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THE PREDICTION OF RISK OF WELDING DEFECTS AT THE PROCEDURE STAGE USING COMPUTER KNOWLEDGE BASED SYSTEMS

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ABSTRACT

The purpose of this research was to develop a methodology to evaluate the likelihood of defective welds as a procedure proposal is entered into a computerised database system. The approach developed was assessed for hydrogen induced cold cracking (HICC) since this defect is a major problem in welding technology. An expert system was used to implement the methodology.

The information for the expert system knowledge base was partly gathered from previous work in this area. The technique necessary to analyze and incorporate knowledge was organized in a structured form including the major area to be attacked.

The final system was implemented using an expert system shell. The global task of analyzing a welding procedure was broken-down into three different stages. A welding procedure specification comprised the first stage. In the second stage, an interface between the expert system software and a database was implemented. Having proved the feasibility and advantages of integrating the expert system shell with a relational database the remainder of the work was devoted to the development of a strategy for operating the expert system and in particular dealing with uncertainty.

Detailed validation of the knowledge base and the system as a whole were confined to a single defect type in the belief that the modularity of the system would allow extension to other defect types and the strategies developed in the present work should it be applicable. Results have shown that the system performs well in the specified area. Validation trials using simulated welding conditions generated by the expert system have shown a very good correlation with practical results for different classes of steels. The integration between approved welding procedure records and procedure qualification records could be the basis for a complete welding database management. Practical application of this system could be extended for educational purpose and training facilities.

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TABLE OF CONTENTS

LIST OF FIGURES

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

LIST OF TABLES

Chapter Page

Chapter 2

Chapter 3

Chapter 4

NOMENCLATURE

Abbreviations

HICC	Hydrogen Induced Cold Cracking
LCS	Low Concentration Stress
HSLA	High Strength Low Alloy Steels
HAZ	Heat Affected Zone
CGHAZ	Coarse Grained Heat Affected Zone
WPS	Welding Procedure Specification
PQR	Procedure Qualification Record

Symbol	Definition	Unit
Tp	Peak temperature at a particular distance from the weld fusion boundary	[°C]
T_0	Preheat temperature	[°C]
Tm	Melting temperature	[°C]
T	Work temperature	[°C]
Tc	Temperature of interest at which a cooling rate is determined	[°C]
Ti	Initial uniform temperature of the plate	[°C]
Y	Distance from the weld fusion boundary line	[mm]
ρ	Density of material	[g/cm^3]
C	Specific heat of solid metal	[J/g°C]
ρC	Volumetric specific heat	[$J/mm^{3\circ}C$]
K	Thermal conductivity	[cal/scmC]
th	Plate thickness	[mm]
t	Relative plate thickness	--
HI	Arc energy	[J/mm]

μ	Heat transfer efficiency	--
V	Voltage	[V]
I	Amperage	[A]
v	Welding travel speed of heat source	[mm/s]
R	Welding cooling rate	[°C/s]
$t_{8/5}$	Cooling time between 800 a 500°C	[s]
t_M	Cooling time in which 100% martensite is formed	[s]
t_B	Cooling time in which no martensite is formed	[s]
t_{100}	Cooling time from weld peak temperature to 100°C	[s]
CE_{IIW}	IIW carbon equivalent	[%]
P_{cm}	JSSC carbon equivalent (Ito and Bessyo)	[%]
Pw	Cracking parameter	[kgf/mm^2]
H	Hydrogen content	[ml/100gr]
$(H_R)_{100}$	Retained hydrogen content in ppm at 100°C	[ml/100gr]
H_0	Hydrogen content in fused metal	[ml/100gr]
$(\Sigma D\Delta t)_{100}$	Thermal factor for hydrogen diffusion from solidification temperature to 100°C	[s]
HV_{max}	Maximum hardness value	[HV10]
Hvy	HAZ hardness evaluated by Yurioka equation	[HV10]
Hvd	HAZ hardness evaluated by Düren equation	[HV10]
Hvs	HAZ hardness evaluated by Suzuki equation	[HV10]
σ	Standard deviation	-
R_2	Correlation factor	-
h	Hypothesis	-
e	Evidence	-
ct	Certainty factor	-
cf	Confidence factor	-
cf(h,e)	Confidence factor representing the degree of confirmation of the hypothesis h based on the evidence e	-
cfm	Confidence factor modified	-

MB[*h*,*e*]	Measure of belief that hypothesis is true given evidence	-
MD[*h*,*e*]	Measure of desbelief that hypothesis is true given evidence	-
p	Probability factor	-

CHAPTER 1

INTRODUCTION

This chapter outlines the background to the work, the objectives and the approach adopted.

1.1 TYPES OF WELDING DEFECT

The types of defect which occur in the fabrication of common engineering materials are fairly well established **(Lundin, 1984)** and the experienced welding engineer will be aware of the techniques required for their avoidance. Defects can originate by different mechanisms. Most cracking problems results from metallurgical problems, (ie, hot cracking, cold cracking, stress corrosion cracking, reheat cracking) whilst other defects originate from inappropriate welding conditions (this includes porosity, lack of fusion, lack of penetration, undercut, etc).

In the simplest terms, welding problems fall into two broad categories:

(1) pre-fabrication problems represented by initial difficulties encountered in making welds successfully at designed position.

(2) post-fabrication problems that lead to repairs which may have to be carried out during the service life at positions which cannot be anticipated.

The avoidance of welding problems requires a knowledge of many areas of technology and indication of the magnitude of the problem is given in **figure 1.1**. The quality criteria for a joint is determined by the design or by reference to appropriate codes and standards. In practice the final joint quality is often assessed after welding by a variety of non destructive examination techniques, the significance of any defects is estimated and the necessary corrective action taken as shown in **figure 1.2**.

1.2 CONVENTIONAL WELDING PROCEDURES

Practical attempts to avoid welding problems usually concentrate on the pre-fabrication stage. The establishment of welding procedures which give acceptable joint quality prior to the commencement of production welding is one effective approach. In this case, the welding engineer defines a procedure which gives guidance to the welder in the welding of a particular project. Standards such as BS 4870 give an indication of the requirements for a welding procedure.

Typical procedures consist of:-

- basic information on the design ie; material type, plate thickness;
- weld joint design; the joint type and preparation is specified;
- the specification of the appropriate welding process, equipment, consumables, and initial settings for all welding parameters;
- the definition of weld sequences and control of temperatures such as pre- or post-heat treatment;
- specification for the interpass temperature.

1.3 TYPE AND NUMBER OF CONTROL VARIABLES

It is clear that avoidance of welding problems involves the specification and control of many parameters. Categorisation of these variables and the information they provide is important for understanding the concept of welding process programming and control. Four types of variables may be considered as shown in **figure 1.3**. *Welding variables* provide primary information to characterize the physical welding operations or their results. *Operating variables* provide information to characterize operating conditions (specifics to the welding process, joint and environment). *Intermediate variables* provide information to characterize intermediate physical, chemical, metallurgical and other reactions which occur in the weld area. Finally, *weld quality variables* provide information to characterize weld geometry, integrity and properties.

The common method used to control these variables is established by the welding procedure specification. Although welding procedures are an effective means of control, their development is a time consuming and costly exercise which is best carried out by an experienced welding engineer.

1.4 DATABASE SYSTEMS

During the preparation of a welding procedure the welding engineer is presented with a vast choice of variables but also has the time consuming task of carrying out numerous calculations and consultations in order to set out just one welding procedure. The use of computer software to assist in this task is likely to improve his productivity and increase the reliability of a welding procedure especially in terms of data retrieval. Moreover, a poorly specified welding procedure that results in an unsafe weld can result in enormous economic penalties.

Some progress has been made in the computerisation of procedure records **(Queen, 1990)** and this enables pre-existing procedures to be located easily and can be shown to decrease the cost of procedure storage and retrieval. It seems logical to extend the use of computers to procedure generation and defect assessment and feasibility studies in these areas; this has previously been reported **(Joynson, 1986; Garrido, 1988)**.

1.5 EXPERT SYSTEMS

Expert systems are considered to be a powerful tool especially in areas involved which a vast number of variables. Several expert systems have been designed in welding but many of these concentrate on the post-fabrication stages. At the pre-fabrication stage, expert systems have been developed as welding procedure generators designed to help the welding engineer in his tasks. Many expert systems applications have been extended to welding defect diagnoses. This approach requires careful attention to the user interface; in some cases a protracted question and answer session is required in order to collect all the input data. This may frustrate the user and make him critical of the system. An alternative approach, which has not yet been fully exploited, is the use of expert systems to evaluate a welding procedure proposal generated by the welding engineer. This approach could be very helpful not only in assisting the welding engineer during specification stage but also in investigating the feasibility of the specification prior to the commencement of the welding. In this case general knowledge about welding processes and design may be encoded in rules that can be interpreted by the expert system. The welding procedure specification may be analyzed and checked and further modifications can be advised.

Computer encoding of such knowledge in the form of knowledge base expert systems can provide many advantages. Their use associated with an integrated database system could speed up the welding procedure specification process and improve its reliability. The application of the expert systems approach to check for the likelihood of defective welds as a procedure proposal is entered into a computerised database system can effectively improve the quality of the final welding, with significant improvements to economic and technical outcome. The encoded information generated during the course of an analysis by an expert system could also provide a means of optimising a previous welding procedure. Finally, the storage of previous welding procedures could be used as a future guide for further specifications or even be integrated with procedure qualification records (PQR) in an attempt to provide a completely integrated database management system.

If it is required to use a computer based system to assess the risk of a defect it is first necessary to establish a set of conditions which may be used to determine the cause and the likelihood of the defect occurring. Establishing this set of rules is a complex and time consuming task which entails a process known as *knowledge* *elicitation* and this requires both the experience of the welding engineer and published data to be organised in a manner suitable for use with a knowledge based system. Methodologies to extract the knowledge base usually include interviews, review of information contained in reports, books and standard databases.

1.6 OBJECTIVE OF THE WORK

The present work was carried out to investigate the feasibility of using an expert system approach to check for the likelihood of defective welds as a procedure proposal is entered into a computerised database system. At the same time, a diagnostic was required to indicate the main failure modes in the welding procedure specification. Additionally, an optimisation procedure was envisaged using the results of the analysis and information acquired. Finally, a full diagnostic analysis was required and the procedure details were to be transferred to a database. It was envisaged that this approach would facilitate the development of a fully integrated database management system, as shown in **figure 1.4**.

The following summarises the objectives for this research:

- Provide an interface for the user to obtain information about a particular welding procedure specification (using a format similar to that recommended in BS 4870). Additionally, provide facilities which allow the user to specify a procedure with minimum risk of input data mistakes;

- Develop a clear methodology to interface database/expert system software in order to access information about the welding conditions including parent material, consumables and shielding gas;

- Incorporate a methodology to evaluate the uncertainty of information in the knowledge base;

- Carry out mathematical calculations in order to quantify various aspects of the metallurgical, geometrical and mechanical properties of the welding joint;

- Identify the mode of failure by analyzing the welding procedure specification and suggest appropriate corrective action in order to improve the weld soundness;

- Development of a user interface facility to optimise a welding procedure based on advice and information generated during the consultation;

- Validate the system by comparing practical with simulated results.

1.7 LIMITATIONS OF RESEARCH

In order to make the work feasible, the following limitations were imposed:

- The defect analysis was concentrated on hydrogen induced cold cracking, since this defect is a major concern in the fabrication of ferritic steels.

- The base material was mainly limited to mild or low alloy steels (standards BS, ASTM, API). But, the extension of the analysis to the evaluation of High Strength Low Alloy steels was also considered.

- The welding parameter selection was performed for the GMAW and SMAW processes. The GMAW process was chosen because it has become increasingly popular in recent years and is suitable for automation via industrial robots. The SMAW process was chosen because of its higher susceptibility to the defect analyzed (the methodology developed for these processes can be extended to other arc welding processes subject to minor modifications).

- The consumables did not include flux-cored wires. The consumables specification included standards from BS, AWS and commercial products.

- General data/welding conditions was specified according to British Standard Institutions (BSI).

1.8 THESIS ORGANIZATION

In the following the literature on the subject is reviewed and the methods used in developing the expert system to evaluate the soundness of welding procedure specification are described.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The world economy and society have rapidly become information-oriented. While the rapid development of computer hardware has contributed to such progress, new software technologies have also been developed and offered for practical use. Technological progress in both software and hardware is the key to the realization of an advanced information-oriented society in the future.

Organizations have learned that data constitutes a resource they must manage in the same way they manage raw materials, equipment, and personnel. During the 80s, companies had high stakes in accessing internal and external data. Using state-of-the-art database technology, they invested heavily in the creation of integrated information systems.

After mastering their data, organizations must control the knowledge they use. They face a "knowledge barrier" due to the difficulty of acquiring, assimilating, controlling, and producing knowledge, the difficulty of finding specialists, discovering and exploiting new knowledge and new industrial processes, disseminating knowledge within the company, and controlling its propagation to the outside world. Organizations are beginning to realize that they can manage such knowledge by taking advantage of techniques and tools that originated in the fields of artificial intelligence (*AI*) and cognitive science (Moulin, 1990).

Under such circumstances, expert system technology and its applications to various industries have become popular both in United States, Japan and Europe.

Recently, companies have viewed expert systems as a new technology to be explored and assessed. It is believed that in the past few years 80% of the 500 largest companies in United States have explored expert systems (Barbolak et al., 1991). The same interest has spread worldwide and large number of expert systems applications have been reported. Some companies with previous *AI* experience have implemented organizational strategies to integrate expert systems into their operations. Harmon (highlighted by Moulin, 1990) has identified four main strategies for companies wishing to invest in expert system technology:

- Develop a major expert system application that has a strategic impact on company operations;

- Use expert system techniques to develop or upgrade midsized applications running on workstations or microcomputers;

- Support users with tools that are available on microcomputers;

- Implement expert system techniques to improve conventional applications of information system on mainframes. Such tools have appeared only recently, but seem to have a bright future.

As *AI* is still in the early stage of development, such problems as premature and non-uniform technology, over expectation and undervaluation due to the incomplete permeation of recognition are likely to arise, as well as the shortage of quality personnel involved with *AI* technology. It is essential to precisely understand and solve these problems and continue the research and development required to meet the needs of industry for the sound development of *AI* as well as the realization of an advanced information-oriented society.

All these fact show that expert systems development is not only of interest to academic researchers but also has been put into the agenda of industrial research organizations. In order to have a full assessment of this technology, great efforts need to be taken to guarantee the successful implementation of such systems.

2.2 GENERAL PRESENTATION OF EXPERT SYSTEMS TECHNOLOGY

The concept of the expert system arose in the early 1970s when Artificial Intelligence researchers tried to develop general programs to solve any problem in any field. However, as this strategy did not succeed, scientists concluded that *AI* need a large amount of very specific knowledge to solve only one category of problems at a time. The practical application of this fundamental idea originated the expert systems technique. In a particular domain, such systems exhibit behaviour similar to a human expert performing an intellectual task in a very defined and precise real-world domain (Smati et al., 1988; Agapakis et al., 1988). Figure 2.1 shows the evolution of expert systems during the last few years.

The true definition of expert systems is under debate, but in one simple definition can be generally described as "a computer system which emulates human expertise by making deductions from given information using the rules of logical inference" (Simons, 1985).

Figure 2.2 shows the main structure of an expert system. In its simplest form, an expert system consists of a knowledge base, an inference engine and an user interface. The knowledge base consists of all the information specific to the field of interest (facts and rules). The inference engine carries out the operations on the knowledge during a consultation - selecting questions to ask, drawing inferences and arriving at conclusions. It may contain modules for providing a friendly interface with the user, and for giving explanations. The knowledge base may also contain information about 'control' -i.e., how best to use the knowledge it contains.

It is often stated that the rigid separation of knowledge and inference is one of the characteristics of an expert system. This is not always the case, but it does make a system much easier to modify and expand, just by adding extra rules to the knowledge base. It also gives rise to the idea of an 'expert system shell' (Simons, 1985; Willoughby, 1987) - an expert system which all the knowledge has been removed, leaving just the inference engine, user interface and explanation module. This shell can then be filled with new knowledge on a different topic, to give a new expert system.

As well as embodying a large amount of knowledge, expert systems have the following characteristics (Agapakis et al., 1988; Simons, 1985; Chang, 1990):

- Explicit (and extensive) domain and self knowledge, attainable using a uniform knowledge representation. Within their chosen fields, they can demonstrate expert abilities.
- They incorporate 'rules of thumb' (also known as 'heuristics'). These are rules which are generally true, but perhaps not under all circumstances.
- Ability to deal with uncertainty in the knowledge and data.
- Self explanation ability, made possible by the explicit representation of inference mechanisms..
- They are programmed in a declarative style, usually by means of rules. This is a method of programming which has arisen out of developments in artificial intelligence.

Knowledge in expert systems is substantially different from the typical algorithmic decision-making logic of conventional programs. Conventional computer programs use a 'procedural' language such as FORTRAN, C, Pascal or BASIC. The program tells the computer exactly what to do. Ordering of the program statements is vital - the program will not run if, for instance, certain lines are interchanged. Execution starts at the first statement and continues through to the last, after completing any diversions and loops. Conventional languages have not proved to be well suited to computer applications in expert systems in particular (Simons, 1985). This is due to the fact that expert systems employ a declarative style. The program may be regarded as the specification of the problem, rather than the detailed procedure for solving it. It simply tells the computer the relationships between items without defining exactly what must be done. Order is relatively unimportant. Control passes down the list of statements until it finds one that can be carried out. This is then executed, control passes back to the beginning and the cycle is repeated.

Willoughby (1987) observes that the main advantage of the declarative style is that the program can be easily modified and up-dated. Lines can be added or deleted without altering the rest of the program. It also allows knowledge to be represented in a more explicit manner, rather than embedding it in a computer code as in FORTRAN for example.

Another difference between expert systems and conventional programs is that the former use 'symbolic' processing, and the latter numerical processing. Artificial intelligence languages are, in general, poor at numerical manipulation. They work by matching symbols (i.e. words) between lines of the program, in order to reach logical conclusions.

Of course, the use of a declarative style of programming is not an exclusive prerequisite of an expert system. Simple systems incorporating many of the features listed above, have been written in conventional languages (Barbolak et al., 1991). Sometimes the expert system language or shell is itself written in a lower level, conventional language. Sometimes, also, a system is developed in an *AI* language and then reprogrammed in a conventional language for computational efficiency (Willoughby, 1987).

2.3 APPROACHES TO REPRESENT KNOWLEDGE BASE

The purpose of an expert system is to imitate the problem solving powers of a human expert in a particular domain. The feature which most distinguishes the expert from the layman is the depth of knowledge and understanding of the subject, and the ability to apply that knowledge to new areas which differ in certain respects from those previously encountered. It is clear then that the method of knowledge representation in the computer is a crucial part of any successful expert system.

It is generally held by supporters of artificial intelligence that expert knowledge consists of facts and relationships between facts, both with varying degrees of certainty attached to them, and an understanding of the circumstances in which it is appropriate to use them. The 'expert' part of the knowledge normally consists of the rules and relationships which are used to connect the facts, rather than on the facts themselves. This type of knowledge may be divided into two extreme categories (Willoughby, 1987):

- Heuristic knowledge or 'rules of thumb'; i.e. where experience suggests that, under a particular set of circumstances, a particular conclusion is usually true.

- Causal knowledge or deep reasoning; where the rules are based on scientific facts and a deeper understanding of the underlying causes.

Problem solving by humans employs a mixture of heuristic knowledge and deep reasoning. Rules of thumb are used to arrive at an acceptable solution quickly, but if justification is asked for, the causal relationships will be invoked. The more expert a person is, the more rapidly he jumps to the correct solution; at the same time, the deeper is his understanding of the problem, and therefore the more basic could be the explanations that he can provide.

Another type of skill is called 'meta-knowledge', or control. This consists of rules about rules. For instance, the skill shown by good chess players consists not of mastering the rules (i.e. what moves are allowed for each piece), but in recognising certain combinations of pieces and knowing which rules to apply next.

This view that all human expertise can be expressed in terms of facts and rules has not gone unchallenged. Dreyfus (highlighted by Willoughby, 1987), for example, argues that humans are much more perceptive in their methods of solving problems than this rule-based view would suggest. It is merely competent performers who follow such rules. Dreyfus maintains, therefore, that the application of rule-based methods will never result in machines which can provide truly expert performance, but could nevertheless give rise to 'competent' systems in restricted areas.

In any event, human powers of reasoning are certainly very complex, and are only partially understood. Expert systems can only model a part of the reasoning process satisfactorily. They are constrained, in particular, by the methods which are used to represent knowledge. Simple systems rely on relatively shallow reasoning and have simple methods of control. They are also limited in the methods by which rules, relationships and facts are represented.

Several schemes have been developed for representing knowledge and rules in expert systems such as production rules, semantic networks, triples and frames. It is appropriate, therefore, to examine some of the methods of knowledge representation used in common systems.

2.3.1 PRODUCTION RULES AND INFERENCE NETWORKS

Production rules are rules or relationships written in the form IF (condition) THEN (action or conclusion). Conditions can usually be combined with AND or OR, e.g. *IF (condition_1) AND (condition_2) THEN (action_1).*

The conclusions in the above conditions usually contain a degree of uncertainty. This may be incorporated into the rules by means of the 'certainty factors' or probabilistically (see next section). Production rules, with or without uncertainty, form the basis of many practical expert systems. Many interlinking rules can be combined to form relatively complex structures.

