the welding parameters or workpiece chemical composition variables can be displayed in graphical form. The reliability of the software has been confirmed by comparing calculated HAZ hardnesses with measured values. There is little else to add but to declare that the objective, insofar as calculating cooling times and HAZ hardnesses is concerned, has been met.

Java applets have also been presented for computing weld size and shape, similar to the software contained in Weldsoft and NNworks. By and large, the Java applets are similar to the Weldsoft and NNWorks software. Both technologies incorporate convenient user interfaces and both have been verified against experimental measurements. However, the applet software does not yet permit parametric study whereas the stand alone PC software does have a parametric study facility. The primary reason for this is that, among other things, there is not enough room on one interface to reserve space for parametric graphical display in this module. This researcher opted for the simplicity of a single interface where the calculated results and a display of the weld

cross section can be presented on one screen. One or two further screens would be necessary for parametric display and for a display presenting the effect of polarity and gas cover which is contained in the stand alone version. There is a lot to be said for the simplicity of the one screen display presented in this thesis. Nonetheless, a suggestion for further work would be that the parametric study and polarity/gas cover screens could and probably should be added at some time in the future.

It should be noted that the Java applet systems may be considered “universal” in the sense that the algorithms are meant to be applied to a wide range of welding processes and welding configurations. This is useful because it preserves the simplicity of traditional research where modeling is always intended to be universal as long as the assumptions and conditions under which the model was generated are consistent with the application. The difficulty with the welding process in this regard is that it is not in general a fully controlled process where the set conditions define the result. The culture of the welding community is such that operator skill and tradition are involved in the process and these cannot be quantified. In this sense the so-called universal models are limited and practitioners must know that the results of such calculations are at best approximations. Perhaps the best feature of such models is the possibility of parametric study where engineers can study the effect of one or another variable on the expected output.

However, neural network technology offers the researchers and engineers tools that are able to address the problem of skill and culture based parameters, at least in part. As long as welding professionals are consistent, neural network software “learns” what to

expect from them in terms of output and computations can implicitly take skill and tradition into account. In particular BPN welding models can be custom generated for a job shop or even for a single welding operator. This was Chan's intent when he introduced the software NNworks to the welding community a few years ago. While NNworks has certainly had an impact on the welding community, the objective of this thesis is to make it available on the Internet and to insist that training take place on the server. By insisting on central processing, trained models can be stored and made available to the welding community as a whole; but even more than that the raw experimental data used for training can be captured along with the identity of those who elect to use the process. A large database of training data would be a valuable resource for the welding community as a whole. Data quality and reliability would certainly be an issue with such a system. However, presumably users would select only those data for which they had confidence.

However, generating an on-line BPN system for modeling the welding process has not been easy. In fact it has meant a great deal of work. One of the first obstacles faced by the author was arranging for server services. In the beginning it was assumed that either a university server or an industrial server could be found where administrators would be willing to house the weld modeling software. However, it was found that most servers do not have the computational or database development applications. Beyond this most administrators were concerned that the computing resources necessary to run the weld modeling system would be excessive and in addition, maintaining such a system would be difficult. In view of these difficulties, it was concluded that a dedicated custom configured server would have to be used for this program. Therefore, it became necessary to learn server technology and not only conventional server technology but advanced

server computational functionality as well. While server technology is interesting this was not part of the initial objective.

Nonetheless, this researcher persevered, assembled a local network consisting of a server and a client machine. A server operating system, communications software, computational software and database software were installed and a BPN weld modeling system generated. Interface software was arranged for the convenience of users. In fact this system is faithful to the original objective in all respects. Users submit their raw experimental data (cooling times, HAZ hardnesses, etc.; and welding parameters) to the system which are stored in the database together with information on the user. Training data is selected (on-line) from a remote client machine and submitted to the training server software. Training is done within the server and a set of training weights returned to the user and to the database for central storage. The system is then ready to accept arbitrary welding conditions (within the limits of the training) and return calculated outputs (HAZ hardnesses, etc.). In effect this accomplishes the objective of making the BPN system available to Internet users in the welding community and at the same time a registry of users, experimental data and custom designed models is stored in the database for general use. Moreover, the on-line system eliminates a lot of upgrading problems because the software is stored in the host computer and a one time upgrade in the server automatically upgrades all the software for users.

While the objective has been demonstrated, there are difficulties that will have to be addressed before the system is ready to be fully implemented on-line. The first is the length of time necessary for training. As documented in section five, several hours are

necessary in some cases to train a single model. While training is going on, the server is largely dedicated to this activity. During this time the server is either not functional for other users and at best, it means a very slow response for other functions such as communicating with the database. This will not be workable in practice, as Internet users are accustomed to instant response of some kind. It would seem that a dramatic increase in server computing resources or a dramatic increase in the efficiency of the training software would be needed to solve this problem. It may be that a dedicated computational computer could be arranged in parallel with the server, whereby training jobs would be spooled for processing and the weights returned sequentially to the database. Clearly more work is needed to address this problem.

Alternatively, this researcher has suggested that the training data could be downloaded to client machines for off-line training with NNworks. In fact the “Data View” module is designed for that purpose. The difficulty with this is that there is no guarantee that the user would resubmit his/her trained module to the server, nor is there any guarantee that the user would leave his/her raw training data. It would essentially be an honor system. On the other hand, it would give users access to all of the data and models that have been registered in the database. It seems to this author that this kind of “data exchange” philosophy offers considerable potential and it should be considered carefully in the future.

Another difficulty with the current demonstration system is file transfer. For the convenience of users, automatic file transfer technology between modules should be implemented. As it now stands raw data and weight set submission are transferred

manually between modules, and there is always the possibility of transfer error, quite apart from the inconvenience. Yet this is not as easy as one might suppose. It is not possible to send data in normal text format, since it has to be registered in the database software. To do this, special formatting is required. Data transfer from one format to another is troublesome at the moment but is something that should be addressed in future work.

While there are difficulties with the demonstration system that have to be addressed before it becomes a fully implemented Internet system, this author would contend that the principle of training on-line, capturing user information and experimental data has been established. Captured data is then available to any user in keeping with Internet tradition. Thus the objective of making the weld process modeling software widely available to the welding engineering community has been met.

Chapter Seven

Conclusions and Contributions

- 1) Java versions of the PC stand-alone weld process software “Weldsoft” and “Nnworks” for computing HAZ hardnesses and weld features (weld size and shape) have been presented. The software is housed on a central Internet server and downloaded in response to client request for off-line remote processing.
- 2) To evaluate the Java software computed values of HAZ harnesses and weld size and shape have been compared with experimentally measured values and general agreement was found.
- 3) A server system that accepts raw training data from clients and returns trained custom generated weld process models to the user has been presented. At the same time user information, raw training data and trained models are captured by the server database for general use by the welding community.
- 4) The training process causes host computer overload, which would not be acceptable for such a system in practice. Further work will be necessary to address this problem.
- 5) There is a need for automated data exchange between modules in the server system which will also have to be addressed before this system becomes practical.

Chapter Eight

Future Work

The shortcomings of both the applet remote processing system and the on-line server system have been discussed at length in the thesis, especially in the general discussion.

Therefore they will only be listed here as a summary:

1. A parametric study facility should be added to the weld features Java applet. In all likelihood this would involve arranging for two additional user screens, one for graphical presentation and one to present pictorial weld cross section representations depicting the effect of polarity and gas cover.
2. The difficulty of excessive training time for the on-line BPN weld process system must be addressed. This might involve more efficient software, or it might involve a computer paralleled with the server and dedicated to training only. A spooling system would have to be arranged for processing training jobs sequentially and weights would then be returned to the database for recording.
3. The data exchange principle put forward by the author whereby, training data is provided from the server to the client for training off-line with NNworks might be developed to address the training time problem. In this way remote client machines could be used to provide the computing resources necessary for training. The server would then be free for communication with clients.

4. Automatic data exchange between modules should be developed to avoid the inconvenience and potential for error caused when computed results are transferred manually.
5. The weld features BPN system should be extended by training and testing with data for welding processes other than GMAW, e.g., SMAW, SAW, FCAW, etc.

While many other suggestions could be put forward the five suggested here would undoubtedly move the technology a long way toward a fully working system. It is the authors view that these are the issues that should receive priority and focus.

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Appendix I

Cooling Time Data

This appendix is composed of three different groups of cooling time data. They were all used for verifying the cooling time software as described in chapters 3 and 4. The first set is extracted from the work of Kohno et al [3-5] which is based on the submerged welding process. The second set is gas metal arc weld cooling times from the work of Signes et al [3-7]. The last set of cooling time is based on the shielded metal arc weld investigation of Yurioka et al [3-8].