Inference networks are similar to production rules, except that they are written in reverse order, the conclusion being inferred from the conditions.

As an aid to programming, network diagrams are commonly used to describe the relationship between inferences. Figure 2.3 shows a simplified network that might be used to determine an appropriate level of hydrogen value for use in cold cracking assessment. This type of representation can be programmed equally well by production rules. At the top of the inference network is a series of inputs to the system (e.g. a decision or a piece of advice). At the bottom is a series of inputs to the system, which are usually obtained from the user in the form of answers to questions. In between are various 'nodes', which represent intermediate conclusions.

2.3.2 STATIC KNOWLEDGE

Production rules and inference networks are means of implementing dynamic knowledge; i.e. facts which can become true (or partially true) during the course of running the system. There is another type of information known as static knowledge which is always true, regardless of the state of the consultation. Static knowledge can also be used to incorporate an element of common sense into the system and to represent the meanings of words. A database of facts is not usually incorporated into simple systems. Nevertheless, it is of interest to look at the ways in which this can be achieved.

2.3.2.1 TRIPLES AND FRAMES

Triples consist of three parameters to describe an item, these being the name of the item, a relevant attribute, and the value of that attribute. For instance, a triple could be set up to describe the current used in a particular welding procedure as follows (Willoughby, 1987):

Item	Attribute	Value
Procedure	Current	(Amps)

For instance, a current of 50 amps used in procedure 1 could be described as:

Procedure 1, current, 50

Similarly, a voltage of 20 volts could be described as:

Procedure 1, voltage, 20

In this way large amounts of data can be inserted into the system. This method of knowledge representation is used in expert systems such as MYCIN, XCON and in the OPS5 expert system shell.

Frames are an extension of triples, in which many pieces of information may be assembled into a pre-determined pattern. The frame provides a framework for organising the information, and contains 'slots' in which the information resides.

These slots typically consist of attribute/value pairs. It is similar to the idea of a page of data from a database. Willoughby (1987), describes for instance, that the frame WELDING PROCEDURE could be set up as follows:

Name	WELDING PROCEDURE
Process	XXX
Thickness	XXX
Material	MATERIAL
Current	XXX
Voltage	XXX
Position	XXX
Electrode	ELECTRODE

etc.

The XXX represent values to be filled in. Values in capital letters, such as MATERIAL, give the names of other frames, in which more detailed information resides. In this way, frames can be set up to form a network of data about the subject area.

Representation of knowledge by means of frames is common in expert systems which are programmed in LISP, and in so-called expert system 'environments' or 'tool kits' also using LISP.

2.3.2.2 SEMANTIC NETWORKS

In a semantic network, information is represented as a set of nodes connected to each other by a set of arcs representing relationships among these nodes. It is purely declarative structure which shows how different (but not completely independent) objects, concepts, and ideas may be related to each other. Also, it is widely used to represent a variety of kinds of knowledge. In order to contain enough information in a system so that it appears to be reasonably conversant with a particular topic, a very extensive semantic net would be required. However, when the number of nodes and arcs becomes important, combinatorial explosion may result (Willoughby, 1987). It is not surprising, therefore, that the use of semantic nets is normally confined to very large scale systems and are not usually available in commercial shells.

2.3.3 DEALING WITH UNCERTAINTY

The ability to handle uncertainty is regarded by some as a fundamental property of expert systems. Uncertainty arises from a variety of sources, and confounds system designers in different ways (Keung-Chi et al., 1990). This is assumed by the fact that not all the knowledge being represented is exact and certain. It is frequently required to reason with inexact or incomplete information. Even areas such as engineering, which are traditionally regarded as exact can give rise to uncertain reasoning. Keung-Chi (1990) describes that uncertainty can arise from the four main sources: unreliable information, imprecise descriptive languages, inference with incomplete information, and poor combinations of knowledge from different experts.

Considerable discussion on the merits and demerits of uncertainty representation has taken place. Several paradigms have been proposed to handle uncertainty in expert systems, some probabilistic or quantitative and some qualitative. The literature is reviewed in Keung-Chi et al., (1990), Wise et al., (1986), Horvitz, et al., (1986), Pearl (1988) and Buchanan et al., (1984). The quantitative methods include subjective probability theory, Dempster-Shafer theory, possibility theory, certainty factors and Prospector's subjective Bayesian method (Duda et al., 1990). The main qualitative or non-numeric approach is Cohen's theory of endorsements.

Probability theory, Dempster-Shafer theory, and fuzzy sets were all developed before expert systems became popular. In the early 1970's, Shortliffe (highlighted by Buchanan et al., 1984) developed the certainty factor approach - among the first and most notable of the schemes - to represent uncertain information in MYCIN. Another expert-system-specific scheme, Prospector's subjective Bayesian method was developed by Duda et al. in the 1970's, in order to resolve the difficulty of representing Prospector's uncertain information with other numeric paradigms (Duda et al., 1990). In the 1980's, Paul Cohen (highlighted by Keung-Chi, 1990) developed the theory of endorsements - the primary non-numeric paradigm for uncertainty management - as an attempt to represent uncertain information qualitatively, rather than quantitatively. Also, Edwards (1990) describes a modified form of protocol analysis which enables the knowledge engineer to gain insight into how the expert handles uncertainty without requiring the expert to quantify his expertise.

2.3.3.1 CERTAINTY FACTORS

The probability-theoretic approach to uncertainty management requires a prodigious amount of data. Hence, some weakly substantiated approximations and assumptions are usually used to reduce the requisite number of probability assessments. When Shortliffe (1990) began work on MYCIN, he felt that probability theory would not be appropriate to medicine because of the following:

- Often, not enough good data exists for a particular medical problem to create a statistical knowledge base.

- Medical knowledge and the heuristics for solving medical problems must be explicitly represented. Probability cannot easily accomplish this.

- Explaining the line of reasoning is very important if physicians are to accept the program.

In view of these potential problems, Shortliffe (1990) proposed a new approach called certainty factors. He added that in an expert system using certainty factors, the knowledge base consists of a set of rules in the following form: "If <evidence> Then (*CF*) <hyphotesis>", where *CF* denotes hypothesis belief given observed evidence. This method for managing uncertainty has seen widespread use in rule-based expert systems.

Before any combination or propagation of evidence can be performed, two intermediate functions must be calculated. These functions, *MB[h,e]* and *MD[h,e]*, measure the degrees to which belief in hypothesis **h** would be increased if evidence **e** were observed, and the degree to which disbelief in **h** would be increased by observing the same evidence **e**, respectively. They are defined as follows:

$$MB[h,e] = \begin{cases} 1 & if\ p(h)=1 \\ & otherwise \\ \dfrac{\max[p(h/e),p(h)]-p(h)}{\max[1,0]-p(h)} & \end{cases} \tag{2.1}$$

$$MD[h,e] = \begin{cases} 1 & if\ p(h)=0 \\ & otherwise \\ \dfrac{\min[p(h/e),p(h)]-p(h)}{\min[1,0]-p(h)} & \end{cases} \tag{2.2}$$

The values of *MB[h,e]* and *MD[h,e]* range between 0 and 1. If more than one piece of evidence supports a hypothesis, a combination function for MB and MD is used in computing *cf*. Evidence is then propagated by computing *cf* from MB and MD, where

$$cf = \frac{\mathrm{MB}-\mathrm{MD}}{1-\min[\mathrm{MB},\mathrm{MD}]} \tag{2.3}$$

The value of *cf* can range from the -1 to +1; -1 indicates the confirmation of h's negation, and +1 indicates h's confirmation.

When two or more rules affect the same hypothesis, the individual *cf s* obtained from the rules are combined to give a combined *cf* for the hypothesis as follow (Buchanan et al., 1984):

$$cf_{combine}(X,Y) = \begin{cases} X + Y(1-X) & \text{if both } X,Y>0 \\ \dfrac{X+Y}{1-\min[\,|X|,|Y|\,]} & \text{if one } X,Y<0 \\ X + Y + XY & \text{if both } X,Y<0 \end{cases} \tag{2.4}$$

One of the most attractive features of the certainty factor model is that it represents, combines, and propagates the effects of multiple sources of evidence in terms of joint beliefs or disbeliefs in each hypothesis. Since the model was originally designed only to represent change in belief induced by evidence, rather than an absolute degree of belief, certainty factors avoid the need for prior probabilities, thereby addressing one of the more contentious challenges to probabilistic belief propagation. Horvitz et al., (1986) and Heckerman (1986) however, showed that certainty factors cannot represent some particular classes of dependencies among uncertain beliefs efficiently and naturally. Heckerman (1986) further contended that *AI* researchers will find belief networks an expressive representation for capturing the complex dependencies associated with uncertain knowledge.

On the use of certainty factors to represent uncertainty, several applications have been described in Kopcso (1988) and Leung (1988). Blumberg (1990) for instance, extended the use of certainty factors by inducing an expert system to learn from examples.

2.4 SYSTEM CONTROL

Many systems have an in-built method of control, which is either 'forward chaining' or 'backward chaining', see figure 2.4.

In forward chaining, the system begins with the evidence and then tries to see which 'goals' or possible solutions it can prove. For the network represented in figure 2.4, for instance, it could start by asking questions 1,2 and 3, from which it might be able to prove goal 1 or goal 2 (depending on the answers). If not, it would ask question 4 and try to prove goal 3.

In backward chaining, the system begins with the first possible solution and tries to prove it. In order to do this it would need to ask questions 1 and 3. If this was unsuccessful, it would move onto goal 2, for which it would then need to ask question 2, and so on. Thus the ordering of questions is different in this example between backward and forward chaining.

In a simple network such as figure 2.4, either method of control produce approximately the same results. In a complex system, the line of questioning could be very different. In general, forward chaining is suited to the case where there relatively few questions to be asked and a large number of solutions, whereas backward chaining is better for cases where the possible questions are many and the solutions few (Willoughby, 1987).

Simple methods of control such as forward or backward chaining are in reality poor representations of the methods of problem solving adopted by humans. In many cases a combination of forward, backward and sideways chaining will be adopted. One might work forwards from the evidence and backwards from the possible solutions, skirting around any dead ends, so as to meet somewhere in the middle. Only after the solution has been found will the expert justify it by producing a simple, continuous line of reasoning.

2.5 PROSPECTS IN EXPERT SYSTEMS TECHNOLOGY

At the present stage, expert systems technology has been concentrated in deductive methods of reasoning which moves from the general to the particular (Winstanley, 1991). The model builder attempts to produce a system which encodes general rules concerning the knowledge which is gathered from experts. One of the current difficulties involved with this approach is that the knowledge of the human expert is often difficult to express in a form that is suitable for expert systems. This difficulty can arise because the expert can find it difficult to articulate his knowledge in a coherent form.

Another approach, however, has been conceived. In this case the rules are not known, and the expert system derives its own rules from a series of definitive examples provide by the expert. This is the process of induction - that of going from the particular to the general (Willoughby, 1987; James, et al., 1986; Baker et al., 1988; Alberry et al., 1988). The relation between these types of knowledge is shown in figure 2.5. As described by Willoughby (1987), an application of this technique could be extend the choice of welding parameters for achieving an acceptable weld. One could conduct a number of experiments in which the parameters were all varied, and the outcome noted, and the program would then derive a rule giving the best combination of parameters for the desired result.

Despite the very attractive feature of such conceived systems, some major difficulties have been reported from its development by Lucas (1987) and Alberry et al. (1988). Firstly, if there are too many definitive examples available the system cannot readily converge to a set of rules in a finite time. Secondly, reliability of the rules and decision processes depends on the quality of the examples used. Finally, examples must be very carefully formulated since the induction process assumes that all important factors have been identified and expressed in the examples. It remains to be seen whether or not the science of welding has progressed sufficiently from the ignorance of black-art craftsmanship for expert systems to make an impact.

An interesting approach that has been discussed at the present time is the possibility of transferring knowledge into new applications. There has been also some description of different methodologies to do this. Some of these mention the knowledge modularity as an effective method to give some interdependence between the knowledge. For instance, in COMPASS (a telecommunication expert system that analyzes maintenance printouts from telephone company central office switching equipment and advises actions) the modularity concept was used (Prerau, 1990). This methodology provide an effective way to expand this system from GTE Laboratories Inc. According to the authors the modularity of an expert's knowledge aid in the maintainability of that knowledge. As a result, separate parts of the system may be more interdependent than is desirable for software engineering reasons. Yet, the system must be modularized in such a way that each phase can be developed independently from the others phases. Thus, dividing the program into several knowledge bases, some corresponding to a recognizable subtask of the expert task, and some providing necessary abstractions, was the solution proposed by the developers to successfully implement the expert system.

In the next generation, computer scientists predict that this programming approach will allow computers users who are not engineers to tailor their own software to perform complicated tasks simply by mixing pre-designed modules. For example, a manager who wanted to retrieve data from a computer, perform calculations on it and draw a graph of the results could link modules called "objects", to perform each of those jobs.

Such an approach has been discussed in using the same methodology for welding technology applications. In an expert system called WASPS (Weld Advisory System for Process Selection) which has been developed by University of Southhampton the modularity concept has been used to design the system (Curtis, et al., 1990(a), 1990(b)). This expert system selects the most appropriate welding process taking into consideration several interdependent parameters. An advisory system for the process choice helps the user selection. According to the author, the knowledge representation and inference engine of the expert system are classic in nature, but the knowledge base is modular to facilitate the addition of further information. In designating the knowledge base in modules, the aim is to be able to extend to further processes and welding situations. According to the authors the objective is to include input modules to enable the user to produce an expert system tailored to his own applications.

2.6 LANGUAGES AND SHELLS

An expert system consists, in its simplest form, of a collection of information and relationships concerning the field of interest (the "knowledge base"), the program which acts on the information to make deductions (the "inference engine") and a user interface to present the questions and conclusions to the user (see figure 2.2). A 'shell' consists essentially of an expert system from which the knowledge base has been removed; it is then available to form new systems by the addition of fresh knowledge. Several such shells are now available commercially.

2.6.1 LISP, PROLOG AND POPLOG

Several languages have been used to represent expert systems. Traditional programming languages have not proved to be well suited to computer applications in Artificial Intelligence in general and expert systems in particular. It is possible to create expert systems in BASIC, PASCAL, COBOL or other procedural languages, but such languages are far from ideal. Problems may arise in representing the real-world knowledge required by many *AI* systems or in providing the flexible exploratory style needed by programmers in a highly unpredictable new area. It is largely the emergence of new programming tools that has stimulated the development of *AI*-related systems (Willoughby, 1987).

Special languages, notably LISP and PROLOG, have been developed to facilitate the programming of *AI* applications. Such tools are often dubbed "descriptive" or "logic programming" languages, though LISP is historically rooted in mainstream computational theory whereas PROLOG derives in part from formal logic (Willoughby, 1987).

LISP is a very powerful and versatile language, so that the programmer is completely free to choose his own methods of knowledge representation, inference and control. The implication of this, however, is that none of the standard features expected of an expert system (e.g. inference mechanisms, fuzzy logic and explanation facilities) are provided, and the programmer must write them himself. LISP is used extensively in the USA for building large scale expert systems.

PROLOG (Programming in LOGIC) was developed in the early 1970s as a method of automating the process of logical deduction. It is more structured but less versatile than LISP. It provides an in-built method of knowledge representation and deduction (in the form of a database and production rules) and works by backward chaining. Facts, semantic nets and rules of the form IF ... THEN ... can be readily implemented. As with LISP, fuzzy logic and explanation facilities must be provided by the user if required.

Many of the original ES were written in an *AI* language LISP. This language is very popular in the US, though PROLOG is favoured in Europe and Japan (Simons, 1985). The hallmark of this language is flexibility and expressiveness. Conventional languages have been used for some of the small ES, but most of the larger ones have been written in Lisp or in Lisp-based languages such as OPS5.

There is a continuing debate between the respective advocates of Lisp and Prolog. The advantages and disadvantages of the two languages are widely agreed (e.g., the simplicity of Prolog and its inefficiency in searching a large knowledge base), and there is a consensus that neither language, taken in isolation, suits everyone. Efforts to integrate the two languages, or to develop dialects superior to either, have proceed on several parallel tracks. However, Poplog, a high level language developed by Sussex University, incorporates the capability of integrating the main *AI* languages including Prolog, POP 11 and LISP, but its use is in practice only restricted to larger computer work-stations (Poplog, 1992).

2.6.2 PROGRAMMING VIA AN EXPERT SYSTEM SHELL

A radically different approach to writing an expert system is the use of a commercial shell i.e. instead of writing the program from first principles. A shell is an expert system which has had the knowledge base removed, and can therefore provide new systems by the insertion of new data. Most current commercial expert systems employ rule based knowledge representation and this can impose severe constraints on some forms of knowledge. Some of the early expert system shells were somewhat limited in this respect, but the rate of development in this area now means that the use of shells is becoming increasingly attractive (Norrish and Strutt, 1988). A growing sector of suppliers are now offering shells intended to run on microcomputers. Again it is worth emphasizing that such shells, often directed at the IBM Personal Computer, have obvious limitations when compared with systems intended for mainframe computers. System shells intended for micro computers include MicroExpert, EMYCIN, KAS, EXPERTEASE, APES, ES/P Advisor, KAB, Expert Edge, Savoir, Crystal, Extran and Expertech (Simons, 1985). Figure 2.6 illustrates the architecture of an ideal expert system shell. The shell is made up of a number of components:

- The knowledge base. The repository of rules that represent the domain-specific knowledge.

- The inference engine. That component which drives the system in the sense of making inferences from the knowledge base.

- The working memory. This is a data area for storing the intermediate or partial results of problem solving.

- Development tools. These are the means for building and testing the knowledge base.

- User interface. This mechanism provide explanation and debugging facilities. This enables the user to ask questions of the system, about how, for instance, the system came to a particular conclusion. In most shells, this form of explanation is more likely to be useful to the model builder as an aid for debugging, rather than to the user. One facility, more helpful to the user is the ability to amplify questions on demand.

Another important feature of a shell is the external function. A complex system will probably need to call external functions in order to do more complex arithmetic, plot graphs, etc. The ability to gain access to external databases will also be important for those shells which do not provide an in-built representation of facts. To facilitate this, the shell should provide an interface to external programs.

Most shells support at least five components mentioned. Some shells support at least one other component, usually in the form of some knowledge acquisition facility. This is a set of facilities which are designed primarily to enable a domain expert to transfer his expertise to the system directly, without the intervention of a knowledge engineer.

A number of advantages result from the use of shells. For instance :

- As the knowledge representation facilities are readily available, highly experienced programmers (ie in Lisp or Prolog) are not required. There is no doubt that, for the majority of companies, the use of commercial shells is the only cost-effective means of preparing expert systems. Furthermore, the time-scale required to prepare a working prototype will be cut from several years to a matter of months (Lucas and Brightmore, 1986).

- The often limited resources can be concentrated on the knowledge elicitation and application aspects of the system.

2.7 TYPICAL APPLICATION OF EXPERT SYSTEMS

Expert systems technology has been used worldwide. Several systems have been designed successfully and many more are under tests and development. Originally this technology only attracted the interest of big companies. With the possibility of representing knowledge of a particular domain, small companies started to recognise the potential of this technology for access to a wider range of expert knowledge or even started to design their own applications. This gave a great boost to expert systems which can be seen by the great number of expert systems now available.

Expert systems have been applied to every area of the human knowledge. Typical applications ranging from medical diagnosis, mineral exploration, military tactics, transport strategies to mechanical engineering have been reported. Some systems such as MYCIN and CADECUS for medical diagnosis, CALLISTO for modelling large manufacturing projects, PROSPECTOR for mineral exploration, COMPASS for electrical failure among others have used different forms of representation, but are successful in their range of specification (Simons, 1985).

2.8 APPLICATIONS IN WELDING TECHNOLOGY

Computers have been applied in welding technology. Computer applications covers a vast range of fields such as design and planning, process selection, process control and welding robots, quality assurance and inspection (Feder, 1988). The aim of applying expert systems has been to encapsulate welding engineers' knowledge for future generations. This could be a very low cost and effective way to quickly spread specialised welding technology knowledge. Welding is related to many different engineering fields of a very wide spectrum. Therefore it may be considered that there are too many factors involved and in addition the relations among these factors are much too complicated (Fukuda, 1988). Expert systems offer the potential to be used in welding technology and interest in expert system development has been spread worldwide, notably in United States, Japan and Europe (Inoue, 1990). At the present time several expert systems have been successfully developed and implemented in the welding industry as shown in table 2.1. Many others are still under development or evaluation stages or have been produced for use within individual companies as summarised in table 2.2. The systems cover a wide subject area including process, consumable and equipment selectors, procedure generators, risk evaluation, equipment/process diagnostics and defect assessment (Barbolak et al., 1991; Agapakis et al., 1988; Norrish and Strutt, 1988; Budgifvars, 1991; Lucas, 1987).

2.8.1 PROCEDURE GENERATORS

The development and maintenance of welding procedures form a major part

Table 2.1 - Commercially available expert systems in welding (Barbolak, 1991).

NAME or DESCRIPTION	TYPE	SOURCE
Weldselector	Electrode Selector	CSM
Weldsymple	Symbol Generator	CSM
Weldcrack Expert	Diagnostic	Stone & Webster Engineering
Welding Procedure Selection Expert System	Procedure Generator	Stone & Webster Engineering
Weld Qualification Test Selection Expert System	Test Selector	Stone & Webster Engineering
Weld Defect Diagnosis Expert System	Diagnostic	Stone & Webster Engineering
Weld Estimating Expert System	Cost Analysis	Stone & Webster Engineering
Miller Expert Program	Diagnostic	Miller Electric

Table 2.2 - General welding expert systems under development (Barbolak, 1991).

NAME or DESCRIPTION	TYPE	SOURCE
Weld-Assist	Procedure Generator and Diagnosis	Kuhne, Cary & Printz
Steam Pipe Expert system	Procedure Generator	Marchwood Engineering Labs
Weld Costing System	Cost Determination	James & Baker
Weld Procedure Selection Program	Procedure Selection	Southampton University
Hot Wire TIG Expert System	Diagnostics	Framatome Heavy Fabricating Facility
Newcs	Real-time Monitoring Diagnostics	General Digital Industries
Camtech 1000 and Adaptitech 1000	Real-time Monitoring Diagnostics	Adaptive Technologies
Weldex	Procedure Generator	Technical University of Berlin
SAW Expert System	Procedure Generator	Queen's University Belfast
Weld Procedure Enquiries	Procedure Generator	NEI- Internal Combustion Limited
Weld Scheduler Expert System	Procedure Generator	Babcock & Wilcox
Expert Robot Welding System	Procedure Generator	Sicard & Levine

of the work load of many welding engineers. Several expert systems have been developed to assist in the task of procedure generation. This type of program usually prompts the operator for information about the joint to be welded, and, using the inference techniques described above, the system produces a suitable procedure.

The knowledge used for the decision is based on experimentally determined data and the accumulated experience of experts which is collated by the system designer.

The development of systems of this type has been reported by several authors (Alberry et al., 1986; Taylor, 1986; Ko et al., 1988; Taylor et al., 1988; Queen, 1990) but many of these systems are designed for specific applications or still undergoing user trials.

An expert system for submerged arc welding (SAW) process that assists in generating welding procedures conforming to BS-4870 for shipbuilding steels was constructed as a feasibility exercise (Taylor et al., 1988). This system was based on a Savoir expert system shell and covered structural steel in the range 5 to 55 mm. The user is expected to input details of the joint (eg. thickness) as well as answers to questions on the consumable (eg, the cleanliness of the wire and the type of flux). Alternative choices and recommendations are presented to the user during the consultation with the computer. The final output in terms of welding current, voltage, travel speed, preheat, and joint preparation is based on the production of the correct bead geometry as well as the avoidance of defects such as hydrogen and solidification cracking.

Alberry et al. (1986) describes the development of a prototype expert systems for the generation of welding procedures for low alloy creep resisting steels. Again this system uses a Savoir shell. Inputs include joint type, position, thickness, material composition etc, and the program offers interactive advice to the user on alternative choices, for example the system will display recommended electrode sizes for a particular run or advise the user if an unusual joint angle is selected.

A welding design/procedure generator called "WELDEX", developed by Technical University of Berlin (Dorn et al., 1988) is divided in modules written in Turbo Prolog. This software package combines the artificial intelligence programming techniques of expert systems and natural language interfaces connected with a database. The end result is a package that advises on correct welding procedure, joint design, welding parameters and welding defects. It is claimed that the capability of handling uncertainty is being added.

A computerised database management system for welding procedure - Weldpool- is described by Queen (1990). The database is used for the construction, repair, maintenance or improvement of offshore structures operated by Shell UK. The system was designed with the objectives of improving total quality of fabricated construction and reducing overall costs from elimination of multiple welding procedure qualification. It is also able to perform failure assessment and remedial activities.

A similar approach has been used by Ko et al. (1988) in designing a database system for welding procedure specification (WPS) and procedure qualification records (PQR). This system was primarily designed to satisfy in-house company requirements and allow great number of welding data to be handled. The same technique has been used for the development of a welding information system for offshore fabrication (Rostadsand et al., 1990). This project uses a computer based system to help a fabrication contractor to effectively establish, update and submit PQR's and WPS's for use by all involved parties during fabrication, operation and maintenance in offshore projects. Several benefits from using such system have been reported.

Smith et al. (1990) describes a system for preparation and processing of weld procedures in high integrity pipework fabrication. This system has been under operation and has been reported to be efficient and effective, giving substantial improvements in quality and productivity when compared with manual preparation of welding procedures and weld procedure qualification records. Also, an arc welding procedure generator, has been developed by TWI as part of EUREKA project involving several EEC countries (Brightmore, 1990).

The development of integrated welding information systems is a very interesting development of computer technology specially for companies involved in projects with different parties. Fukuda (1988) describes a system being developed in

Japan which would serve every participating companies needs and provide a fundamental framework for similar problems. Several analogous systems using extensive amount of database management to generate welding procedures have been developed or are under test by many industries (Bernasek, 1989; Cantrel et al., 1989; Carter et al., 1990).

An expert system for determining the cost of producing welds by a range of processes in materials of different types, dimensions and preparations was proposed by James et al. (1986). This expert system was constructed to show that knowledge-based systems can be built quickly and at low cost by somebody with no prior knowledge of computers or programming languages on personal computers. An application of this system is being used to produce a demonstration computer knowledge base concerned with design against fracture and to develop a cost effective means of building such a knowledge base (Baker et al., 1988). The system called CAMS4 is also being used to assist the engineer in analysis and materials selections (Willoughby et al., 1988; Willoughby et al., 1990).

2.8.2 PROCESS, CONSUMABLE AND EQUIPMENT SELECTION

Several expert systems have been designed to deal specifically with the problem of selecting the optimum process, consumable or equipment for a given welding application. Process selection may form part of a procedure generator as described above, and will require similar inputs (eg material type, thickness). Process economics may also be introduced to ensure that the recommendations made are cost effective.

Many systems of this type use any expert system approach in conjunction with a large database. An expert system based on this approach and known as 'Weldselector' has been developed by the Colorado School of Mines in the USA for the selection of welding electrodes for particular applications (Texas Instruments, 1987). This forms the base for the development of EUROSEL, an expert system for parent metal and consumable selection as a part of the EUREKA project EU259

(Anderdahl et al., 1990). A similar approach was used in development of CIG-WES (Oldland et al., 1988), which recommends the most appropriate welding consumables, equipment and safety equipment for specific applications in welding. A system for selecting the most suitable robot for given applications (welding and non welding) has been developed at Cranfield Institute of Technology, and a similar commercial system has also been reported (Norrish and Strutt, 1988). Brightmore (1988) describes some expert systems that have been developed at The Welding Institute using inductive process. Such systems can create decision trees and enquiry systems based on examples. Once the inputs had been defined, the examples were entered to relate the attributes to the outcome (choice of process).

Tonkay (1987) describes an expert system for the selection of welding parameters for gas metal arc welding. His main research was centred on developing a methodology to aid welding engineers in the generation of a welding schedule for the GMAW process. Validation of the system allowed him to conclude that the expert system equalled or outperformed the average expert who contributed knowledge to the system. The system was inplemmented in LISP and Tonkay affirms that the use of a hierarchical frame structure, where each task was broken down into its elemental sub-tasks, was a good implementation choice for the type of expert system developed.

Fukuda (1988) describes an expert system called WELDA, a welding advisor prototype for the selection of cutting, bending, and welding methods. The system was developed using OPS83 and it processes not only symbolics but also numerics. As the production of a welding procedure specification is a task of design in nature, the use of expert systems approach with special attention paid to the problem of coupling symbolics with numerics and data bases has been reported to be very effective. A methodology that combines the power of decision-making capability of expert systems with the power of data bases and conventional software has been the base of PROWELD design (Seidel et al., 1990). This expert system is aimed at defining strategies to increase the productivity of arc welding processes and the quality of welded products. According to the authors, results obtained so far have shown significant productivity improvement of arc welding operations in the local industry.

Other works involving one or other of the approaches described above have been mentioned in further publications (Triouleyre, 1986).

2.8.3 EQUIPMENT/ PROCESS DIAGNOSTICS

Expert systems have been developed for the diagnosis of problems in the performance of welding process and equipment. Although conventional logic may be used to identify the failure of a component, it is often found that this type of diagnostic only indicates the symptom and not the cause of the problem, and an engineer would need to call on his experience of the process to know where to look for more 'clues', and to assess the cause of the problem based on the information collected.

Framatome in France has applied this approach to design an expert system for hot wire TIG (Bonnieres et al., 1986; Boutes et al., 1987). The expert system is provided with a description of the welding system which includes the likely malfunctions and the observable symptoms associated with the malfunction. A more general system for use on microcomputers and written in Prolog has now been made available commercially by Framatec and this is known as Maintex.

The development stages of an expert system called the Naval Expert Welding Control System (NEWCS) is described by Reeves et al. (1988). The expert system approach is used as a means of providing intelligence for process control during the execution, or in-process phase of welding with particular emphasis on small-batch arc weld operations of the naval shipyard environment. This methodology would conduct the weld in the same fashion as the human operator, but with enhanced reliability and performance and thus increasing confidence in the overall operation.

Hobart Bros, together with Carnegie Mellon University have developed a program called Weld-Assist (Kuhne et al., 1987), designed to help operators with limited welding experience to select and improve welding parameters for a given application. The system incorporates modules to provide the initial recommendation for welding parameters, advise the user how to deal with defects and discontinuities and assist the operator to improve bead geometry and operating conditions. An expanded version of Weld-Assist program allows direct interfacing to a welding robot (Kuhne et al., 1988). All expert system recommendations regarding the welding data (voltage, current and travel speed) are directly fed to the power source, the wire feeder, and the robot.

Steffens et al. (1988) applied the fault diagnosis method for the development of expert systems in thermal spraying units. The use of intelligent diagnostic devices is intended to increase the economic application of the system in reducing faults and breakdowns.

The use of expert systems in a more advanced stage involving robotisation have expanded (Inoue, 1990). Using robotized welding to its full advantage requires the continuous adjustment of welding parameters to suit the actual welded joint configuration (Prunele et al., 1986). It is reported that a system which uses the Texas Instruments Personal Consultant Plus shell has been used successfully for robot applications (Norrish and Strutt, 1988). Similar procedures were used in the development of WELCAS, an expert system for the selection of welding parameters of multi-layer weld of thicker plates in order to assist welding engineers and/or welding robot operators in decision making (Matsui et al., 1990). Also, some new steps in the robotisation of MIG-MAG welding procedure through the use of expert systems is described by Abernake et al. (1988). Lusth et al. (1988) has showed that it seems feasible to control welding robot via an expert system despite some problems observed in development of a real time expert system for controlling a gas tungsten arc welding process for butt welding thin metal plates. The system was developed in LISP and the approach was to identify weld characteristics that could be measured and used in making real time corrections to the welding process. The expert system was used to analyze the incoming data and generate appropriate commands to change weld parameters before sending the information to a robot unit.

These expert systems rely on input of information on the performance of the welding machine or process by an operator, but there is obviously scope for direct link between sensors on the welding package and the computer. Some move in this direction has been made by the introduction of purpose designed process monitoring packages and recent work on statistical process control. The exciting prospect in this area is the ability to diagnose and correct process problems before they cause serious quality deterioration.

2.8.4 DEFECT ANALYSIS AND RISK EVALUATION.

An alternative approach to the application of expert systems is their use in the evaluation of risk associated with a proposed welding procedure. In this approach the main objective is to detect the presence of welding defects in a welding procedure or evaluate the influence of defect occurrence on the overall performance of a welding structure.

A system on this line has been developed by Haut Commissariat a la Recherche CDTA, Algeria (Smati et al.,1988). It uses the LISP language and runs on a microcomputer. The welding processes covered are MIG, TIG and MMA and the defects considered are porosity, lack of fusion, lack of penetration, slag inclusions, undercut and tungsten inclusions. The user is asked to input the type of defect found, the process used, materials, heat input, joint type and size and surface condition of the material.

A system developed by The Welding Institute uses a probabilistic reasoning (Bayes rules) to diagnose the presence of welding defects (Perozek et al., 1988). The system assumes at the beginning the same likelihood to all defects. As the user starts to answer questions about the welding conditions, the expert systems start to change the likelihood until a definite result has been found. A similar approach was used in development of SIRACUS, an expert system to assist the operator in determining the nature of indications detected during ultrasonic testing of pressure vessel welds (Bieth et al., 1988). This system uses the concept of certainty factor as reasoning methodology to inference conclusions from the answers provides by the user.

A prototype expert system called WISP (Weld InSPection) is described by Agapakis et al. (1988). The system establish the significance and propose possible causes for a established defect. The system is also connected to a robot using a vision system that can detect surface defects.

The concept of expert systems has also been used for generation of sophisticated non-destructive tests. Edwards (1988) pointed out the main aspects to be considered when developing test procedures according to BS 3923. A similar approach uses the expert system analyses the ultrasonic sensing in order to identify those signals that indicate an acceptable or an unacceptable welding pool penetration (Carlson et al., 1988). In another project, an integrated approach involving expert systems and decision-support criteria was used as an analysis methodology for estimating ultrasonic testing in PVRC as reported by Fong et al. (1986). Expert system applications to NDT examination has also been extended to radiographic inspections. Kato et al. (1990) describes the development of a computer aided radiographic inspection system using an integrated image processing and expert system technique to detect weld defects, this is claimed to have almost all the capabilities of a human inspector.

2.8.5 WELDING DESIGN

Welding design offers a potential area for the application of computers and has becoming a more common practice in the welding industries. Mainframe computers may be necessary to conduct simulations of the welding process or service behaviour of the finished product. Technical knowledge can be established through mathematical modelling with experimental verifications. Microcomputers are adequate for information management and effective use of the information. Computer-aided welding design, expert systems for computer-aided welding manufacturing, and diagnostic computer software for in-process control are all beneficial to a successful welding production. Additionally, management of knowledge and full integration with robot provide a very powerful application towards of a completely automated system. Several applications following this approach has been reported (Kuhne et al., 1988; Tsai et al., 1986; Tsai, 1988; Chandra, 1988). Tsai (1986, 1988) describes iterative procedure implementation and analyses through the integration of computer-aided welding design(CAWD) and analysis(CAWA). The same procedure has been considered by Weyn (1990) in design of an expert system for the 'postweld heat treatment specification' of pressure vessels.

2.9 CAUSES OF DEFECTS AND THEIR PREVENTION

Welding is an important manufacturing process and its effectiveness may be measured by its ability to produce joints of acceptable quality at the lowest possible cost. Unacceptable joint quality may arise from a failure to comply with the specified design or from the incidence of weld defects. These problems are, however, preventable if their causes are understood and the correct operating procedures are followed.

Several important aspects have to be considered to obtain a sound welded structure. General defects in welding, specially weld cracking, are influenced by several interacting factors, including:

- plate chemistry;
- the chemistry of the electrode and the reactions that occur in the welding arc;
- the solubility of hydrogen in the weld pool and the rate of diffusion there from;
- the plate thickness and geometry of the joint;
- the temperature of the plate prior to welding (preheat temperature);
- the welding heat input to the plate;
- the cooling rate of the weld and the heat-affected zone;
- the restraint of the joint.

Much research has been carried out in an attempt to appraise these factors and their interrelations as they affect weld cracking. Substantial progress has been made and, today, critical welds can be placed in all types of weldable steels with a reasonable assurance that cracking will not occur under the design stress.

The types of defect which occur in the fabrication of common engineering materials are fairly well established (Lundin, 1984) and the experienced welding engineer will be aware of the techniques required for their avoidance (Atkinson, 1970). Defects can originate by different mechanisms as described in Savage (1966) and Thielsch (1966). Most cracking problems are derived from metallurgical problems, ie, hot cracking, cold cracking, stress corrosion cracking, reheat cracking. Other defects originates from inappropriate welding conditions and includes porosity, lack of fusion, lack of penetration, undercut, etc.

The identification of causes of welding defects associated with the use of probability factors, provides the possibility of determine the likelihood of occurrence of defects and consequently their elimination. Clough (1968) reported that the welding engineer can influence the performance of fabricating firm towards the elimination of defects insisting upon the application of "Zero Defects" principles based on statistical studies.

The risk of Hydrogen Induced Cold Cracking (HICC) is a major concern in the fabrication of ferritic steels. The understanding of the nature of this defect can be an effective way to avoid its occurrence. Efforts have been made to establish appropriate methodologies to control the welding parameters to avoid HICC. Some have proved to be successful when applied to specific conditions, for instance the IIW methodology for carbon manganese steel. Though considerable work has been carried out to understand the phenomenon of HICC, there are still many attributes of the phenomena that are not fully understood (Lundin et al., 1990).

2.10 WELDING ASPECTS INVOLVING THE DETERMINATION OF HICC SUSCEPTIBILITY

The concept of weldability involve many areas and analytical calculation methods have been used in determining the weldability of steels (Hrivnak, 1984). In the last 50 years, HICC has been considered one of the main factors controlling the weldability of steels. Consequently it has received attention from fabricators and researchers and as a result substantial improvements in steel manufacture, consumables and welding techniques have been observed. The main approach has been to attempt to improve the HAZ (heat affected zone) properties with respect to hardenability, and consequently cold cracking. In addition, it has become technically possible to weld steels over a wider range of heat inputs with limited preheat. Recently, however, there have been significant efforts to minimize preheat as a cost reduction measure, and the hydrogen introduced into the weldment via the consumables has become of greater importance.

Cold cracking in the weld metal and HAZ is caused by a combination of susceptible microstructure, hydrogen and stress. Cold cracking does not initiate until the weldment has cooled to below about 204°C and may be characterized by an incubation period that is complete in one or two days after welding (Davidson et al., 1989). Cold cracking commonly occurs in the grain-coarsened region of the HAZ and may also occur in the weld metal, but this is less common in welds in conventional structural steels because of the low carbon contents (Lancaster, 1987).

All of the conditions which affect HICC are naturally correlated with a series of secondary factors such as the carbon equivalent of the material, the cooling rate after welding, the level of restraint, which in turn are dependant on the joint design and the welding parameters. The relationship between these factors and the risk of HICC is illustrated in figure 2.7.

2.10.1 EFFECT OF CHEMICAL COMPOSITION

The chemical composition of a steel, along with the peak temperature attained during welding, and the cooling rate through the austenite transformation temperature range determines the microstructure developed in the HAZ. The carbon content defines the maximum hardness obtained in the HAZ, whereas the carbon and other elements (carbon equivalent) determine the hardenability (Lundin et al., 1990). The HAZ cooling rate is affected by many factors, including plate thickness, joint geometry and position of the weld bead, energy input, efficiency of energy transfer from the arc to the weldment, preheat temperature and extent of preheat. The peak temperature affects grain size and homogeneity of the austenite, which affects the transformations characteristics.

2.10.2 EFFECT OF STRESS

The development of stresses that cause HAZ cracking is complex and difficult to evaluate since stresses will always be present due to transformation in welding. The presence of welding stress depends on the degree of restraint (which is a function of joint geometry, plate thickness and welding sequence), welding procedure, thermal contraction, and metallurgical transformations of both HAZ and weld metal during cooling. It is recognized that welding stress is inter-related with hydrogen presence. This is asserted by the fact that hydrogen is introduced to the HAZ from the weld metal. Since hydrogen is more soluble in austenite than ferrite and the weld metal transforms to ferrite before the HAZ (because of the difference in hardenability), hydrogen in the weld metal migrates to the austenitic HAZ when the weld metal transforms. Thus the last region of the HAZ to transform is already bounded by previously transformed material and a high concentration of hydrogen in a highly stressed condition. Further increases in stress may occur subsequently from fit-up and welding at an adjacent location, from movement of the weldment for repositioning or transit, or as a result of service, which may also initiate cold cracking (Davidson et al., 1989).

Very little can be done to modify the welding stresses as they depend mainly on restraint. However, models have been recently developed to precisely calculate the distribution of local stresses by selection of the design and welding processes (Masubuchi, 1980).

2.10.3 EFFECT OF HYDROGEN

Hydrogen in a weldment exists in combined (molecular) and diffusible (atomic) form. It is the diffusible hydrogen which is responsible for cold crack initiation (Lundin et al., 1990). The main sources for the introduction of hydrogen into a weldment are:

- chemically bonded and absorbed water in the electrode coating and fluxes,
- moisture in shielding gas from GMAW and GTAW welding processes, and atmospheric humidity,
- surface contaminants.

Typical contents of diffusible hydrogen in the weldments may vary from 1 to 40 mL/100gr (Lundin et al., 1990) depending on the type of consumables and fluxes used, their storage conditions and atmospheric humidity. Figure 2.8 shows range of hydrogen contents expected in a weldment when different welding processes are employed.

The content of hydrogen presence in the weldment is directly influenced by the temperature since the hydrogen diffusivity coefficient at high temperature is not followed at lower temperatures as shown in figure 2.9. It has been shown that at temperatures above 150-200°C trapped hydrogen can escape with great ease. Diffusion however becomes progressively more difficult with decrease in temperature.

Diffusible hydrogen content is recognized to play an important role in initiating cold cracking. Work is under way to understand the mechanism of hydrogen distribution as a function of microstructure and stress presence (Lundin et al., 1990).

Additionally, hydrogen content in the weld region can be minimized by allowing hydrogen to diffuse out of the weldment by postheat or by decreasing the cooling rate by means of increased preheat or increased arc energy (Davidson et al., 1989).