Appendix I

Cooling Time Data

*from Different Welding Processes*_[1-22]

Kohno et al [3-5] SAW $t_{8/5}$ experimental data ($\eta_{proc} = 0.95$ for calculating heat input)

Heat flow	Voltage (volts)	Current (amp)	Speed (mm/s)	Thickness (mm)	Heat in (kJ/mm)	Preheat (°C)	$t_{8/5}$ (s)
3-D	36	530	11.92	25	1.52	20	9.80
3-D	36	510	10.83	25	1.61	20	7.15
3-D	30	920	18.50	25	1.42	20	7.60
3-D	30	900	18.50	25	1.39	20	5.15
2.5-D	30	520	5.00	25	2.96	20	23.43
2.5-D	36	690	8.33	25	2.83	20	20.20
2.5-D	35	700	8.33	25	2.79	20	19.20
2.5-D	40	880	11.83	25	2.83	20	16.20
2.5-D	40	900	11.83	25	2.89	20	16.25
2.5-D	30	710	4.69	25	4.31	20	38.35
2.5-D	34	890	5.12	25	5.61	20	69.17
2.5-D	35	860	5.12	25	5.58	20	67.50
3-D	35	520	11.50	25	1.50	20	7.80
3-D	35	490	11.50	25	1.42	20	6.95
3-D	35	480	11.50	25	1.39	20	7.40
3-D	30	880	18.00	25	1.39	20	6.10
3-D	30	870	18.00	25	1.38	20	5.27
2.5-D	31	500	5.00	25	2.95	20	19.80
2.5-D	30	520	5.00	25	2.96	20	20.80
2.5-D	35	680	8.17	25	2.77	20	18.15
2.5-D	35	710	8.17	25	2.89	20	17.50
2.5-D	40	900	12.00	25	2.85	20	15.03
2.5-D	30	700	3.50	25	5.70	20	70.25
2.5-D	31	700	3.50	25	5.89	20	69.10
2.5-D	35	900	5.25	25	5.70	20	73.33

Yurioka et al [3-8] SMAW $t_{8/5}$ experimental data ($\eta_{proc} = 0.80$ for calculating heat input).

Heat flow	Voltage (volts)	Current (amp)	Speed (mm/s)	Thickness (mm)	Heat in (kJ/mm)	Preheat (°C)	$t_{8/5}$ (s)
3-D	24	120	3.58	20	0.64	20	3.01
3-D	24	120	3.58	20	0.64	100	4.13
3-D	24	120	3.58	20	0.64	200	6.43
3-D	25	170	2.5	20	1.36	20	7.00
2.5-D	25	170	2.5	20	1.36	100	9.50
2.5-D	25	170	2.5	20	1.36	200	14.87
2.5-D	29	285	1.83	20	3.61	20	24.55
2.5-D	29	285	1.83	20	3.61	100	37.90
2-D	29	285	1.83	20	3.61	200	50.15

Signes et al [3-7] entire GMAW $t_{8/5}$ experimental data
($\eta_{proc} = 0.7$ for calculating heat input).