2.11 CARBON EQUIVALENT

Carbon equivalent, as developed 50 years ago by Dearden and O'Neill, is generally used as an index to assess the weldability of steels. As described for Bailey (1990), carbon equivalent have been related to hardenability, critical hardness and the risk of cracking of steels during welding. More recently they have been used to rationalise the strength properties, microstructure and cracking tendencies of weld metals. Later formulae have become more complex, involving cooling rate parameters, to allow hardness to be calculated directly (Yurioka, 1990; Meester, 1990). It also facilitates an assessment of resistance to cold cracking in association with the hydrogen content and the stress involved. Several formulae have been proposed and table 2.3 shows some of the carbon equivalents so far proposed and accepted.

Yurioka (1990) suggests that these carbon equivalents can be divided into three groups. Those of Group A are characterized by 1/6 as the coefficient of Mn. This group includes the well known CE(IIW), CE(WES) and CE(Stout II), which have been in worldwide use for decades. These carbon equivalents may assess well the weldability of higher carbon steels of more than 0.18%, or, in the case of welding conditions requiring slow cooling $t_{8/5}$ longer than about 12 secs (Meester, 1990). Group B includes Pcm, CE(Graville) and CE(Düren, 1990). As the coefficient of manganese in this group is 1/16 or 1/20, carbon is regarded as more important than other alloying elements. These of Group B have been proposed lately and they tend to assess well the weldability of modern steels (Yurioka, 1990) with carbon contents of less than approximately 0.22% and, in the case of rapid cooling, $t_{8/5}$ shorter than 6 secs (Meester, 1990). Group C, including CE (Stout I) and CEN, has interaction between carbon and other elements. CEN was proposed to evaluate the weldability of a wide variety of steels. It has been suggested (Yurioka, 1990; Meester, 1990) that in the higher carbon range, the CEN value is close to the CE's of group A, while at low carbon contents it becomes similar to those of Group B since the accommodation factor *A(C)* varies with carbon content.

Table 2.3 - Carbon equivalent to assess weldability (**Yurioka, 1990**).

GROUP	FORMULA
A	$CE_{IIW}=C+\frac{Mn}{6}+\frac{Cu+Ni}{15}+\frac{Cr+Mo+V}{5}$ $CE_{WES}=C+\frac{Mn}{6}+\frac{Si}{24}+\frac{Ni}{40}+\frac{Cr}{5}+\frac{Mo}{4}+\frac{V}{14}$ $CE_{StoutII}=C+\frac{Mn}{6}+\frac{Cu}{40}+\frac{Ni}{20}+\frac{Cr}{10}+\frac{Mo}{10}$
B	$P_{CM}=C+\frac{Mn}{20}+\frac{Si}{30}+\frac{Cu}{20}+\frac{Ni}{60}+\frac{Cr}{20}+\frac{Mo}{15}+\frac{V}{10}+5B$ $CE_{Graville}=C+\frac{Mn}{16}-\frac{Ni}{50}+\frac{Cr}{23}+\frac{Mo}{7}+\frac{Nb}{8}+\frac{V}{9}$ $CE_{Duren}=C+\frac{Mn}{16}+\frac{Si}{25}+\frac{Cu}{16}+\frac{Ni}{60}+\frac{Cr}{20}+\frac{Mo}{40}+\frac{V}{15}$
C	$CE_{StoutI}=1000.C(\frac{Mn}{6}+\frac{Cr+Mo}{10}+\frac{Ni}{20}+\frac{Cu}{40})$ $CE_{N}=C+A(C).(\frac{Mn}{6}+\frac{Si}{24}+\frac{Cu}{15}+\frac{Ni}{20}+\frac{Cr+Mo+Nb+V}{5}+5B)$ where A(C) = 0.75 + 0.25 tanh (20(C-0.12))

2.12 METHODOLOGIES TO ASSESS HICC SUSCEPTIBILITY

In order to assess HICC susceptibility two approaches - Hardness Control and Hydrogen Control - are in common use. In the Hardness Control approach, the hardenability of steels is represented by the CE(IIW) carbon equivalent, whereas in the Hydrogen Control approach the Pcm defines the hardenability.

2.12.1 HARDNESS CONTROL APPROACH

The cold cracking susceptibility of steels can be assessed by determining a proper preheat temperature using a hardness control approach. This approach was based on work conducted on C-Mn steels at The Welding Institute and forms the basis of the requirements in BS:5135 (1984). This model is based on the observation that the occurrence of HAZ cracking is greatly reduced when the maximum HAZ is below a certain critical value. The hardness of the HAZ is controlled by limiting the cooling rate to a certain level below which the critical HAZ hardness is never achieved.

The hardness control method takes into account the combined effect of restraint, chemical composition, plate thickness, arc energy, and hydrogen level to establish an appropriate preheat temperature to avoid cold cracking as described by Coe (1973). The minimum preheat temperature can be determined from a nomogram available in BS 5135 (see figure 2.10). In this approach the carbon equivalent (IIW - table 2.3) is used as a chemical composition characterizing parameter.

Boothby (1982) has observed, however, that the prediction of heat affected zone hydrogen cracking of C-Mn steels using the method in BS 5135 can be subject to error. Based on this, Cottrell (1984) has proposed a new hardness equivalent and weldability equivalent indexes. These indexes take into consideration the effect of elements such as nitrogen and sulphur which are not considered in the carbon equivalent formulae. Cottrell suggests that their use can provide more accurate information on weldability than the currently used carbon equivalent formulae. More recently, the same author proposed an improved prediction method, based on a larger number of CTS test results, for avoiding HAZ hydrogen cracking (Cottrell, 1990), which is claimed to be much safer and more accurate than the current method based on BS 5135.

2.12.2 HYDROGEN CONTROL APPROACH

This model was developed in response to the recognition that cracking did not always occur when the critical hardness was exceeded. Preheated welds tolerated higher hardness than unpreheated, due to the fact that hydrogen can diffuse more easily out of the HAZ.

A welding cracking parameter was first proposed by Ito-Bessyo, after they carried out a series of groove welding experiments for a wide range of low alloy steels. The parameter, Pw, which includes a chemical composition influence parameter, Pcm, diffusible hydrogen content (see table 2.3), HJIS(mL/100g), and intensity of restraint, K(kg/mm^2) was defined by the following equation:

$$P_w = P_{cm} + \frac{H_d}{60} + \frac{R}{40000} \tag{2.5}$$

The critical Pw is related to the time for the weld to cool to 100°C as shown in figure 2.11. The cooling time to 100°C is a measure of the amount of time available for hydrogen to diffuse out of the weldment. The cooling time can be measured experimentally or a preheat temperature related to a given cooling rate can be estimated from empirical formulations or diagrams. It is recognized that if the actual cooling time is greater than the calculated critical cooling time, cold cracking will not be expected to occur.

More recently, Yurioka et al. (1983) proposed an equation that takes into consideration the influence of a stress theoretical concentration factor, Kt, a mean stress acting on the weld metal, σ_w, and a different carbon equivalent, CEN. This formula is defined as below:

$$P_w = CEN + 0.15 log H_{JIS} + 0.30\log(0.017 K_t \sigma_w)^{61} \tag{2.6}$$

Yurioka's carbon equivalent as described below contains an accommodation factor that changes with the carbon content.

Following the same line of research, several other formulas have been reported for the weld cracking parameter, Pw. These formulas differ only in the degree of refinement of the hydrogen diffusion equation and the method of determining the stress in the weld.

Graville (highlighted by Lundin, 1990) proposed a more generalized approach by assuming that cracking occurred only if a critical hydrogen level remained in the weld after it had cooled to 50°C. The amount of hydrogen diffusing out was represented by a diffusion parameter βt, according to the equation:

$$\beta_t = 12P_{cm} + \log H_{IIW} + constant \tag{2.7}$$

where Pcm is Ito-Bessyo carbon equivalent, H_{IIW} is the hydrogen content in mL/100g of deposited metal and the constant term depends on the restraint level. The minimum preheat temperature required to avoid cold cracking is obtained from standard tables giving values of preheat temperature for various thicknesses, restraint levels and susceptibility indexes (AWS D1.1, 1988).

There have been discussion about the suitability of the two approaches described before. Graville (highlighted in AWS D1.1, 1988) observed that hardness control is most appropriate for carbon steels since these steels have a steep hardening curve allowing a precise determination of critical cooling rate. However, the hydrogen control method is more suitable for lower carbon steels with significant alloy and microalloy element present. These steels have flatter hardening curves and thus reducing the cooling rate has less of an effect on the hardness.

To assist in deciding which method is appropriate, Graville proposed a diagram divided in particular zones on the basis of carbon and carbon equivalent as shown in figure 2.12. According to this work, hydrogen control method is more appropriate to determine preheat for steels in zone I and III, while zone II is better assessed by hardness control approach.

Both the hardness and hydrogen control approaches take into account all three parameters, namely chemistry, diffusible hydrogen content, and stress, to estimate the preheat temperature for crack-free welding. However, the degree of emphasis placed on different parameters is not the same. For example, in the hydrogen control approach greater emphasis is placed on hydrogen diffusion and restraint, while in the hardness control approach these two factors are not significantly represented and greater attention is paid to the microstructural factor by defining a critical HAZ hardness above which HICC can occur.

2.13 HARDNESS OF THE HEAT AFFECTED ZONE

Measuring the hardness in the heat affected zone of welds is often considered to be a convenient means of obtaining information relative to the weldability of structural steels. The hardness of a steel after cooling depends upon its chemical composition and its microstructure at the time of decomposition of the austenite during cooling and the cooling rate. In order to predict accurately the hardness in the HAZ it is also necessary to take into account the microstructure change influenced by welding thermal cycles, the imposed cooling rates and also any reheating due to subsequent welding passes or post-weld heat treatment. The maximum underbead hardness occur at the vicinity of fusion line because at that location the cooling rate is fastest, the maximum temperature reached is highest and times at high temperature are longest (Meester, 1990). In consequence grain coarsening and more complete solution and diffusion of carbides may occur, increasing the hardenability of the microstructure (Cochrane, 1990; Meester, 1990).

It is now generally recognized that it is not possible to predict with sufficient accuracy the maximum underbead hardness, even for simple bead-on-plate test specimens, by only taking into account the chemical composition of the base material expressed in a single carbon equivalent formula. The relative effect of individual alloying and residual elements on the maximum underbead hardness is greatly influenced by the cooling rate, usually characterized by the cooling time between 800°C and 500°C (Meester, 1990).

Several equations have been formulated for predicting hardness in the HAZ. The most recent formulae proposed for predicting the maximum underbead hardness in bead-on-plate test specimens under various welding conditions can be found in table 2.4. Even though these neglect a number of possible factors of influence, other than the chemical composition and cooling rate, it appears under normal welding conditions they give reliable predictions provided they are applied within the validity range for which they were originally derived, as described by Meester (1990).

Among the formulae proposed and described in table 2.4, Boothby (1982) presents a method to predict the level of HAZ hardness in steel weldments based on

Table 2.4 - Formulae for hardness prediction (Tecco, 1992).

Reference	Equation %	
Dearden, O'Neill	$H_v=1200.(C+\frac{P}{2}+\frac{Cr}{5}+\frac{Mn}{6}+\frac{Mo}{4}+\frac{Ni}{15}+\frac{Cu}{13}+\frac{Co}{150})-200$	a
Edson	$\log(Hv_{10})=1.957+1.141.C+0.193.Mn+0.086.Ni+0.160Cr+0.363Mo+0.180V+0.030Cu$ Note: SMAW, 2.3Kj/mm, 12.7mm thick plate	b
Kihara, Suzuki	$Hv_{max}=666.(C+\frac{Si}{24}+\frac{Mn}{6}+\frac{Ni}{40}+\frac{Cr}{5}+\frac{Mo}{4})+40$	c
Ito Nakanishi	$Hv_{max}=1450.Ceq$ at 1.7Kj/mm $Hv_{max}=1250.Ceq$ at 3.5Kj/mm $Hv_{max}=783.Ceq+58$ at 4.5Kj/mm $Ceq=C+\frac{Si}{30}+\frac{Mn}{20}+\frac{Cu}{20}+\frac{Ni}{60}+\frac{Cr}{20}+\frac{Mo}{15}+\frac{V}{10}+5.B$ Note: Plate thickness not specified.	d
Beckert, Holz	$(Hv_{max}-Hv_{min}).\exp[-(b.t_A)^2]+Hv_{min}$ $Hv_{max}=939.C+284$ $Hv_{min}=167(C+\frac{Si}{11}+\frac{Mn}{2.9}+\frac{Cu}{3.9}+\frac{Ni}{17}+\frac{Cr}{3.2}+\frac{Mo}{3.4})^{2.42}+137$ t_A = cooling time from 850 to 500°C (s)	e
Seyffarth and Frank	$Hv_{30}=323.6-114.6\ln(t_A)+11.33.(\ln(t_A))^2+123.7\ln(t_A).Ceq-15.58(\ln(t_A))^2Ceq-1299.C-79.11.Si-120.7Mn-539Cr+79.22Ni+2830Cr.C+620.8Ceq+875.4.Pc$ $Ceq_I=C+\frac{Si}{24}+\frac{Mn}{6}+\frac{Cr}{5}+\frac{Ni}{40}+\frac{Mo}{4}+\frac{V}{14}$ $P_c=C+\frac{Si}{30}+\frac{Mn}{20}+\frac{Cr}{20}+\frac{Ni}{60}+\frac{Mo}{15}+\frac{V}{10}+\frac{Cu}{20}+\frac{B}{0.2}$ t_A = cooling time from 850 to 500°C (s)	f
Satoh, Terasaki	$H_v=812.C+293$ for $\sigma<t_M100$ $H_v=(992.C+230.C_{eq}+250).\exp[-3\sigma/(310)C_{eq}]+188.C_{eq}+80$ for $\sigma>t_M100$ $C_{eq}=C+\frac{Mn}{3}+\frac{Cu}{5}+\frac{Ni}{8}+\frac{Cr}{12}+\frac{Mo}{2}$ σ = cooling time from 850 to 500°C (s) t_M100 = cooling time from 850 to 500°C for 100% martensite fraction (s)	g
Yurioka et al	$H_v=406.C+164.Ceq_I+183-(369C-149Ceq_I+100).\arctan\frac{(\log\sigma-2.822.Ceq_{II}+0.262)}{(0.526-0.195.Ceq_I)}$ $Ceq_I=C+\frac{Si}{24}+\frac{Mn}{6}+\frac{Cu}{15}+\frac{Ni}{40}+\frac{Cr}{5}+\frac{Mo}{4}+\frac{(Nb+V)}{5}+10.B$ $Ceq_{II}=C-\frac{Si}{30}+\frac{Mn}{5}+\frac{Cu}{5}+\frac{Ni}{20}+\frac{Cr}{4}+\frac{Mo}{6}+10.B$ σ = cooling time from 850 to 500°C (s)	h
Lorenz, Duren	$H_{V10(M)}=802.C+305$ $H_{V10(B)}=350.Ceq_B+101$ $H_{v10}(x)=2019.[C(1-0.5\log\sigma)+0.3(\frac{Si}{11}+\frac{Mn}{8}+\frac{Cu}{9}+\frac{Cr}{5}+\frac{Ni}{17}+\frac{Mo}{6}+\frac{V}{3})]+66.(1-0.8\log\sigma).$ $H_{v10}=802C-452C.A+350.C.Ceq_B+305.(1-0.67.A)$ $Ceq_B=C+\frac{Si}{11}+\frac{Mn}{8}+\frac{Cu}{9}+\frac{Cr}{5}+\frac{Ni}{17}+\frac{Mo}{6}+\frac{V}{3}$ $A=\frac{H_{V10(M)}-H_{V10(X)}}{H_{V10(M)}-H_{V10(B)}}=\frac{(100-\%Mart.)}{100}$ σ = cooling time from 850 to 500°C (s)	i
Boothby	$325H_V:1/\sqrt{R}=2.05.(C_{eq}+0.045)-0.57$ $350H_V:1/\sqrt{R}=2.01.(C_{eq}+0.045)-0.59$ $375H_V:1/\sqrt{R}=1.97.(C_{eq}+0.045)-0.61$ $400H_V:1/\sqrt{R}=1.93.(C_{eq}+0.045)-0.63$ $450H_V:1/\sqrt{R}=1.72.(C_{eq}+0.045)-0.61$ $C_{eq}=C+\frac{Mn+Si}{6}+\frac{Cr+Mo+V}{5}+\frac{Ni+Cu}{15}$ $1/\sqrt{R}=[\frac{6.2.c}{[t(1+0.001t)(0.335c+1.06)]}+0.044]+[\frac{1}{[t(1+0.001t)(0.335c+1.06)]}-0.00001]e$ R = cooling rate at 300°(°C/s) c = combined thickness (mm) t = 300-Preheat Temperature (°C) e = Heat Input (J/mm)	j
Cottrell	$H_V=80+800(C+3.N+0.29).\exp-[0.25.r^{1.5.Ceq}+Ni/(Mn^2)]^{-1}$ $Ceq=C+\frac{Mn}{6}+\frac{Cr}{5}+\frac{Mo}{5}+\frac{V}{3}+\frac{Nb}{(4.C)}+\frac{0.0001}{S}$ r = $0.0264.(t-t_0)^2(\mu.HI)$=cooling rate at 620°C (s) μ = heat transfer efficiency factor (%) HI = heat input (Kj/mm) t_0 = preheat temperature (°C) t = temperature, equal to 620 in the present case (°C)	k

Composition limits(%):

a). C<0.6; Mn<1.6; Mo<0.6; Cr<1.0, Ni<3.3; 0.5<Cu<1.0; V<0.14; 0.10<P<0.15; Co<2.3 b). C<0.5; Mn<1.75; Mo<0.4; Cr<1.25; Ni<3.75; Cu<2.0; Al<0.05; V<0.30; Si<0.40 c.) not specified d.) not specified e.) not specified f.) 0.07<C<0.18; 0.21<Si<1.08; 0.33<Mn<1.91; 0.02<Cr<1.45; 0.01<Ni<1.01; Mo<0.43; V<0.20; 0.02<Cu<0.58; B<0.007; Ti<0.060; 005<Al<0.19; Nb<0.11; 0.0001<N_2<0.026 g.) not specified h.)0.018<C<0.254; 0.68<Mn<1.89; 0.04<Si<0.45; Cr<0.85; Cu<0.23; Ni<0.81; Nb<0.052; V<0.068; 0.010<P<0.025; 0.002<S<0.012; B<18ppm; Mo<0.47; Ti<0.018 i). 0.02<C<0.55; 0.45<Mn<2.11; 0.03<Si<0.75; Cr<0.33; Ni<3.50; Cu<0.60; Nb<0.10; V<0.12; Mo<0.50 j.) not specified k.) 0.06<C<0.23; 1.01<Mn<2.00; Mo<0.54; Si<0.55; Cr<0.20; Cu<0.30; Nb<0.05; V<0.15; 0.002<S<0.043; 0.003<N<0.010; Ni<0.89.

The Welding Institute methodology for predicting welding procedures to avoid HAZ hydrogen cracking. Boothby's equation takes into consideration the effect of the cooling rate at 300°C, preheat, arc energy and combined thickness on the hardness level. Meanwhile this equations may need a correction because in many cases the transformation of C-Mn and low alloy steels is greater than 300°C, the temperature at which the cooling rate is given.

Dearden and O'Neill (highlighted by Düren, 1990) also offered an equation for calculating the hardness value, although this only applies to fillet welds. For a welding condition such that the cooling time (t8/5) can be kept at 12s the maximum hardness in the HAZ can be established by the equation:

$$HV_{\max}=1200CE_{IIW}-200 \tag{2.8}$$

By linking the C-equivalent to the microstructural constitution and the t8/5 cooling time, the following equation proposed by Düren (1990) could be used:

$$HV=2019[C(1-0.5logt_{8/5})+0.3(CE_{B}-C)]+66[(1-0.8logt_{8/5})] \tag{2.9}$$

where,

$$CE_{\beta}=C+\frac{Si}{11}+\frac{Mn}{8}+\frac{Cu}{9}+\frac{Cr}{5}+\frac{Ni}{17}+\frac{Mo}{6}+\frac{V}{3}$$

The Düren formulation was suggested for practical applications involving short cooling time ranges. This also covers the validity range of the formula proposed by Ito and Bessyo. After several different tests, Düren (1990) suggested that where longer cooling times are involved, the IIW formula could provide a good approximation to the real hardness in the HAZ.

Suzuki (1985) proposed a new formula represented by the following equations:

$$HV=H_{\infty}+\frac{K}{[(1+\exp(\alpha(\log t_{8/5}-Y_{5}))]} \tag{2.10}$$

where :

H_∞=884C+287-K ; K=237+1633C-1157P_{CM} and αK=566+5532C-2880P_{CM} .

These formulae were tested by Suzuki for 70 steels with chemical composition in the following ranges: C<0.33; 0.48<Mn<2.06; Si<0.65; Cu<0.47; Cr<1.06; Ni<2.06; Mo<0.66; V<0.07; Nb<0.06; Ti<0.02 and B<0.0020.

Yurioka (1987, 1990) derived the following connecting two characteristic points, the full martensite (Hm,tm) and the nil-martensite (Hb,tb), by smooth arc-tangential curve:

$$HV(aswelded)=\frac{(\mathrm{Hm}+\mathrm{Hb})}{2}-\frac{(\mathrm{Hm}-\mathrm{Hb})\arctan(\mathrm{x})}{2.2} \tag{2.11}$$

where,

$$x(rad)=4\frac{[\log(\tau)-\log(\tau m)]}{[\log(\tau b)-\log(\tau m)]}-2 \tag{2.12}$$

and,

τ, welding cooling time between 800-500°C (s); τm, critical cooling time for full martensite; τb, critical cooling time for null martensite.