Heat flow	Voltage (volts)	Current (amp)	Speed (mm/s)	Thickness (mm)	Heat in (kJ/mm)	Preheat (°C)	$t_{8/5}$ (s)
3-D	27	250	1.43	76.4	3.30	204	33.80
	27	250	2.15	76.4	2.20	204	20.70
	27	250	1.72	76.4	2.75	21.1	11.80
	27	250	4.30	76.4	1.10	21.1	4.40
	27	250	1.43	50.9	3.30	204	33.80
	27	250	4.30	50.9	1.10	204	8.44
	27	250	2.15	50.9	2.20	149	12.80
	27	250	1.43	50.9	3.30	93.3	20.00
	27	250	2.87	50.9	1.65	93.3	9.47
	27	250	2.15	50.9	2.20	65.6	9.32
	27	250	1.72	50.9	2.75	21.1	12.50
	27	250	2.87	50.9	1.65	21.1	7.45
	27	250	4.30	50.9	1.10	21.1	4.40
	27	250	1.43	38.2	3.30	204	42.10
	27	250	2.15	38.2	2.20	204	18.80
	27	250	2.15	38.2	2.20	149	16.40
	27	250	4.30	38.2	1.10	93.3	5.61
	27	250	1.43	38.2	3.30	21.1	14.90
	27	250	2.87	38.2	1.65	21.1	7.77
	27	250	1.43	31.8	3.30	21.1	19.30
	27	250	2.15	31.8	2.20	21.1	10.10
	27	250	4.30	31.8	1.10	21.1	4.73
	27	250	4.30	25.5	1.10	204	9.59
	27	250	2.15	25.5	2.20	21.1	9.80
2.5 - D	27	250	1.43	25.5	3.30	204	64.20
	27	250	2.87	25.5	1.65	204	15.90
	27	250	1.72	25.5	2.75	149	28.70
	27	250	1.43	25.5	3.30	93.3	31.50
	27	250	2.15	25.5	2.20	93.3	13.80
	27	250	1.43	25.5	3.30	21.1	20.60
	27	250	1.43	19.1	3.30	93.3	77.90
	27	250	2.15	19.1	2.20	93.3	23.80
	27	250	2.87	19.1	1.65	21.1	7.95
	27	250	4.30	12.7	1.10	149	23.40
	27	250	2.15	25.5	2.20	204	28.20
	27	250	2.15	25.5	2.20	204	22.10
	27	250	2.15	25.5	2.20	149	18.70
	27	250	2.15	25.5	2.20	93.3	15.20
	27	250	2.87	19.1	1.65	204	23.30

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	27	250	1.43	19.1	3.30	21.1	54.00
	27	250	2.15	19.1	2.20	21.1	15.20
2 - D	27	250	1.43	19.1	3.30	204	62.20
	27	250	1.43	19.1	3.30	149	47.00
	27	250	2.15	12.7	2.20	204	75.80
	27	250	2.87	12.7	1.65	204	46.00
	27	250	1.43	12.7	3.30	149	141.00
	27	250	2.15	12.7	2.20	93.3	39.90
	27	250	2.15	6.37	2.20	204	190.00
	27	250	4.30	6.37	1.10	204	75.80
	27	250	4.30	6.37	1.10	149	52.50
	27	250	2.15	6.37	2.20	93.3	120.00
	27	250	4.30	6.37	1.10	21.1	35.10
	27	250	4.30	4.78	1.10	149	78.00
	27	250	4.30	4.78	1.10	65.6	56.50
	27	250	2.15	4.78	2.20	21.1	137.00
	27	250	2.87	4.78	1.65	21.1	96.20

Appendix II

AMCA Hardness Data

AMCA [3-13] HAZ hardness data were used for verifying the network hardness knowledge as outlined in Chapter 3 and 4. The original study includes both 800 to 500 °C cooling time and HAZ hardness. The cooling time data are included in Appendix IV as the work of Bala et al [3-13].

Appendix II

AMCA Experimental HAZ Hardness Data [3-13].

AMCA SAW $t_{8/5}$ experimental data are listed in Appendix IV.

AMCA [3-13] tested steels chemical composition.

Steel	C	Mn	Si	Cr	Mo	V	Ni	Cu	P	S	Nb	Al	N	CE	Pcm
B1	0.05	0.42	0.23	0.73	0.21	0.002	1.03	1.06	0.01	0.009	0.042	0.023	0.010	0.448	0.200
B2	0.12	1.29	0.26	0.15	0.05	0.10	0.15	0.006	0.01	0.006	0.01	0.03	0.006	0.405	0.217
B3	0.16	1.42	0.30	0.02	0.01	0.01	0.03	0.07	0.012	0.011	0.02	0.03	0.006	0.411	0.247

AMCA HAZ Hardness (VHN) [3-13].

$t_{8/5}$ (s)	Steel B1	Steel B2	Steel B3
3.1	308	379	433
5.0	277	350	340
6.4	271	306	348
10.0	267	283	308
13.8	254	281	290
21.5	246	265	277
31.0	246	238	246
48.5	250	246	238
62.0	250	238	227

Appendix III

Gas Metal Arc Weld Size Data

Note from thesis supervisor M.J. Bibby: The data that was to occupy pages 153-164 were to come from the weld size and shape investigation from Northern College [5-4] – 182 sets of GMAW data with C25 and M2 cover gas. These data were used as the training and verification information for the weld size and shape features module. Mr. Morinishi did not finish this section but the data may be found in the doctoral thesis of Dr. Billy Chan [5-1].