The HAZ hardness estimation of Yurioka equation is valid for most of ferritic steels whose compositions are: C≤ 0.8; Si≤1.2; Mn≤2; Cu≤0.9; Ni≤10; Cr≤10; Mo≤2. This formula is far more general than other equations which are valid only for steels with a narrow range of compositions: C≤0.20; Ni≤1 and Cr≤1. They also do not take into consideration the effect of boron and inclusions.

2.14 COMPUTATIONAL METHODS TO ASSESS HICC SUSCEPTIBILITY

On the basis of recent knowledge, some computer programs have been proposed to assess HICC susceptibility (Okada et al., 1986; Bragard et al., 1983). Rodwell (1986) describes a microcomputer program called PREHEAT which gives guidance on the prevention of HICC of carbon and carbon-manganese steels having carbon equivalents within the range 0.32 to 0.60. This program is based on the prediction methods proposed by The Welding Institute and adopted by BS 5135. A similar program following the same procedure was developed by Garrido (1988). On the same line of reasoning, Bragard (1983) developed a model to take into account the influence of main welding parameters under cooling at 100°C. A computer program based on this model, determines the necessary conditions for welding without hydrogen cracking.

2.15 COMPUTER PREDICTION OF HAZ BEHAVIOUR

Some computational methods for determination of HAZ properties have been recently described in the literature(Thier, 1990; Buchmayr, 1990). These methods usually involve the determination of microstructural development during welding using metallurgical principles. Many incorporate finite-element methods (FEM) to establish a mathematical model of heat transfer in arc welding. Chuasong (1991) describes a model based on FEM analysis to determine the cooling time (t8/5) of the metal adjacent to the weld junction. Based on this technique, a quantitative relationship between the welding process parameters, the value of t8/5, the microstructures and the properties of a welded joint can be established. Buchmayr (1990) used a similar technique to model microstructural changes during welding of HSLA steels. More recently, Palotas et al. (1990) have extended the use of FEM analysis to improve the efficiency of arc-welding robots.

CHAPTER 3

METHODOLOGY AND PROGRAM INTRODUCTION

3.1 GENERAL ASPECTS

This chapter describes the approach developed here for defect analysis in a welding procedure specification at the design stage and forms the basis for a computational approach in transferring the knowledge base into an expert system environment. Some consideration of the extension of the methodology to the evaluation of welding procedure for HSLA steels is discussed.

Knowledge elicitation is a crucial step in the development of expert systems and some aspects of the techniques used are outlined. A methodology for obtaining the knowledge involved in the assessment of the risk of defects is delineated.

Consideration of the techniques that can guide expert systems in their reasoning processes when uncertainty is an inescapable facet of the problem is discussed and a methodology based on the MYCIN system was adopted as a mechanism of knowledge representation.

As a feasibility study, the knowledge base extracted for this project concentrated on Hydrogen Induced Cold Cracking evaluation. In the future, the same methodology could be extended to other defects.

3.2 KNOWLEDGE ELICITATION CONSIDERATIONS

Knowledge elicitation is the process by which facts, rules, patterns, heuristics, and operations used by humans to solve problems, in the particular domains are elicited.

Besides humans, knowledge may be elicited from several sources including books, journals, reports, manuals, databases and case studies. Knowledge elicitation is a critical first step in the construction of expert systems, since the time required by this phase affects the cost-effective development of the application. The performance of the expert systems in terms of the systems reliability, validity and utility also depends on the reliability, validity and accuracy of the elicited knowledge. Knowledge elicitation often poses a significant bottleneck to the process of building expert systems.

3.2.1 IMPORTANT ISSUES IN KNOWLEDGE EXTRACTION

A concise and formal statement of the problem of knowledge elicitation precludes the possibility of making explicit the many diverse but interacting factors that contribute to it. To this effect, the statement of the problem is preceded by an examination of issues identified as important to this problem. These include the identification what knowledge should be elicited. **Garg-Janardan et al. (1988)** has identified two kinds of knowledge which are referred to as; process and content. Process knowledge is defined as the strategies and procedures used in problem solving. Content knowledge represents the actual facts and rules used by the human in solving problems. These two kinds of knowledge cannot, however be divided into mutually exclusive classes. Process knowledge includes the methods by which a subset of the content knowledge is accessed, combined and used to solve problems. Combinations of content and process knowledge and heuristics may be used successfully so often that they become automated and stored as chunks by the human expert.

In the context of knowledge extraction, it may be impossible for the knowledge engineer to assert that only one type of either process or content knowledge will be elicited.

The kind of knowledge that is of primary interest may vary from domain to domain. Elicitation of content knowledge may be the chief concern in analysis situations; whereas in synthesis applications elicitation of both process and content knowledge may be equally important. Analysis problems arise when all possible solutions can be enumerated ahead of time. Synthesis problems are those where unique solutions may be built from components of inputs. In synthesis problems it is not possible to enumerate all possible solutions, at the very outset.

3.2.2 METHODOLOGY TO INTEGRATE THE KNOWLEDGE-BASE USING A THEORY OF PROBLEM SOLVING

Most of the theory in this area originates from the natural observation of the behaviour or the methodology used by the humans to coordinate the ideas and to integrate all of the knowledge in a format that can easily be used in problem solving. In such attempts several researchers have concentrated their efforts on generation of a general format for elicited knowledge. Kelly's (highlighted by Garg-Janardan, 1988) theory of a personal constructs indicates that each individual seeks to predict and control events by forming theories, testing hypothesis and weighting evidence. He believes that people think in terms of constructs, it is inferred that people can perceive similarities and differences. It is asserted that they can perceive similarities and differences only because they associate characteristics at certain values with given states, events and situations. Individuals anticipate a set of intermediate states and find outcomes based on the characteristics which they perceive in a given initial situation, event or state. The choice of action or operation to be performed on the given state (call it state 1) is determined by the element in the set of anticipated outcomes that the individual wants to reach. This outcome (call it outcome 1) becomes a state (state 2) and the individual performs another action or operation to reach outcome 2, which is state 3. The only distinction between state 2 and outcome 2 (which is state 3) is that the values of certain characteristics are different. This continues until the desired final state or final outcome is reached.

In essence, it is asserted that an individual's definition perception and interpretation of a state is determined largely by the characteristics (and values of the characteristics) which the individual associates with the state. Thus knowledge that should be elicited from the individual includes characteristics of components, range of values of these characteristics, intercorrelations between the characteristics (values), sets of characteristics that may or may not occur together (and the constraining factors), states of the system, the set of predicted outcomes and the actions that allow realization of a desired outcome, given a particular state should be detailed in a problem solving knowledge.

This methodology is currently being developed and validated. Personal constructs theory was first applied by Kelly (1955) to elicit the client's perception of individuals who played an important part in his life. Since then the theory has been applied to many applications from helping determine the causes for strained employer employee relations to knowledge extraction for building expert systems (Garg-Janardan, 1988).

Figure 3.1 shows the framework that provides guidelines regarding the knowledge to be elicited and the sequence and format that should be used in knowledge elicitation.

3.2.3 KNOWLEDGE ELICITATION

The methodology adopted here was that used by Kelly based on personal constructs theory. Basically all the factors that affect the specific domain were targeted. The methodology used may be detailed as follow:

- Initially the different domains to be targeted were identified;

- Establish for each domain the space problem correlated. Identified one problem space, an outcome to be reached have to be defined. This outcome becomes a new problem space that demands a new outcome to be reached. All of this procedure will be repeated until the final outcome is reached;

- The invariant parts of each problem space and its characteristics were established;

- Finally, an integration of all of problem spaces and domain problems were completed.

In every phase above a set of actions and operations must be defined in an attempt to find all the limits that can influence that particular domain. These actions were performed in terms of input interactions, characteristics and values for the particular domain mentioned, the objective and outcome to be reached, the relation of this space with other problem spaces. Using the knowledge elicitation specified, a set of rules (if ... then) that represent the specific domain were generated together with the predicted set of actions. Finally one specific action or actions that will be effectively taken in this case will close the elicitation in each space.

After establishing the knowledge base involved, the domain problem can be easily represented. Many advantages will be generated with this kind of assumption. All the information generated can be checked and changed all the time. On the other hand this elicitation allow us to find a better way to transfer the knowledge into the computer, because all of the knowledge has been characterized together with the set of actions to be taken.

3.3 HYDROGEN INDUCED COLD CRACKING KNOWLEDGE ELICITATION

The risk of Hydrogen Induced Cold Cracking (HICC) is a major concern in the fabrication of ferritic steels. It is known that HICC is likely under the combined influence of susceptible microstructure, hydrogen presence and high stress. Cold cracking does not initiate until the weldment has cooled to below about 204°C. As described before (**sections 2.12.1 and 2.12.2**) efforts have been made to develop methodologies to avoid the occurrence of this defect and these fall into two groups, ie. hardness and hydrogen control approach.

All of conditions which affect HICC are naturally correlated with a series of secondary factors such as the carbon equivalent of the material, the cooling rate after welding, the level of restraint, these in turn are dependant on the joint design and the welding parameters. The relationship between these factors and the risk of HICC has been identified and can be seen in **figure 2.7**.

Joynson **(1986)** using information extracted from interviews, books and reports has identified the main parameters influencing HICC. The information was organised in a series of reports that fulfil the main areas involved with HICC problem and the knowledge gathered has been basically used and further extended in this project. The main sub-domain problems were identified and set of initial states, intermediate states, tasks and type of conclusions or results from the central issue were defined. Additionally a predicted set of actions was delineated, based on the knowledge established. Confidence factors were also derived from the information. Parts of the knowledge base involved is enclosed in **appendix A**.

From the conditions established, four sub-domains were considered:

Sub-domain 1: Susceptible microstructure;

Sub-domain 2: Hydrogen presence;

Sub-domain 3: Critical temperature;

Sub-domain 4: Weld stress.

The parameters influencing each particular sub-domain have been identified and can be seen in **figures 3.2-3.5. Figure 3.6** shows the relation between factors influencing HICC, and established links with extrinsic factors, ie. involving base material, weld process and joint design specification. The complexity of specifying a procedure which effectively minimises the risk of just this one defect is apparent from this analysis and gives some indication of the magnitude of the welding engineer's task.

3.4 APPROACH USED IN HYDROGEN INDUCED COLD CRACKING ANALYSIS

Wherever it is possible, appropriate quantitative and qualitative methods should be used to analyse the elicited data, so that any implicit relations, trends and patterns in the elicited knowledge are made explicit (Garg-Janardan, 1988). To analyse HICC in a structured way a series of aspects involving thermal evaluation, hydrogen and welding stress need to be addressed.

Welding affects the microstructure of the base metal adjacent to the weld deposit and thus the heat affected zone (HAZ) has different properties than that of the weld deposit and base metal. In the HAZ itself there is also a point-to-point variation in microstructure and hence properties.

It is well known that the presence of hydrogen in steels is a prime contributor to cracking and structural failure. Electrode coating, fluxes, local contaminants (such as oil, paint, rust) can often introduce moisture directly to the joint area. Since preheating slows down the cooling rate, hydrogen may have enough time to escape from the steel immediately after the austenite transformation. On the other hand, the resulting stresses and the presence of a susceptible microstructure (such as martensite and upper bainite) may cause weld metal or heat affected zone cracking. Preheating may also lower the thermal stresses imposed on the brittle martensite or upper bainite, and the amount of susceptible microstructure which is formed.

In the following sections, some analytical methods which may be used to determine the structure of the HAZ under the influence of the welding conditions will be discussed. Its use combined with the main knowledge previously defined can give a very positive indication of the risk of HICC in a particular welding procedure specification.

3.4.1 APPROACH USED TO EVALUATE THE PREHEAT TEMPERATURE IN C-Mn STEEL WELDING

The Welding Institute (TWI) nomogram has been demonstrated to be a practical and useful approach to assessment of Hydrogen Induced Cold Cracking in C-Mn steels. A series of established graphs obtained from practical tests allows a preheat temperature to be determined which is likely to avoid the risk of cold cracking. **Figure 3.7** shows the principle of a diagnostic tree which covers the weld preheat assessment.

A previous project (**Garrido, 1988**), established the basis for using a trigonometric approach to convert graphical data from TWI nomogram (**figure 2.10**) into a more general mathematical algorithm. This enables an assessment of a safe preheat temperature for the welding of C-Mn steels by using computational methods.

Four carbon equivalent scales, derived from **figure 2.10**, which are chosen in this technique according to the hydrogen potential of the process, are established in **table 3.1**. In order to fit a mathematical model, the carbon equivalent scales were converted in terms of only one scale (scale A) which results in a series of formulas indicated below:

$$CE_A = CE_{IIW} \tag{3.1}$$

$$CE_A = \frac{54\,(CE_B + 0.05)}{56} - 0.05 \tag{3.2}$$

$$CE_A = \frac{51.8(CE_C + 0.07)}{56} - 0.05 \tag{3.3}$$

$$CE_A = \frac{46.1(CE_D + 0.053)}{56} - 0.05 \tag{3.4}$$

Considering the TWI nomogram, trigonometric relationships can be used to correlate the full hydrogen value with the established hydrogen value according to the following relation:

$$h_{value} = \frac{0.032hl_{value}}{(CE_A - 0.21)} \tag{3.5}$$

Working on the right side of TWI nomogram (**figure 2.10**), Garrido (1988) derived a trigonometric equation to associate the relationship between combined thickness (CT), arc energy (HI) and full hydrogen value, and this can be expressed as

$$hl_{value} = \frac{13HI}{\frac{(ct)}{15} + \frac{(ct)^3}{32} + 1.3} + 4 \tag{3.6}$$

Table 3.1 - Carbon equivalent scales

Carbon Equivalent Scale	Hydrogen level (ml/100 gr)
A	$h_{level} > 15$
B	$10 < h_{level} < 15$
C	$5 < h_{level} < 10$
D	$h_{level} < 5$

In **figure 2.10** if h_{values} are placed horizontally and preheat vertically, a line representing preheat temperatures against h_{values} is obtained. The necessary preheat temperature to avoid HICC will be a function of the h_{values} as shown in **table 3.2**.

Table 3.2 - Preheat temperature correlate with h_{values}.

h_{value}	Preheat Temperature
$6.3 \le h_{value} \le 8.4$	$\frac{[(8.4-h_{value})25]}{2.1}+175$
$8.4 \le h_{value} \le 9.8$	$\frac{[(9.8-h_{value})25]}{2.9}+150$
$9.8 \le h_{value} \le 13.3$	$\frac{[(13.3-h_{value})50]}{3.5}+100$
$13.3 \le h_{value} \le 17$	$\frac{(17-h_{value})100}{3.7}$

The calculated preheat temperature can be compared with the preheat temperature used in order to assess the cracking susceptibility. In this case, if the preheat used is higher than that predicted, the welding procedure may be safe. If the opposite occurs cracking susceptibility will increase, ie. as the predicted preheat temperature increase above the level which it is proposed to use.

3.4.2 APPROACH USED FOR THERMAL EVALUATION

The events that occur in the HAZ can be theoretically predicted and several treatments have been proposed. The hardness level, cooling rate, cooling time, peak temperature and microstructure prediction are important in order to trace the thermal characteristics of the HAZ during the welding cycle.

3.4.2.1 HARDNESS AND MICROSTRUCTURE VOLUME DETERMINATION

Of the welding effects determined from the welding parameters, HAZ hardness prediction has been one of the major considerations. The use of a model which can predict with a reasonable margin of confidence the hardness level at the HAZ is an important indication of the joint properties which are likely to be developed during thermal cycle. Some authors have even reported a direct correlation with HICC occurrence. This forms the basis of the Hardness Control approach previously described.

Several models have been proposed and the results generated from them are fairly consistent. Certain models do however seem to give better results especially if used inside a restricted range of validity. Three different models have been considered here. These are Suzuki, Yurioka and Duren equations applied to carbon-manganese steel. The Yurioka model is usually applied to steels with a wider chemical composition range than that used by Suzuki and Duren. This equation was used in the present work when the range validity was outside that of Suzuki and Duren. The predicted hardness generated by these techniques (mean value and standard deviation) provides an idea of the range of variation between the predicted values.

Another important factor to be considered in the HAZ evaluation is the percentage of any particular microstructural constituent generated as a result of the application of specific welding conditions. Yurioka has correlated the hardness prediction with the martensite and bainite fraction. He proposed a formula to estimate the volume proportion of martensite and it is presumed that if the Yurioka formula is applicable to C-Mn steel with a reasonable accuracy, the martensite hardness should also be applicable.

The following formula was employed to estimate the volume (vol%) martensite in the CGHAZ :

$$\text{Vol\% martensite} = 0.5 - 0.455\arctan(x) \qquad (3.6)$$

and

$$x(\text{radian})=\{4[\log(t_{8/5}/t_M)]/[\log(t_B/t_M)]\} - 2$$

where t_M is the cooling time below which 100% martensite is retained; t_B is the cooling time above which no martensite is formed and $t_{8/5}$ is the cooling time between 800-500°C.

3.4.2.2 TEMPERATURE CYCLE IN THE HEAT AFFECTED ZONE

In the majority of fusion welding processes, the workpiece is subjected to severe thermal loads. The quality of the welded joint depends to a great extent on the heat flow, that is, the temperature and the time-temperature distribution during heating and subsequent cooling.

To predict the cooling rate/cooling time from welding parameters attempts have been made to relate it to the effective heat input of the process.

In arc welding the energy input of the process is given by

$$HI=\mu\frac{V.I}{vs} \qquad (3.7)$$

where HI is the arc energy, V is the arc voltage, I is the arc current, v is the welding speed and μ is the thermal efficiency.

The thermal efficiency changes for different arc welding processes and is generally greater than 0.8 and often close to 1.0 (Welding Handbook, 1981).

The metallurgical transformations that take place during a welding process can be understood from figure 2.13. Considering the point located directly outside the fusion line, when the rising temperature reaches Ac1 the pearlite grains in the structure transform to austenite. Around 1200°C particles such as AlN, Nb(C,N), V(C,N) dissolve. The period of time necessary for dissolution is of the order of 0.01s **(Thier, 1990)**. In the absence of these particles grain growth occurs. Having passed the peak temperature the cooling time is so short that reprecipitation of particles is impossible. The periods of time necessary for nucleation and growth of particles is much longer than for their dissolution. So the retransformation of the coarse austenite in the absence of grain refining particles leads to a coarse secondary structure of martensite and bainite. The retransformation is controlled by the cooling rate, and is usually characterized by t8/5, the time between 800°C and 500°C. The influence of cooling time on the retransformation can be quantitatively described by a Continuous-Cooling-Transformation (CCT) diagram. The task of the welding engineer is to control the time t8/5 by a proper choice of welding parameters on the basis of a CCT-diagram for the base material.

3.4.2.3 WELD COOLING RATE

Weld cooling rates (R) are not the easiest thing to determine. Weld cooling rate depends upon various parameters such as initial or preheat temperature (T0), heat input from the welding arc (kJ/mm), the plate thickness (th) and the geometry of the joint (**Blodgett, 1984**). In addition, cooling rates depend upon thermal conductivity and specific heat of the material, which in turn changes continually with changes in temperature as shown below:

$$K=0.1552-1.2553(10^{-4})T+2.497(10^{-8})(T^2)+8.026(10^{-12})(T^3) \tag{3.8}$$

where T is the work temperature (°C); K is the thermal conductivity for steels (cal/s.cm.°C). Above 1400 °C, K is 0.05 (cal/s.cm.°C)

On the other hand, specific heat is given by:

$$C = 0.94487 + 2.7894(10^{-4})T - 1.6885(10^{7})T^{2} - 4.7829(10^{-9})T^{3} + + 1.478(10^{-11})T^{4} - 1.0946(10^{-14})T^{5} \tag{3.9}$$

where T is the work temperature (°C); C is the specific heat (cal/g°C). Above 850 °C, C is 0.16 (cal/g°C)

For a three dimensional heat flow characterized by a plate which is relatively "thick", the cooling rate, R, is defined by (Welding Handbook, 1981)

$$R = \frac{2\pi K(T_c - T_0)^2}{HI} \tag{3.10}$$

where Tc is the particular temperature of interest at which the cooling rate can be determined. In case of this project, a temperature of 550°C was adopted, which is quite satisfactory for most steels.

The cooling rate is a maximum on the weld centerline. However, the cooling rate near the weld fusion boundary is only slightly lower than on the centerline. Accordingly, the cooling rate equation may be considered to apply to the entire weld and immediate heat-affected zone.

For a two dimensional heat flow, characterized by a thin plate, the cooling rate R is defined by

$$R = 2\pi K\rho C\left(\frac{th}{HI}\right)^2 (T_c - T_0)^3 \tag{3.11}$$

The difference between thick and thin plates is in mode of heat transfer. The thick plate equation is used when heat flow is three-dimensional, downward as well as laterally from the weld. The thick plate equation would apply, for example, to small bead-on-plate weld pass deposited on thick material. The thin plate equation would apply to any single pass, full penetration welding. Sometimes, it is not obvious whether the plate is thick or thin because the terms have no absolute meaning. For this reason, it is helpful to define a dimensionless quantity called "the relative plate thickness",

$$t=\sqrt{\frac{\rho C(T_c-T_0)}{HI}} \qquad (3.12)$$

It is established **(Welding Handbook, 1981)** that if t is higher than 0.9, than the plate is considered thick; smaller than 0.6 plate is thin and between 0.6 and 0.9 will depend on the value.