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Appendix IV

SAW Experimental Cooling Time

The following are the submerged arc weld 800 to 500⁰C cooling times - data gathered from four individual works: Rodruges et al [5-4], Adrichem et al [5-5], Bibby et al [5-6], and Bala et al [5-7]. These data were used for training and verifying the cooling time networks as outlined in Chapter 5.

Appendix IV

SAW Experimental Cooling Time [5-4, 5, 6, 7]

For submerged arc welding $\eta_{\text{proc}} = 0.95$ was used for calculating heat input.

Reference	Heat-flow	Voltage (volts)	Current (amp)	Speed (mm/s)	Thickness (mm)	Heat in. KJ/mm	Preheat °C	$t_{8/5}$ s
5-4	3-D	30	650	5.00	40.00	3.71	100	39.5*
		30	650	6.67	40.00	2.78	100	22.5
		30	480	5.00	40.00	2.74	100	23.0
5-5		32	350	10.00	22.20	1.06	20	3.1
		32	350	10.00	31.80	1.06	20	3.6*
		32	350	5.00	31.80	2.13	20	8.1
		32	510	5.00	31.80	3.10	20	12.6
		32	350	10.00	25.40	1.06	20	3.7
		32	350	5.00	25.40	2.13	20	9.3*
		32	700	10.00	31.80	2.13	155	23.2*
		32	700	10.00	50.80	2.13	130	14.0
		32	350	10.00	19.00	1.06	20	3.5*
		32	350	10.00	37.50	1.06	20	3.1
		32	350	5.00	37.50	2.13	20	8.6
		32	510	5.00	37.50	3.10	20	12.9*
		32	510	3.75	37.50	4.13	20	19.1
		32	350	10.00	50.80	1.06	20	4.0*
		32	350	5.00	50.80	2.13	20	7.8
		32	510	5.00	50.80	3.10	20	12.6
		32	510	3.75	50.80	4.13	20	19.7
		32	700	10.00	37.50	2.13	137	15.9
5-6		20	434	10.00	38.10	0.82	20	5.1*
		20	558	10.00	38.10	1.06	20	6.0
		20	890	10.00	38.10	1.69	20	10.5
		20	1200	10.00	38.10	2.28	20	13.6
		20	1863	10.00	38.10	3.54	20	20.0
		20	2684	10.00	38.10	5.10	20	32.0
5-6		26	150	7.60	63.00	0.49	22	3.1*
		25	250	7.60	63.00	0.78	22	5.0
		27	300	7.60	63.00	1.01	22	6.4
		26	500	7.60	63.00	1.63	22	10.0
		30	550	7.10	63.00	2.21	22	13.8*

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		30	600	5.00	63.00	3.42	22	21.5
		34	700	4.60	63.00	4.92	22	31.0
		34	700	3.00	63.00	7.54	22	48.5
		34	750	2.50	63.00	9.69	22	62.0*
5-5	2.5-D	30	650	3.33	40.00	5.56	100	67.5
		35	850	5.07	40.00	5.57	100	66.0*
5-6		32	350	10.00	15.90	1.06	20	3.9*
		32	350	5.00	15.90	2.13	20	17.5
		32	350	5.00	22.20	2.13	20	9.4
		32	510	5.00	22.20	3.10	20	18.3
		32	510	3.75	22.20	4.13	20	38.6
		32	510	3.75	31.80	4.13	20	20.9*
		32	510	5.00	25.40	3.10	20	17.2
		32	700	10.00	15.90	2.13	130	46.4
		32	700	10.00	22.20	2.13	15	24.0*
		32	700	10.00	25.40	2.13	15	22.8
		32	350	10.00	12.70	1.06	20	6.3
		32	350	5.00	19.00	2.13	20	11.6
		32	510	5.00	19.00	3.10	20	25.0
		32	510	3.75	19.00	4.13	20	47.3
		32	700	10.00	19.00	2.13	140	30.6*
5-5	2-D	32	510	5.00	15.90	3.10	20	36.6
		32	510	3.75	15.90	4.13	20	71.9*
		32	700	10.00	12.70	2.13	150	59.2*
		32	350	5.00	12.70	2.13	20	24.4*
		32	510	5.05	12.70	3.07	20	56.6
		32	510	3.75	12.70	4.13	20	96.8*

Note: *) 20 selected data set used for web BPN system verification.

Appendix V

Experimental HAZ Hardness Data

The following are the original HAZ hardness data from the work of Yurioka et al [3-6]. These data were used to train and test the backpropagation networks for estimating HAZ hardness, given the 800 to 500 °C cooling time and steel chemical composition as described in chapters 3 and 4. Hardnesses, cooling times and the chemical compositions of the fourteen steels used in the investigation are included in this Appendix.

Appendix V

Yurioka et al [5-3] Experimental HAZ Hardness Data
(with Steels Composition)

Steel	C (wt%)	Si (wt%)	Mn (wt%)	S (wt%)	P (wt%)	Cu (wt%)	Ni (wt%)	Cr (wt%)	Mo (wt%)	V (wt%)	Nb (wt%)	Ti (wt%)	B (wt%)	Pcm (wt%)	CE (wt%)
A1	0.160	0.400	1.410	0.020	0.008	0.000	0.000	0.000	0.000	0.059	0.038	0.000	0.0000	0.250	0.407
A2	0.159	0.370	1.400	0.180	0.012	0.000	0.000	0.000	0.000	0.026	0.000	0.000	0.0000	0.244	0.398
A3	0.173	0.450	1.480	0.021	0.116	0.000	0.000	0.000	0.000	0.056	0.046	0.000	0.0000	0.268	0.431
A4	0.142	0.410	1.440	0.025	0.003	0.000	0.200	0.000	0.000	0.034	0.016	0.000	0.0002	0.235	0.402
A5	0.099	0.360	1.460	0.013	0.004	0.150	0.170	0.000	0.000	0.040	0.039	0.000	0.0006	0.201	0.372
A6	0.231	0.270	1.190	0.019	0.007	0.000	0.000	0.000	0.000	0.036	0.000	0.000	0.0005	0.306	0.437
A7	0.254	0.270	1.370	0.016	0.005	0.140	0.160	0.150	0.140	0.000	0.000	0.000	0.0002	0.359	0.560
A8	0.240	0.290	0.870	0.019	0.005	0.000	0.130	0.120	0.000	0.000	0.000	0.000	0.0003	0.303	0.418
A9	0.141	0.300	1.330	0.020	0.006	0.000	0.000	0.000	0.000	0.055	0.000	0.000	0.0002	0.224	0.374
A10	0.065	0.280	1.380	0.013	0.003	0.000	0.000	0.210	0.210	0.038	0.000	0.000	0.0015	0.179	0.387
A11	0.130	0.290	0.880	0.010	0.005	0.220	0.810	0.540	0.470	0.044	0.000	0.000	0.0018	0.280	0.556
A12	0.112	0.240	0.870	0.019	0.006	0.230	0.000	0.850	0.330	0.046	0.000	0.000	0.0005	0.247	0.518
A13	0.049	0.290	1.560	0.017	0.005	0.000	0.270	0.000	0.250	0.068	0.049	0.007	0.0002	0.166	0.391
A14	0.034	0.150	2.060	0.021	0.002	0.000	0.310	0.000	0.300	0.000	0.056	0.018	0.0010	0.172	0.458

Steel	800 to 500° cooling times $t_{8/5}$										
	3	4	6	8	10	15	20	30	40	60	
A1	375	355	325	305	290	265	250*	235	225	200*	
A2	360	340*	305	285	270	250*	240	225*	215	200*	
A3	390	375	340*	320	305*	290	270	255	240	225	
A4	385	370	350	325*	310	275	255	235	225	215	
A5	355*	340	315	295	280	260	245	228	220	215*	
A6	450	445*	415	385	350*	300	275	250	235*	220	
A7	485*	485	485	485	480	450	430	380*	350	305*	
A8	460	440	400	360	330	275*	250	230	225	215	
A9	375	360	330	305	295	255	245*	220	215	205	
A10	335	325	303	290	280	265	235	225*	220	210	
A11	400*	400	400	400*	390	380	355	320	295	270*	
A12	380	375	370*	365	360	335	320	295	280*	255	
A13	285*	280*	260	252	245	235	225	220	215	210*	
A14	320*	315	310	305	300	295	285	275	265	250*	

Notes : *) The 30 sets of training data.