A more specific parameter is the cooling time t8/5. From the solution of Rosenthal's moving heat source theory (**highlighted by Myers et al, 1967**), the three dimensional cooling time between 800°C-500°C is defined as:

$$t_{8/5}=\frac{HI}{2\pi Kth}[\frac{1}{500-T_p}-\frac{1}{800-T_p}] \qquad (3.14)$$

For a two dimensional heat flow the cooling time t8/5 is defined as,

$$t_{8/5}=\frac{HI^2}{4\pi Kth^2}[\frac{1}{(500-T_0)^2}-\frac{1}{(800-T_0)^2}] \qquad (3.15)$$

3.4.2.4 PEAK TEMPERATURE

Predicting or interpreting metallurgical transformations at a point in the solid metal near a weld, requires some knowledge of the maximum or peak temperature reached at a specific location. The distribution of peak temperature in the base metal adjacent to the weld can be predicted by the following expression **(Welding Handbook, 1981)**:

$$T_p=\frac{HI(T_m-T_i)}{4.13\rho C.th.Y(T_m-T_0)+HI}+T_i \qquad (3.16)$$

The peak temperature equation can be used for several purposes including:

- the determination of peak temperatures at specific locations in the heat-affected zone[1];
- estimating the width of the heat-affected zone, and
- indicating the effect of preheat on the width of the heat-affected zone.

One of the simplest and most important conclusions to be obtained from the peak temperature equation, is that the width of the heat-affected zone is directly proportional to the net energy input.

Although the peak temperature equation can be very instructive and useful, it is important to recognize certain restrictions in its application. The most important of these is that the equation is derived for the so-called "thin-plate" condition in which heat conduction takes place along paths which are parallel to the plane of the plate. In fact, this equation only applies to full penetration arc welds which are accomplished with fewer than four passes.

3.5 ASSESSING THE WELDABILITY OF MICRO-ALLOYED STEELS

High-strength low-alloy (HSLA) steels, also referred to as microalloyed steels, can be defined as steels possessing a yield strength of at least 43 kPa/mm^2, achieved by microalloying or special thermomechanical processing or a combination of both. The more common of these steels are of the C-Mn type with additions of Nb and/or V to increase the strength through grain refinement and precipitation hardening. Several steels have been developed which use additions of Ti and B together with controlled rolling and controlled cooling which results in extremely fine grain sizes thus achieving high strength with low carbon content. A careful control of the nitrogen content and the aluminium level is important to the processing of these steels.

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[1] In case of this project, the peak temperature was determined at a distance of 0.5mm from the weld fusion boundary.

HSLA steels have some differences in behaviour compared with plain C-Mn steels when welded. In order to estimate the preheat temperature for crack-free welding, two approaches - Hardness Control and Hydrogen Control - are in common use. In the Hardness Control approach, described in detail in **section 2.12**, the hardenability of steels is represented by CE_{IIW} carbon equivalent, whereas in the Hydrogen Control approach P_{cm} defines the hardenability. Neither method appears to provide a full assessment to the weldability of HSLA. The Hardness Control approach is based on the assumption that if the CGHAZ (Coarse Grain Heat Affected Zone) hardness is kept below a certain critical hardness, the risk of cracking is greatly reduced. Critical hardness is assumed to be independent of carbon equivalent. However, it has been shown that critical hardness decreases with decreasing CE. Therefore, modern steels with low CE's may still show some risk of crack if the Hardness Control approach is used to estimate the preheat temperature. Most HSLA steels however lie outside of the validity limits of the P_{cm}, the characterizing parameter in the Hydrogen Control approach. Moreover, Lundin (**1990**) has reported that in a certain classes of steels, the P_{cm} was inadequate as an indicator of hardenability. Alternative method which is receiving considerable attention is the Critical Stress Control approach. In this technique, a lower critical stress (LCS) is determined experimentally (implant cracking test) as a function of preheat temperature and hydrogen content. To apply the results from the LCS to the actual welding condition, it is necessary to obtain a stress field parameter responsible for crack initiation. Some investigators have successfully determined stress field parameters using theoretical and experimental approaches. If the lower critical stress from the implant cracking test is greater than the stress field parameter, the probability of hydrogen-assisted cracking is greatly reduced. The parameter is still difficult to calculate with a great deal of confidence as it depends on the groove geometry, bead length, yield strength of the material, etc. Lundin (1990) added that the weldability of the steels may be assessed by measuring an index represented by the ratio of the lower critical stress and yield strength. It is assumed if the ratio of LCS and YS is one or greater than one, the steel can be safely welded under the welding conditions chosen and hydrogen levels employed during the implant test.

3.5.1 PREDICTION OF THE LOWER CRITICAL STRESS (LCS).

Several investigators have tried to evolve relationships in order to calculate the lower critical stress from a combination of carbon equivalent, diffusible hydrogen content, maximum HAZ hardness, volume percent martensite in the CGHAZ (Coarse Grained Heat Affected Zone), cooling time from 800 to 500°C, cooling time from the fusion temperature to 100°C, cooling time from 300 to 100°C, and thermal factors. These equations are generally only applicable to the class of steels for which they were developed and thus far no equation of universal applicability has been proposed. Some of these equations are represented below.

(i) ITO's FORMULA

Ito published the following formula for estimating the LCS in high strength steels:

$$LCS\ (kg/mm^2)=-242P_{cm} - 22.5\log[H] + 50\log t_{100} - 3$$

where [H] is the content of diffusible hydrogen in ml/100 g (measured by the JIS method), t_{100} is the cooling time (in sec) from weld peak temperature to 100°C and P_{cm} is the CE formula proposed by Ito and Bessyo (described earlier).

The Ito formula was developed based on the steels with the following chemical composition limits:

C,0.04 to 0.17%; Mn,0.81 to 1.59%; Si,0.24 to 0.42%; Ni,0 to 1%; Cr,0 to 0.48%; Mo,0 to 0.44%; Cu,0 to 0.24%; V,0 to 0.04%; Nb,0 to 0.02%; B,0 to 0.001%.

(ii) INAGAKI's FORMULA

Inagaki proposed the following formula for estimating the LCS in implant cracking tests:

$$LCS(kg/mm^2)=68.9-121P_{cm}-24\log([H]+1)+1.75\Delta t_{800-500}+1.65x10^{-2}\Delta t_{100}$$

The above equation was derived from data obtained from HT 50 and HT 80 steels with P_{cm} in the 0.16 to 0.282 range. The hydrogen content in this case was varied from 1 to 21 ml/100g (JIS) and the cooling time from 800 to 500°C from 5 to 20 sec.

(iii) TERASAKI's FORMULA

Terasaki proposed the following formula for estimating the LCS in implant cracking tests:

For $(H_R)_{100} \geq 2$ ppm

$$LCS(kg/mm^2) = -20\log(H_R)_{100}) - 0.20H_{max} + 125$$

For $(H_R)_{100} < 2$ ppm

$$LCS(kg/mm^2) = -75\log(H_R)_{100}) - 0.20H_{max} + 145$$

where $(H_R)_{100} = H_O \exp[-75(\Sigma D\Delta t)_{100}]$

and $H_0 = 1.26H_F$

where $(H_R)_{100}$ is the retained hydrogen content in ppm at 100°C; H_0 is the hydrogen content in fused metal just after solidification; H_F is the diffusible hydrogen content (measured by JIS method); $(\Sigma D\Delta t)_{100}$ is the thermal factor for hydrogen diffusion, summed from solidification temperature to 100°C on cooling; and H_{max} is the CGHAZ hardness in HV.

Terasaki's equations to estimate the lower critical stress were based on the steels with chemical composition, H_{max} and hydrogen content in the following ranges:

C,0.07 to 0.42%; Mn,0.42 to 1.47%; Si,0.06 to 0.48%; Ni,0.02 to 9.35%; Cr,0.02 to 2.3%; Mo,0.01 to 1.00%; Cu,0 to 0.39%; V,0 to 0.059%; Nb,0 to 0.42%; B,0 to 0.014%; Al,0 to 0.58%.

and, $1.2 \leq [H] \leq 13$ppm

and, $300 \leq H_{max} \leq 500$ HV

3.5.2 APPLICABILITY OF LCS PARAMETER TO HIGH-STRENGTH LOW-ALLOY STEELS

Lundin **(1990)**, measured the capability of the equations described above into two categories of HSLA. The calculated LCS of steels belonging to the lower strength category (HSLA-80-1, HSLA-80-2, HSLA-80M and DQ-80) and the higher strength category (HSLA-100, HSLA-130, HY-130 and DQ-125) were compared with actual LCS. Lundin observed that LCS in the higher steels were generally considerably higher than predicted by the formulas, and this was reflected by the poor correlation factor (R_2=0.34). For the lower strength steels the predicted LCS was closer to the actual value and the correlation factor was higher. Lundin concluded that the calculated and actual LCS values did not show a good linear correlation. As a consequence, the implant cracking data were also analysed for different preheat temperatures of 75°F and 150°F. Under these new welding conditions, a considerable improvement in the predictive accuracy of all the formulas was noticed. After comparing the results, Ludin judged that the best conditions that could represent the actual LCS for the set of steels used, can be summarised by the following linear regressions equation:

(i). For the steels HSLA-80-1, HSLA-80-2, HSLA-80M and DQ-80

a. 75°F

$$\mathrm{LCS(act)}=52.29 + 0.68\,\mathrm{LCS(cal\text{-}Ito)} \qquad R^2=0.832$$

b. 150°F

$$\mathrm{LCS(act)}=53.46 + 0.56\,\mathrm{LCS(cal\text{-}Inagaki)} \qquad R^2=0.809$$

(ii). For the steels HSLA-100 and HSLA-130

a. 75°F

$$\mathrm{LCS(act)}=-40.68 + 2.45\,\mathrm{LCS(cal\text{-}Terasaki)} \qquad R^2=0.805$$

b. 150°F

$$\mathrm{LCS(act)}=67.70 + 0.65\,\mathrm{LCS(cal\text{-}Terasaki)} \qquad R^2=0.960$$

(iii). For the steel HY-130

a. 75°F - 150°F

$$\mathrm{LCS(act)}=93.62 + 0.67\,\mathrm{LCS(cal\text{-}Ito)} \qquad R^2=0.928$$

(iv). For the steel DQ-125

a. 75°F - 150°F

$LCS(act)=77.13 + 0.64LCS(cal\text{-}Ito) \qquad R^2=0.631$

It is evident from these new relations that the correlation factors were closer to the actual values, and this can lead to a more close accuracy in a predictive LCS factor.

3.6 HICC PREDICTION REASONING UNDER UNCERTAINTY - GENERAL CONSIDERATIONS

Hydrogen induced cold cracking is a major problem in the welding environment. This problem is likely under the combined influence of susceptible microstructure, hydrogen presence and high welding stress. Cracking usually occurs when the temperature falls below 310-100°C. Models have been proposed to predict the occurrence of this problem. Some of these models consider the hydrogen control approach as an indication of HICC susceptibility. Other models consider the hardness control approach. This methodology predicts a safe preheat temperature which is likely to prevent the occurrence of the defect, and is derived usually by the combined influence of plate material thickness, hydrogen presence level, joint design and carbon equivalent. The Welding Institute has used a nomogram that takes into consideration the influence of these parameters.

In this work the Hardness Control approach was adopted, since the HICC is strongly influenced by the metallurgical aspects of the welding. It has been observed that the Welding Institute Nomogram based on a hardness control approach has been applied successfully worldwide for HICC cracking prediction of C-Mn steels. Its range of application is sometimes limited in certain aspects, specially when welding materials with low carbon equivalents. On the other hand, many authors have suggested that if HICC is strongly influenced by the metallurgical aspects of the HAZ, the hardness prediction value in this region could be an effective indication of the cold cracking occurrence. Obviously, this factor does not take into consideration the weld stress and hydrogen concentration level present in the welding. If the stress originated into the weldment can be evaluated and if the concentration of hydrogen level could be determined, the information could then be combined and a full assessment of HICC risk can be predicted. lt is recognised that the stress field parameter has a major influence on crack initiation. Some investigators have been successful in determining stress field parameter from theory and experiments. The parameter is still difficult to calculate with a great deal of confidence as it depends on the groove geometry, bead length, yield strength of the material, thickness, heat input, restraint level. The influence of these parameters acting together can however be evaluated using a subjective analysis under the uncertainty evaluation considering the relative influence of any particular parameter. This consideration was adopted in this work and is fully assessed later.

All the information has been combined under a rule approach expert systems environment. Usually the application of expert systems is related to a decision system procedure in order to infer conclusions from hypothesis. Usually several sets of evidence support the same hypothesis, and in this case it is necessary to determine the correct conclusion. Distinct systems have been used in some case for this purpose, for instance, decision tables (Gregory, 1988 and Martinez, 1988). Uncertainty analysis represents an important approach to decision analysis. Since that uncertainty decision model can attribute a degree of importance to each piece of evidence, the combination of the implication of each evidence with the uncertainty value of the evidence can generate a measured degree of confidence. In order to look at these aspects and the way in which uncertainty reasoning can be applied it is necessary to examine the principles of uncertainty analysis in more detail.

3.7 SYSTEMS THAT DEPEND ON REASONING UNDER UNCERTAINTY

Several methodologies have been adopted for uncertainty evaluation. These methodologies are generally based on one of two approaches and use probabilistic or non probabilistic reasoning. Bayes theory and fuzzy logic are examples of probabilistic methods of uncertainty evaluation, and theory of endorsement is an example of a non probabilistic emphasis in knowledge representation.

It is observed, however that probabilistic representation is the most popular technique. Bayes theory, based on conditional probability has been adapted for use in probabilistic representation. It has been reported that this kind of representation is too cumbersome for real problems (**Marcellus, 1989**). This problem gets worse for chains of reasoning that involve successive use of implications in a rule based statement, where individual probabilities could be difficult to establish. For this reason, most expert systems abandon reasoning from conditional probability. Instead most systems implement some approximate reasoning to conditional probability that becomes less rigorous and more useful in terms of knowledge representation. This is the mechanism that was used by MYCIN and which was extended into a more general pattern for EMYCIN, which became the ultimate form of this program.

3.7.1 APPROXIMATE REASONING USED TO REPRESENT UNCERTAINTY

Schemes for approximate reasoning have to handle the probability of some implications to quantify how strongly underlying implications support the conclusion.

Consider a single piece of evidence in an implication represented by the rule:

IF(e) THEN(c)

An effective way of handling this is to attach certainty measures to the evidence and to the implication as a whole. This allows the computation of certainty for the conclusion. Often this technique is used in place of probability.

If we denote certainty by **ct** and probability by **p**; in the simplest case, we can write

certainty of the evidence = ct(e) = cf(e) ≈ p(e)

certainty of the implication = ct(i) = cf(h,e) ≈ p(c/e)

So, the certainty will be roughly equivalent to the probability that the evidence (as a proposition) is true (Bayes Rules approximation).

The normal calculation that can be used to associate certainties with conclusion is

ct(conclusion)= ct(evidence) * ct(implication) (3.17)

To use this approach, we need to be able to evaluate the certainty of the evidence. The evidence is the entire logical expression between the "IF" and the "THEN" in the rule. Except for simple implications, this expression will be made up of atomic pieces of evidence, each with its own certainty, linked by logical operations.

Two different situations arise when combining different types of rules. A logical combination of evidence within a single rule presents quite a significant difference when multiple rules support the same conclusion.

3.7.1.1 REPRESENTATION USED IN LOGICAL COMBINATIONS OF EVIDENCE WITHIN A SINGLE RULE

The simplest logical combination is a conjunction (AND) between two atomic pieces of evidence. The implication we are trying to deal with would look like this:

IF(e1 and e2) THEN(c)

The approximation made in EMYCIN is that the certainty of the evidence is the certainty of the weakest piece of evidence; that is ,

ct (e1 and e2) = min (ct(e1),ct(e2)). (3.18)

Notice that this is quite a conservative approximation, but it seems to work well; as reported by **Marcellus (1989)**.

Another simple form is a rule with a disjunction (OR) linking two pieces of evidence:

IF(e1 or e2) THEN(c).

The normal combination rule for the certainty of the evidence is that the certainty of the disjunction is equivalent to the certainty of its strongest part; this is,

$$\mathbf{ct\ (e1\ or\ e2) = max\ (ct(e1),ct(e2)).} \qquad (3.19)$$

3.7.1.2 LOGICAL COMBINATIONS WHEN MULTIPLE RULES SUPPORT THE SAME CONCLUSION

This situation arises when for instance two rules both appear to be applicable, and they both support the same conclusion.

Consider the case for example:

Rule 1:

If (e1) then (c) ct(conclusion)= ct1

Rule 2:

If (e2) then (c) ct(conclusion)= ct2

In this case, the reasoning system for reaching a composite certainty can be combined in a different way depending the conditions established by the certainty factor individually and is expressed by conditions established in **equation 2.4**.

As we can see from the two reasoning system, the rules will be processed as group of two conditions every time. If we have more than two conditions, the rules will be decomposed in pairs and the conclusion obtained from this analysis will be the input for the next. **Table 3.3** tabulates all the possible ways that two certainties can combine according to these rules. It is observed that according to this model, when one certainty is +1 and the other is -1 then the ctotal is null.

Figure 3.8 shows a equivalence between inference net notation and rule notation that is used in this project.

So far we have just considered simple reasoning situation where the final conclusion was separated from evidence by one reasoning step. A more typical situation is to have a network in which the final conclusions are separated from the evidentiary base by many intermediate conclusions. Such a situation calls for multi-step reasoning.

For discussing multi-step reasoning, it is convenient to represent the pertinent rules in a form which makes the possibilities in the rules stand out more clearly. Any system of interlocking rules, such as the one we have been using, can also be shown in a graphic representation called an inference network. This is a graph that shows how the rules relate to one another. It also clearly shows all possible supporting structures of intermediate conclusions under any higher level conclusion. The inference network does not exist anywhere except in our imagination. It is the rules that are given a concrete form, but they always imply an inference net.

3.7.2 APPLICATION OF REASONING UNDER UNCERTAINTY TO A REAL SITUATION

In the specific risk evaluation covered here (HICC), the information concerning the hardness control approach can be represented by the statement of the following rules.

Rule 1:

If HAZ hardness is high
then risk of HICC is high ct(implication)=cf(h,e)= 0.7

Rule 2:

If preheat evaluated is insufficient
then risk of HICC is high ct(implication)=cf(h,e)=0.9

In each statement, the relation between the evidence and hypothesis was associated by an implication factor (confidence factor) representing a change about a belief in a hypothesis given that evidence is true. In the case of rule 1, the main aspects considered was the thermal aspects affecting the HAZ, especially in terms of microstructure presence. In this case the certainty of the implication as a whole was considered 0.7. In the case of rule 2 the certainty of the implication was evaluated to be 0.9, since the methodology used to evaluate the preheat temperature is more complete

Table 3.3 - Composite Certainties Resulting When Two Rules of Varying Strengths Support the Same Conclusion

						c1					
c2	-1	-.8	-.6	-.4	-.2	0	.2	.4	.6	.8	1
1.0	0	1	1	1	1	1	1	1	1	1	1
.8	-1	0	.50	.67	.75	.80	.84	.88	.92	.96	1
.6	-1	-.50	0	.33	.50	.60	.68	.76	.84	.92	1
.4	-1	-.67	-.33	0	.25	.40	.52	.64	.76	.88	1
.2	-1	-.75	-.50	-.25	0	.20	.36	.52	.68	.84	1
0	-1	-.80	-.60	-.40	-.20	0	.20	.40	.60	.80	1
-.2	-1	-.84	-.68	-.52	-.36	-.20	0	.25	.50	.75	1
-.4	-1	-.88	-.76	-.64	-.52	-.40	-.25	0	.33	.67	1
-.6	-1	-.92	-.84	-.76	.-.68	-.60	-.50	-.33	0	.50	1
-.8	-1	-.96	-.92	-.88	-.84	-.80	-.75	-.67	-.50	0	1
-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	0

than in the case of rule 1. It is important to observe that information about hydrogen and weld stress presence could reinforce the decision system but in this particular case these information were ignored.

In each rule, the evidence base needs to be fully assessed prior to the evaluation of the final rule and as a consequence it will become a new hypothesis to be tested. A confidence factor have to be associated and this will be dependent on the conditions imposed by each piece of information. In the specific case of rule 1, the evidence (high hardness) will become a new hypothesis whose confidence factor can be determined by arranging the hardness value evaluated through specific ranges as shown in **table 3.4**. The same procedure can be used by the rule 2 and in this case it was found that by considering the evaluation of preheat using the TWI nomogram, the assessment of HICC can be represented by comparing the evaluated preheat with the original value specified by the user (T0) through a confidence factor shown in **table 3.4**.

Table 3.4 - Preheat and hardness combined under the uncertainty analysis.

CONDITION	cf	cfm
1. Insufficient preheat		
Preheat evaluated < T0	0.2	-0.6
Preheat evaluated > T0 - 1.3T0	0.6	0.2
Preheat evaluated > 1.3T0 - 1.5T0	0.8	0.6
Preheat evaluated > 1.5T0	0.9	0.8
2. High hardness		
Hardness < 300	0.2	-0.6
Hardness 300-325	0.4	-0.2
Hardness 325-350	0.8	0.6
Hardness > 350	0.9	0.8

As observed in table 3.4, the confidence factor attributed to each piece of information (cf) was transformed in a confidence factor modified (cfm) by using a linear interpolation. It was assumed that for a cf value of +1 (completely true) the correspondent cfm was +1 and for a cf value of 0 (completely false) the correspondent cfm was -1.

Considering that evidence e1 is the confidence factor related to the hardness information (rule 1), e2 is the correspondent confidence factor related to the preheat evaluated (rule 2) and ct1 and ct2 are the conclusions related to each of the rules, the combined information could be summarised according to the logical combination of rules. In this particular case the two rules both appear to be applicable and they both support the same conclusion. This can be expressed by the following:

if e1 then c ct(conclusion)=ct1=e1*i1

and

if e2 then c ct(conclusion)=ct2=e2*i2

In this case, the composite certainty of the conclusion can be combined by the use of a bipolar certainty figures and determined by the relations considered in **equation 2.4**. **Table 3.5** summarises the conclusion inferred from the combination of both sets of evidence according to a formal judgement and bipolar certainty figures.

Table 3.5 - Results of preheat and hardness combined under the uncertainty analysis.

COMBINATIONS	1		2		3		4		5		6		7		8	
Preheat	C[*]	0.72	C	0.72	C	0.72	C	0.72	≈C	0.54	≈C	0.54	≈C	0.54	≈C	0.54
Hardness	C	0.56	≈C	0.42	≈NC	-0.14	NC	-0.42	C	0.56	≈C	0.42	≈NC	-0.14	NC	-0.42
Results	C	0.88	C	0.84	≈C	0.67	≈C	0.52	C	0.80	≈C	0.73	≈C	0.46	≈NC	0.20
COMBINATIONS	9		10		11		12		13		14		15		16	
Preheat	≈NC	0.18	≈NC	0.18	≈NC	0.18	≈NC	0.18	NC	-0.54	NC	-0.54	NC	-0.54	NC	-0.54
Hardness	C	0.56	≈C	0.42	≈NC	-0.14	NC	-0.42	C	0.56	≈C	0.42	≈NC	-0.14	NC	-0.42
Results	≈C	0.64	≈NC	0.52	≈NC	0.05	NC	-0.29	≈NC	0.04	≈NC	-0.20	NC	-0.58	NC	-0.73

[*] C/NC - Cracking/No cracking tendency - personal evaluation

The use of bipolar certainty figures differ quite remarkable from the decision table support system representation. But in another sense, both depend on personal judgements representing the feeling about a particular situation. In case of decision tables the conclusions are represented by personal preferences based on the evidence. In an uncertainty analysis, each piece of information is inferred with a confidence factor and conclusions are based on the assessment of information.

Considering the cold cracking presence risk from the point of view of critical preheat temperature and critical HAZ hardness previously discussed, it can be seen from **table 3.5** that both decision support systems agreed on its conclusions for most situation.

The certainty of a cold cracking under the combined influence of preheat and hardness evaluation shows a very close range of agreement with the formal judgement. However, the use of a conventional evaluation can lead to some difficults. In the present example, the risk of cold cracking susceptibility using a conventional technique (decision tables) is represented by 16 (2^4) possibilities to be combined according to the user input and the result will be given by the knowledge judgement. In a normal application with a great number of conditions, a system based on decision tables can lead to a combinatorial explosion of information and obviously can undermine the decision support system. This kind of problem is avoided by the present methodology based on the use of bipolar certainty figures, since the propagation of uncertainties can be governed by the conditions discussed in the previous section.

In an uncertainty analysis, each piece of interacting evidence will be processed according to the confidence factor established and combined according to the conditions established. However, an observation needs to be added at this stage. It has been reported (Marcellus, 1990) that the use of such form of representation only works well for rules that are completely reversible. This can be determined by the negation of the rule. If in this new condition the rule does not apply and the rule is non-reversible then evaluation under the present methodology can only be used if the certainty factor inferred is positive. If the certainty factor is negative its evaluation can be discarded. In previous considerations of the cold cracking evidence presented here, both rules are reversible, and in this case the evaluation is set to be correct.

So far, we have only dismissed a one-step level. In a more typical situation represented by a network in which the final conclusions are separated from the evident base by many intermediate conclusions the information will be processed separately and progressively combined by multi step reasoning as described above.

3.7.3 SCHEME APPLIED TO HICC ANALYSIS

An inference network representation was used to illustrate the particular knowledge in a graphical structured form. This network is meant to show the possibilities in a multi-stage reasoning problem in a more useful way than a simple statement of the rules.

A certainty factor, which is the measure of confidence that could be placed in a given hypothesis, was interrelated with user entries. The certainty factor is defined as the total measure of belief/disbelief, and ranges between -1 (false) to +1 (true), with zero representing ignorance. A modified certainty factor correlated with the user answer every time that the inputs were processed. A procedure default is used to correlate the confidence factor range between 0 (false) and +1(true) contained in each statement. An interpolation converts the user's belief to a certainty factor that can be used by the system. A characteristic of the system is that the procedure default can be changed or then adapted with the user expertise, in order to modify the analysis according to experience or judgement. This option is offered at the beginning of the system and can be updated every time the system runs.

In the case of the HICC check procedure, the conditions are established by the combination of the critical conditions in each particular knowledge involving microstructure susceptibility, hydrogen presence and welding stress presence when cooled at a critical temperature range of 300-100°C. The knowledge from each problem space was gathered from the knowledge elicitation and depicted in a form of network representation, considering the influent factors shown in **figures 3.2-3.5**. The confidence factors for each piece of evidence, represented by a node, and the intrinsic implication factors between evidence were attributed. **Figures 3.9-3.12** shows the microstructure, hydrogen, critical temperature and welding stress inference network representation using the notation discussed.

The nodes at the bottom of the tree represent pieces of evidence (conditions) acquired by questions to or measurements from the external world. The interior nodes are conclusions. Between the nodes there is a certainty that represent the implication that supports that particular node. The implication factor is particularly important because it represents the attribute of significance of an assertion and the effect of the evidence on a conclusion. It can even translate the heuristic fact presents on it. The certainties of the interior nodes are completely determined by the reasoning process, the implication rules, and the evidence that is being acquired from the outside world.

The conditions for microstructure susceptibility analysis are summarised by **table 3.6** which represents the associated confidence level for the measurement gathered from the user. The information concerning evidence and hypothesis was represented using the follow formalism:

(evidence -> cf(e))

The same formalism was used in the representation of the implication factors. In this case the logical form correlating hypothesis and evidence (ie, AND or OR) had to be defined according to **figure 3.9**. and this was symbolized according to the following:-

(logical factor; (evidence); (hypothesis)-> cf(h,e))

Table 3.7 shows the associated implication factors between the evidence and hypothesis for each particular condition in the microstructure evaluation.

Tables 3.8-3.11 summarises the associated confidence levels from the information supplied by the user and the associated implication factors between evidence and hypothesis involving hydrogen presence, welding stress and critical temperature analysis.

The network has all the elements defined and present implication of the various sorts: simple, AND and OR. Reasoning consists of starting at the bottom of the tree, where things are defined, and using the implication rules to find the certainty of the nodes that the low level information supports. This process is continued, node by node, until the certainty of every conclusion is determined. The calculation were processed according to the logical combination of the rules.

Table 3.6 - Confidence factor associated with microstructure analysis according to user input information.

```
High carbon content: (e1)
((c>0.3%, mn>1.4%) -> 0.7)
((else), -> 0.3)

Low amount of individual elements:(e2)
((O2>0.002%,N2>0.002%,B>0.001) ->0.8)
((else) ->0.4)

High boron: (e3)
((b>0.0005) ->0.7)
((else) -> 0.3)

High amount of several elements: (e4)
((c> 0.2%, CE(iiw) > 0.37%) -> 0.7)
((c<0.2%, Pcm >0.2%  ) -> 0.7)
((else) -> 0.3)

High sulphur: (e5)
((s>0.008%) ->0.9)

Insufficient arc energy: (e6)
((HI>1.5 Kj/mm) -> 0.3)
((HI - 1 - 1.5Kj/mm) ->0.6)
((HI<1Kj/mm) -> 0.8)

Incorrect polarity: (e7)
((polarity - DC+) -> 0.4 )
((polarity - DC-) -> 0.8 )
((polarity - AC ) -> 0.6 )

Insufficient preheat temperature: (e8)
((preheat used>=preheat evaluated) -> 0.2)
((preheat used<preheat evaluated) -> 0.8)

Insufficient inter-pass temperature: (e9)
((interpass used>=interpass evaluated) -> 0.2)
((interpass used<interpass evaluated) -> 0.8)

Insufficient grain refiners: (e10)
((Ti,W,V,NB,Al,Mn>0) -> 0.20)
((Ti,W,V,NB,Al,Mn=0) -> 0.80)

High peak temperature
((tpeak > 1200) -> 0.9)
((tpeak - 1000-1200) -> 0.6)
((tpeak < 1200) -> 0.3)
```

Table 3.7 - Implication factors associated with microstructure analysis according to network showed in figure 3.9.

```
Risk of high boron: (e2,e3;cm1)
(OR,(e2), risk of high boron ->0.8)
(OR,(e3), risk of high boron ->0.8)

Risk of high amount of individual elements: (e1,cm1;cm2)
(OR,(e1), risk of high amount individual elements ->0.8)
(OR,(cm1), risk of high amount individual elements ->0.8)

Risk of high amount of several elements: (e4;cm3)
(-,(e4), risk of high amount of several elements ->1)

Risk of low amount of individual elements: (e5;cm4)
(-,(e5), risk of low amount of individual elements ->0.9)

Risk of high hardenability - chemical composition: (cm2,cm3,cm4;cm5)
(-,(cm2), risk of high hardenability - high amount individual elements ->0.7)
(-,(cm3), risk of high hardenability - high amount several elements ->0.9)
(-,(cm4), risk of high hardenability - low amount individual elements ->0.5)

Risk of insufficient heat - process parameters: (e6,e7;cm6)
(OR,(e6), risk of insufficient heat process parameters ->0.7)
(OR,(e7), risk of insufficient heat process parameters ->0.7)

Risk of insufficient heat - preheat: (e8;cm7)
(-,(e8), risk of insufficient heat due preheat ->1)

Risk of insufficient heat - interpass: (e9;cm8)
(-,(e9), risk of insufficient heat due interpass ->1)

Risk of fast cooling rate: (cm6,cm7,cm8;cm9)
(-,(cm6), risk of fast cooling rate - insufficient heat process parameters ->0.9)
(-,(cm7), risk of fast cooling rate - insufficient heat due preheat ->0.8)
(-,(cm8), risk of fast cooling rate - insufficient heat due interpass ->0.8)

Risk of insufficient grain refiners: (e10,cm10)
(-,(e10), risk of insufficient grain refiners ->0.6)

Risk of high peak temperature: (e11,cm11)
(-,(e11), risk of high peak temperature ->0.9)

Risk of grain growth: (cm10,cm11;cm12)
(AND,(cm10), risk of grain growth - grain refiners ->0.8)
(AND,(cm11), risk of grain growth - peak temperature ->0.8)

Risk of susceptible microstructure: (cm5,cm9,cm12;cm13)
(-,(cm5), risk of susceptible microstructure - high hardenability ->0.9)
(-,(cm9), risk of susceptible microstructure - fast cooling rate ->0.9)
(-,(cm12), risk of susceptible microstructure - grain growth ->0.6)
```

Table 3.8 - Confidence factor associated with hydrogen presence analysis according to input user information.

```
Standoff excessive:(e1)
((standoff >  25) ->0.9)
((standoff -> 20-25) ->0.6)
((standoff <  20) ->0.3)

Electrode orientation:(e2)
((orientation >  70) -> 0.8)
((orientation -> 40-70) -> 0.2)
((orientation <  40) -> 0.8)

Moisture gas line:(e3,e4)
((gas line leaking = yes) -> user define (cf))
((gas line leaking = no) -> user define (cf))
((condensation presence = yes) -> user define (cf))
((condensation presence = no) -> user define (cf))

Hydrogen presence shielding gas:(e5)
((gas purity > 90%) -> 0.2)
((gas purity < 90%) -> 0.6)

Welding site:(e6,e7,e8)
((welding site =external, cover tenting=yes) -> 0.3)
((welding site =external, cover tenting = no, excessive windy = yes) -> 0.5)
((welding site =external, cover tenting = no, excessive windy = no) -> 0.4)
((welding site =internal) -> 0.2)

Hydrogen presence plate material:(e9,e10)
((contamination presence (rust, dust, grease, etc) = yes) -> 0.8)
((contamination presence (rust, dust, grease, etc) = no) -> 0.2)

Hydrogen presence consumables:(e11,e12)
((moisture presence (oil, grease, etc) = yes) -> 0.8)
((moisture presence (oil, grease, etc) = no) -> 0.2)
```

Table 3.9 - Implication factors associated with hydrogen presence analysis according to the network showed in figure 3.10.

```
Risk of hydrogen presence - standoff excessive:(e1;ch1)
((standoff excessive), risk of hydrogen presence -> 1)

Risk of hydrogen presence - electrode orientation:(e2;ch2)
((orientation), risk of hydrogen presence -> 1)

Risk of hydrogen presence - moisture gas line:(e3,e4;ch3)
(OR, (leaking condition gas line), risk of hydrogen presence -> 0.7)
(OR, (condensation gas line), risk of hydrogen presence -> 0.7)

Risk of hydrogen presence - shielding gas:(e5,ch4)
((gas purity), risk of hydrogen presence -> 0.8)

Risk of hydrogen entrain - gas process combination: (ch3,ch4;ch5)
(OR,(ch3), risk of hydrogen gas process combination -> 0.8)
(OR,(ch4), risk of hydrogen gas process combination -> 0.8)

Risk of hydrogen presence - external welding site:(e7,e8;ch6)
(AND,(excessive wind), risk of hydrogen presence -> 0.4)
(AND,(ineffective cover tenting), risk of hydrogen presence -> 0.4)

Risk of hydrogen presence - welding site:(e6,ch6;ch7)
(OR,(e6), risk of hydrogen presence welding site -> 0.4)
(OR,(ch6), risk of hydrogen presence welding site -> 0.4)

Risk of hydrogen presence - ineffective arc shield: (ch1,ch2,ch5,ch7;ch8)
(AND,(ch1), risk of hydrogen presence ineffective arc shield -> 0.7)
(AND,(ch2), risk of hydrogen presence ineffective arc shield -> 0.6)
(AND,(ch5), risk of hydrogen presence ineffective arc shield -> 0.8)
(AND,(ch7), risk of hydrogen presence ineffective arc shield -> 0.4)

Risk of hydrogen source - arc atmosphere: (ch8;ch9)
((ch8), risk of hydrogen source arc atmosphere -> 0.8)
Risk of hydrogen presence - plate material contamination:(e10;ch10)
((plate material contamination), risk of hydrogen presence -> 0.8)

Risk of hydrogen presence - source of hydrogen plate material:(e9,e10;ch11)
(OR,(e9), risk of hydrogen presence plate material -> 1)
(OR,(ch10), risk of hydrogen presence plate material -> 1)

Risk of hydrogen presence - consumables contamination:(e12;ch12)
((moisture consumables), risk of hydrogen presence consumables -> 0.8)

Risk of hydrogen presence - source of hydrogen plate material:(e11,ch12;ch13)
(OR,(e11), risk of hydrogen presence consumables contamination -> 1)
(OR,(ch12), risk of hydrogen presence consumables contamination -> 1)

Risk of hydrogen presence - hydro-carbon moisture: (ch11,ch13;ch14)
(OR,(ch11), risk of hydrogen presence hydro-carbon moisture -> 0.9)
(OR,(ch13), risk of hydrogen presence hydro-carbon moisture -> 0.9)

Risk of Hydrogen: (ch9,ch14;ch15)
(AND,(ch9), risk of hydrogen presence -> 0.8)
(AND,(ch14), risk of hydrogen presence -> 0.8)
```

Table 3.10 - Confidence factor associated with welding stress analysis according to user input information.

```
user define contraction type:
lateral contraction, angular rotation, angular/lateral contraction

High thickness:
((relative thickness > 0.9) -> 0.9)
((relative thickness - 0.75-0.9) -> 0.9)
((relative thickness - 0.6-0.75) -> 0.9)
((relative thickness < 0.6) -> 0.9)

High arc energy:
((SMAW, HI > 1.2Kj/mm) -> 0.9 )
((SMAW, HI - 0.8-1.2Kj/mm) -> 0.4 )
((SMAW, HI < 0.8Kj/mm) -> 0.2 )
((GMAW, HI > 1.5Kj/mm) -> 0.9 )
((GMAW, HI - 1.0-1.5Kj/mm) -> 0.4 )
((GMAW, HI < 1.0Kj/mm) ->0.2  )

Risk of high restraint condition:
((restraint = yes, level = high) -> 0.8 )
((restraint = yes, level = medium) -> 0.5  )
((restraint = yes, level = small) -> 0.3  )
((restraint = no) -> 0  )
((restraint = don't known) -> 0.5 )

Plate material ductility:
((ductility > 25%) -> 0.2   )
((ductility - 15-25%) -> 0.6   )
((ductility < 15%) -> 0.8  )

Fit-up:
((gap > 4 mm) -> 0.8  )
((gap - 2-4 mm) -> 0.1 )
((gap < 2 mm) -> 0.6 )
```

Table 3.11 - Implication factors associated with welding stress analysis according to the network showed by figure 3.11.

```
User define contraction type
Welding stress mode: Lateral contraction, angular rotation, angular/lateral
contraction


Risk of lateral contraction: (e1,e2,e3;cs1)
(-(e1), risk of lateral contraction due high thickness -> 0.7)
(-(e2), risk of lateral contraction due high arc energy -> 0.7)
(-(e1), risk of lateral contraction due high restraint -> 0.9)


Risk of angular rotation: (e4,e5,e6;cs2)
(-(e4), risk of angular rotation due high thickness -> 0.7)
(-(e5), risk of angular rotation due high arc energy -> 0.7)
(-(e6), risk of angular rotation due high restraint -> 0.9)


Risk of angular/lateral contraction: (e7,e8,e9;cs3)
(-(e7), risk of angular/lateral contraction due high thickness -> 0.7)
(-(e8), risk of angular/lateral contraction due high arc energy -> 0.7)
(-(e9), risk of angular/lateral contraction due high restraint -> 0.9)


Risk of residual stress due material properties: (cs1,cs2,cs3;cs4)
(OR,(cs1), risk of residual stress - lateral contraction -> 1)
(OR,(cs2), risk of residual stress - angular rotation -> 1)
(OR,(cs3), risk of residual stress - angular/lateral contraction -> 1)


Risk of residual stress due joint design: (e10,e11,e12;cs5)
(-(e10), risk of residual stress - small ductility -> 0.9)
(-(e11), risk of residual stress - high joint thickness -> 0.8)
(-(e12), risk of residual stress - fit-up -> 0.7)


Risk of welding stress presence: (cs4,cs5;cs6)
(-(cs4), risk of welding stress residual stress/mater. properties ->0.9)
(-(cs5), risk of welding stress due residual stress/joint design -> 0.9)
```

CHAPTER 4

COMPUTER PROGRAM, KNOWLEDGE REPRESENTATION AND RESULTS

4.1 GENERAL ASPECTS

This chapter is divided in two main parts. In the first part there is a general description of the computational approach used in transferring the knowledge base into an expert system environment. The full structure of the program is outlined and the knowledge representation is extended in order to integrate a reasoning system based on uncertainty analysis. In the second part a series of tests to validate the specific knowledge and the system as a whole are described and the results are presented.

4.2 SYSTEM DESIGN

Cold cracking is a complex welding defect. Several combined welding conditions acting together can initiate this problem. Considerations in terms of computational risk analysis of the welding procedure specification need to concentrate on the combined influence of different factors on HICC. Analysis was carried out on each set of knowledge using a backward and/or forward chaining control. Task strategy checks the data in order to verify the possibility of defect occurrence.

The program structure was designed in such a way that information can be transferred effectively from one program to another. Basically the computer configuration was divided in different modules. Each module encodes different tasks and embodies information related to welding procedure specification, database welding checking, analytical calculation, analysis approach and final diagnostic. Designing the knowledge base in modules, allowed particular knowledge groups to be tested separately, with increasing capabilities in terms of maintenance and checking analysis.

4.2.1 SOFTWARE PROGRAMS

The programme was integrated in an expert system shell software environment (XiPLUS- EXPERTECH). This software was chosen because it is a rule based system which produces output in "plain English", and the system supports both backward and forward chaining inference strategy. The software consists of a language plus a set of facilities for the expression and use of human know-how in a computer program. There are three main components in any Xi Plus expert system application:

- A knowledge base, which contains the problem solving know-how. This is written in the Xi Plus language which use a rule base representation.

- A rule interpreter (or inference engine) which is able to process the knowledge base. This is a basic component of the system.

- An integral database, which holds the current status of consultation of the knowledge base. A record of information entered during consultation and conclusions reached in the current session are maintained in the database for further processing. This database, however, does not have the ability to store conditional information. For this reason the database management was performed using dBASE III Plus software.

An interface was designed allowing easy access to the database and data transfer between the knowledge bases.

4.2.2 BUILDING STRATEGY

Building a knowledge base can be divided into three different phases:

- Planning
- Prototyping
- Refining

4.2.3 SYSTEM CONSIDERATIONS - STRUCTURING THE SYSTEM

Most experts and specialists have a fairly organized view of their world that helps them in dealing with problems. This organized view is a vital part of know-how in that it provides the framework within which it is possible to work quickly and effectively. A consultation with a skilled expert is consequently rarely a haphazard sequence of questions, but rather a well focused progression towards the solution of a problem or the providing of advice.

To be equally effective, an expert system of any significance also needs to be organized and well structured. In part, this structure should reflect the way that the expert approaches the same problem. However, by itself, this may not be enough to ensure a well sequenced and coherent consultation and 'programming' considerations may necessitate additional structuring.

There are two aspects to the structuring of a knowledge base that need to be considered:

- The logical structuring of the knowledge to achieve the objectives of the consultation.

- The physical organization of the knowledge base items to aid understanding and maintenance.

For many systems, most of the required structuring can be organized around the basic backward chaining of the system, using the ordering of conditions in top level rules to manage the sequencing of the consultation. Where this is insufficient, it may be necessary to impose a more formal organization on the knowledge base by adding rules of the form:

if the preliminary information is collected
and the particular problem is Any problem
and a solution of Any problem is Found
and a final report is given
then the task is complete

Where greater flexibility is required in the structure of a consultation, perhaps to cater for unusual combinations of circumstances, this can generally best be achieved in forward chaining, using demons to interject additional intermediate goals into the consultation (XiPlus - User Manual, 1989). For example:

when these particular circumstances arise
then check this aspect of the problem

As far as the physical lay-out of the rules is concerned, experience has shown that a logical organisation can greatly help in the overall performance of the system. It is important to consider that, as far as possible, the rules, demons, etc. of a knowledge base should be grouped together and ordered in the sequence of problem solving. The top level rules that seek a value for the main query should appear first, followed by the rules that can be used to evaluate the conditions of these top level rules, and so on. Rules with similar consequences should generally be physically grouped together, along with associated facts, demons and defaults.

4.2.3.1 MULTIPLE KNOWLEDGE BASES

The development of almost any application will involve the partitioning of the overall application into a number of linked knowledge bases.

Two factors should be considered when planning how to partition an application. Firstly, any natural divisions in the problems to be tacked by the system. Where a system is to deal with a whole range of distinct and completely separate problems, such a system is likely to be partitioned into:

- an introductory knowledge base that identifies which problem have to be solved, and

- separate knowledge bases for each separate group of problems.

Even where only a few rules are needed to solve a problem, there is unlikely to be much to be gained from combining these in one knowledge base with the rules for other problems, unless there is common knowledge.

Where the task being tackled by the system is much more monolithic, there are usually several different stages or phases to the problem solving process. These form the likely divisions for partitioning such applications into multiple knowledge bases.

A second factor to be considered is the physical size of the individual knowledge. Simply from the point of view of building, testing and subsequently maintaining the knowledge, a single large set of rules is generally more difficult to cope with than a comparable number of rules divided into several smaller knowledge bases.

Concluding, when considering a particular knowledge, it is important to delineate a strategy in order to obtain a series of conclusions from the knowledge base. This could be devised by

- Dividing up the task;
- Deciding the type of conclusions or results required from the system;
- Identifying which conclusion is the central issue;
- Listing the most important results which may be expected.

Observing these conditions is a fundamental requisite for both the structure and maintainability of the knowledge base in any application.

4.2.4 PROTOTYPE SYSTEM STRUCTURE

Having considered these system design aspects, a prototype system was designed as outlined in **figure 4.1**. The system was conceived to receive information encoded in a welding procedure specification. The data is typed into fields on the entry screen in the same way that it would be written on a procedure proposal form, following the format of the BS 4870: Part 1: 1981, as seen in **figure 4.2**. The expert system then processes the information in a structured form using a rule based representation. Distinct knowledge-bases, using direct parameters, cover particular situations, for instance, hardenability analysis, see **figure 4.3**. The analysis of the procedure data is performed at several different levels according to the type of information and the rules available. At the final stage a diagnostic analysis is generated and recommended actions are presented to help the engineer to correct the original welding procedure.

In summary, the prototype system was designed to fulfil the general following tasks:

- interface with the user to obtain information about a particular welding procedure specification (using a format similar to that recommended in BS 4870 (**12**)).

- interface with the database in order to access general welding data including parent material, consumable and shielding gas (chemical composition and mechanical properties).

- carry out mathematical calculations in order to quantify various aspects of the metallurgical, geometrical and mechanical properties of the welding joint.

- analyze the information in the welding procedure specification in order to determine the possibility of welding defects.

- suggest appropriate corrective actions.

- optimize the welding procedure by selected welding parameter modifications and using the information generated.

- interface with a database in order to store the fully analyzed welding procedure specification.

4.2.4.1 COMPUTER SYSTEM STRUCTURE

The development of expert systems is frequently associated with the use of extensive databases. It was observed that most expert systems software has a limited capability for dealing with large volume of information and this can compromise the functionability of the system as a whole. On the other hand, extensive question and answer sessions with the user can be both exhausting and susceptible to mistakes (eg. when accessing a chemical composition of a certain type of base material). It was believed that the interactive use of expert systems interfaced with a proper database tool could provide the necessary flexibility that was expected from the proposed system.

WELDCARE, the computer program designed for this application, was developed as a result of consideration of these aspects. The software was designed to run in PC 286 with a minimum of 1Mb of RAM memory. The software structure was basically divided in two fundamental parts:

- database management;
- welding defect analysis.

Figure 4.4 shows a schematic representation of the interaction between the database and expert system software. The welding defect analysis module conducts a trial to detect any possibility of defect in a welding procedure specified. The database management system acts as a practical facility which assists the user in changing or updating the database structure before or after loading the main application. It also allows the details of the welding procedure to be stored for use in other applications. As an example, the integration between a welding procedure specification (WPS) and a procedure qualification record (PQR) could form the basis for a full integrated welding database management.

WELDCARE software involves different stages as shown in **figure 4.5**. Several modules working at a low level are integrated at a high level by a main analyzer structure system representing the main knowledge involved in the application.

4.2.4.1.1 DATABASE MANAGEMENT

A database management module was incorporated to give more flexibility to the system. The user may need to have easy access to the database to modify, add, delete or only to verify a record in more detail. **Figure 4.6** shows a flowchart representing the main steps in the database management system.

It has been reported that one of the great difficulties during the development of an expert system is to find a reasonable form to organise a database system. Expert systems software and especially shells, are very limited in their capability to keep extensive databases. Using normal PC systems the use of large amounts of information can cause memory management problems. On the other hand, there are purpose designed systems that provide the ability to work with complex database system. One of the most common packages of this type is dBASE III Plus and its late version dBASE IV*. These systems also offer a strong programming database language that allows the user to 'customise' the software for a particular application.

In order to improve expert systems capability, an interface between two

---

* dBase III Plus and dBase IV are softwares from Ashton Tate Co.

systems (dBASE III Plus and XiPlus) was developed and the structure is shown in **figure 4.7.** This facility allows the user to access the external database in dBASE III Plus whilst running XiPlus. All the information necessary to locate data will be transferred from the expert system shell. A XiPlus knowledgebase (dbase access) loads the external interface, which in turn will access the dBASE III Plus, run a dbase program and locate the record. The new data is transferred to a new file (dbase results) in a converted DELIMITED format which can be read by an external program interface (read dif) in XiPlus format (dbc). The use of this approach allows data to be easily updated, modified or deleted. In the **appendix B** part of the knowledge base to access the interface expert system/database is represented.

4.2.4.1.2 WELDING DEFECT ANALYSIS - APPROACH USED IN HICC ANALYSIS.

Welding defect analysis is an essential feature of the WELDCARE system (see Appendix C). The processing system is divided into different levels representing the knowledge base and main tasks involved in the welding procedure specification check-up: input user information, analysis level, diagnosis level, optimisation procedure and database interface. Every particular level is divided into different knowledge base that identify which problem has to be solved. **Table 4.1** summarises the levels and tasks involved in each phase. System elements that did not perform analysis were modularised (data about base material, shielding gas and filler material, for example). These modules are knowledgebase only in structure - they do not contain actual expert knowledge. Each knowledge base has its own name space and is saved, loaded, and displayed as a single entity. Also, each phase or major sub-phase was modularized independently. The expert system tasks are carried out with some additional consultation with the user. The main program control the execution of knowledge bases at all levels. **Figure 4.8** shows a view of the system structure.

At the first level, the system is designed to receive information encoded in a welding procedure specification. The data is typed into fields on the entry screen in the same way in which it would appear in a procedure proposal form (following the

Table 4.1 - Knowledge and tasks involved in WPS analysis.

- **Input user information**
  Knowledge bases:
  - welding procedure specification;
  - database information
  Tasks: * identify the main welding parameters;
  * interface with the database.

- **Analysis level**
  Knowledge bases:
  - welding defect analysis;
    a) HICC
      *Sub-knowledge bases:
        - Susceptible microstructure;
        - Hydrogen presence;
        - Welding stress:
        - Critical temperature;
    b) Others defects
      Sub-knowledge bases: to be incorporated
  - analytical module
  Tasks: * identify the influence of the parameters
  on the HICC occurrence.

- **Diagnosis level**
  Knowledge bases:
  - final diagnostic and advice
  Tasks: * verify the WPS soundness;
  * display advice and conclusions.

- **Optimization procedure**
  Knowledge bases:
  - what if conditions
  Tasks: * simulate different conditions by change welding parameters.

- **Database interface**
  Tasks: * interface with database;
  * generate a final optimized WPS record.

feature of the BS 4870: Part 1: 1981), as seen in **figure 4.2**. Windows containing a series of options are offered to the user in order to make it easier to complete the specification and minimize keyboard input and the possibility of resultant typographic errors. This module also accesses the database to standardise the data (eg. providing gas and filler wire compositions from trade names and alloy composition from steel specifications).

The normal procedure proposal data is supplemented with a series of questions involving the general welding conditions; for example the joint details, conditions of the plate and gas lines before welding, welding access restrictions and details of any heat conservation techniques used are requested.

After the system has validated all the input information, an interface between expert system and database system searches for extra data concerning the chemical composition and mechanical properties of the plate material, consumable and shielding gas that are specified. The database interface allows much of the information specified above to be transferred automatically to the system without the need for long question and answer sessions. The database software used was dBaseIII Plus.

After all the information has been accessed, the system starts the analysis procedure. At this second level a master program is surrounded by several specific modules embodying knowledge distributed in different areas of interest. The master program will control the execution of these modules according to the kind of analysis that the user wants to perform. In this project the system concentrated on the detection of HICC risks. In this case the modules encapsulate the knowledgebase involving susceptible microstructure, hydrogen presence, critical temperature and weld stress analysis. Additional sub-modules will provide additional information and calculations when necessary.

The HICC analysis manager performs evaluations in order to identify all the general conditions related to the occurrence of cold cracking. **Figure 4.9** presents a generic algorithm of development and verifications of models used in this analysis. The HICC analysis involves an evaluation of the thermal aspects as a consequence of the welding conditions, for instance, preheat evaluation, HAZ hardness, microstructure composition, cooling time, peak temperature, and grain growth. **Figures 4.10** shows the schematic flow chart representing the thermal aspects analysis. Calculations are processed in a coordinated sequence as described in **section 3.4**.

The presence of cold cracking is very strongly influenced by the hydrogen level. The presence of hydrogen can be clearly evaluated by the user if its concentration has been determined by using one of the methodologies current available (IIW and JIS methods). However, it is often the case that its level is unknown or even if measured this can only be carried out as a preliminary test and may not give an accurate indication of the H_2 level likely to be found in practice. In this case, a common procedure is used in order to evaluate the evidence of hydrogen concentration level. **Figure 4.11** shows a concise flowchart representing the steps adopted for hydrogen analysis. This evaluation is performed according to a series of questions related to the welding conditions. The common procedure used to evaluate the hydrogen presence was combined under a reasoning mechanism involving uncertainty analysis, and processed according to the conditions described in **section 3.7**.

The welding stress is another essential parameter to be fully assessed in order to evaluate HICC risks. As described above, **section 2.10.2**, methods have been proposed to evaluate its level as a consequence of specific welding conditions. This situation is however difficult to evaluate and usually applied to a narrow range of parameter variation. A formal welding stress analysis has been used in this project to identify all of the intrinsic parameters influenced by the welding conditions. The presence of welding stress was evaluated in terms of evidence according to a reasoning mechanism involving uncertainty analysis, and processed according to the conditions described in **section 3.7**. **Figure 4.12** summarises the main steps involved in evaluating welding stress. It is important to note at this point that all of the modules previously mentioned will produce a result together with a certainty factor representing the level of confidence obtained from the combination of all the parameters through an inference network.

The information above forms the input for the diagnosis procedure. A complete knowledge base combines the information with the uncertainty analysis through an inference network propagation. A general diagnostic is then displayed, assessing the evidence of the HICC risk. **Figure 4.13** shows a block diagram representing the main steps used in this kind of evaluation.

The analysis will form the basis for an optimization procedure if the system concludes that the welding specification can lead to failure. In this case some parameter changes will be advised to the user. If the user actually decides to initiate an optimisation procedure, an in-built "what-if" facility will offer a list of parameters. The user can decide which parameter to choose and based on the previous diagnostic and any parameter changes advised he can then apply the modifications and observe the conclusions. The same procedure can be repeated until an optimised procedure can be diagnosed. **Figure 4.14** shows the main steps taken in the welding procedure optimisation.

4.2.5 KNOWLEDGE REPRESENTATION

Knowledge representation is an essential subsequent step to the knowledge elicitation. Several forms of representation may be used as discussed in **section 2.3**. Among the methodologies used, rule base statement and semantic networks are very popular.

In the present work production rules were used for encoding both the welding expertise and the strategic knowledge about the flow of control in the project. The main reason for this decision was that the software used is a rule base system which both backward and forward chaining control strategy. Additionally, this form of representation has been successfully used in many application and offers a very good visualisation of the rules established. This could be very helpful in attempts to expand the knowledge.

Some uncertainty is always present in the knowledge and the representation of this reality is an important step in knowledge base representation. Many arguments have been reported in the literature and different methodologies have been used. Some systems use probabilistic reasoning based on Bayes rules; others use a fuzzy representation and others use a non- probabilistic representation. Some software already has inbuilt routines that deal with uncertainty. However, in others it is necessary to develop the approach in order to represent uncertainty. In this work a methodology to incorporate uncertainty analysis was developed as an auxiliary form of representation.

Welding technology is an obvious area for the expert system application, due to the need for a multi-discipline approach. Uncertainty is common and this should be represented in a way that can be used by the system in a decision process analysis. In this respect, uncertainty management plays a very important role in the knowledge base representation and this was one of the main concerns during the knowledge representation in this project.

4.2.5.1 IMPLEMENTATION

In this project, the required welding knowledge was drawn from the welding literature and documented case studies as well as human experts. The knowledge was encoded in the form of "production rules". This form of representation using IF-THEN statements to represent knowledge in the form of actions appropriate for given situations. Among other characteristics this formal representation of knowledge permits incremental growth of the knowledge merely by adding more rules. The approach is applicable in problems that cannot be easily characterized by a concise unified theory and involve a relatively simple flow of control. The particular problem of weld defect analysis exhibits these characteristics and thus was well suited for encoding by production rules.

4.2.5.2 STYLE OF REPRESENTATION

The control inference strategy involves the use of backward or forward chaining control. A backward chaining control solves large problems by breaking them down into smaller problems and solving each of these in turn. It is particularly easy to control, where the inference engine merely solves problems presented to it in a predefined order. On the other hand, forward chaining control strategy are uncontrolled in the sense that when conditions arise they may cause demons to fire and these in turn generate other conditions from their conclusions. This cycle continues with new conditions causing new forward chaining rules to fire until the inference engine has nothing more to do. No overall goal is derived - just consequences.

The disadvantage with backward chaining, is that the rules in all but the most simple knowledge base soon become filled with consequences not at all concerned with the knowledge itself and this adversely influences sequencing control. But this technique can be implemented by the use of demons to separate these side-effects from the knowledge held in the rules. Additionally a modicum of forward chaining, also implemented by demons, may have profound implication in the overall backward chaining by changing the course of the strategy control.

In face of these considerations a backward chaining inference control was originally adopted with an additional use of forward chaining to implement the sequence of the strategy control. This kind of control approximates to the way that human actually reason.

As a particular characteristic of the knowledge representation, the use of floating variables can improve the efficiency in a production rule representation. A floating variable represents an undefined identifier or value which, for most situations, may be used as an alternative to an explicit identifier or value.

The facility enables generalized statements to be written that do not explicitly name the identifier(s) and/or value(s) to be used. Specific meaning is only assigned to a floating variable dynamically, during the inferencing process, for instance:

```
if      problem is Any problem
and     Any problem is caused by Any fault
then    diagnosis is Any fault
```

A floating variable is represented by one or more words, where the first word begins with an upper case letter. A specific value is assigned to a floating variable during the process of using the rule or other item in which it appears. The floating variable is said to be instantiated by the value assigned. Once a value has been assigned, this is retained for the remainder of the firing of the rule. When the firing is complete, the values assigned to floating variables are discarded. If the rule is subsequently re-fired, because of its generalized nature, then any floating variables may acquire totally different values.

Some of the most interesting uses for floating variables exploit the fact that the value of a floating variable is really no more than a text string which could be either the value of an identifier of the name of an identifier or both.

4.2.5.3 KNOWLEDGE REPRESENTATION FOR THE ANALYSIS STAGE

It is well known that the occurrence of cold cracking, as seen in figure 3.6, is likely under the influence of

- susceptible microstructure;
- hydrogen presence in welding metal;
- critical temperature falling below some level and
- weld stress.

The presence of cold cracking can be fully assessed by the analysis of each condition, in this case each will become a new knowledge base (sub-domain) to be evaluated. Aspects correlating with these sub-domains can be represented by **figures 4.15 and 4.16**. The relation of these sub-domains (microstructure analysis, hydrogen presence, critical temperature, weld stress) with the general domain (cold cracking presence) will be specified by the particular outcome of the sub-domains which will be referred through the rule statement summarised in **table 4.2**.

Floating variables are a facility that can be used as an alternative to specific identifiers in XiPlus. In the table 4.2, Any_factor and This_level are floating variables to which specific identifiers can be assigned during the inferencing process.

Having established the main rules, the system will load each particular sub-knowledge in order to determine the conditions expressed by the rule statement. A

Table 4.2 - A fragment of an expert system showing the style of representation used in a rule based statement.

```
when query Anything
then check Anything

if  factor to be analyzed is Any_factor
and fault tolerance of Any_factor is This_level
then occurrence of Any_factor is This_level

if microstructure is susceptible
and hydrogen presence is likely
and welding stress is critical
and cooling rate at critical temperature is over limit
then fault tolerance of cold crack is considerable high
```

backward chaining control combined with forward chaining control will search for conditions related with the main goal represented in each sub-knowledgebase until all the conditions can be solved.

For instance, hydrogen presence can be analysed according to figure 4.18, and part of knowledge can be represented by the following statement

Rule 1:

```
if      condition to be analysed is This_problem
and     risk of This_problem is Some_level
then    risk is Some_level
```

Rule 2:

```
if      risk of hydrogen arc atmosphere is Some_level
and     risk of source hydro_carbon_moisture is Any_level
then    risk of hydrogen presence HAZ is Any_level
```

Rule 3:

```
if      risk of arc shield is Some_level
then    risk of hydrogen arc atmosphere is Some_level
```

Rule 4:

if risk of hydrogen presence plate material is Any_level
or if risk of hydrogen presence consumables is Any_level
then risk of source hydro_carbon_moisture is Any_level

Inference will continue until a final conclusion can be drawn. Conditions for the susceptible microstructure analysis, critical temperature and welding stress can be represented in the same way as described in section 3.7.3.

4.2.5.4 KNOWLEDGE REPRESENTATION CONSIDERING THE UNCERTAINTY ANALYSIS

In addition to the procedure described, a parallel methodology to evaluate the uncertainty propagation through the specific sub-domains was established. The knowledgebase itself in the specific sub-domains was complemented with a series of certainty factors that give the confidence value contained into the information source. The network propagation of uncertainty was evaluated using an appropriate model, and the rules incorporating uncertainty follow the conditions established in **table 4.3**.

In the simplest logical combination involving a conjunction (AND/OR) between two atomic pieces of evidence, the implication would be as follows;

IF(e1 and e2) THEN(c) ct(implication)=ci1
or **IF(e1 or e2) THEN(c)** ct(implication)=ci2.

The approximation made in EMYCIN is based on the fact that the certainty of the evidence is the certainty of the weakest piece of evidence, in case of AND combination, and the strongest in case of OR combination.

In this work, uncertainty evaluation is performed by invoking forward chaining and backward control. Every time the conditions are instantiated and a conclusion is reached then a reasoning system will be launched in order to check the

Table 4.3 - Uncertainty analysis assumptions.

if uncertainty calculus is required
and Method is a kind of uncertainty calculus
and assumptions of Method are established
then Method is a possible uncertainty calculus

if Method is a possible uncertainty calculus
and assumptions of Method includes Assumption
then check Assumptions values
and record that assumptions of Method are checked

if assumptions of Method includes Assumption
and confidence level of Assumption is determined
and implication factor of Assumption is also determined
then assumptions of Method are checked

if Method is a possible uncertainty calculus
and assumptions of Method are checked
then check uncertainty values

uncertainty propagation between nodes. The logical combination of evidence in this case could be represented by the following rule statement:

if condition 1 is checked
and cf1(condition 1) = Cf1
and condition 2 is checked
and cf2(condition 2) = Cf2
then general condition is checked
and check uncertainty evaluation

where cf(i..n) are the confidence factors attached to each condition. For instance, in the following rule

if grain refiners are not present
and peak temperature is high
then grain growth is likely to happen with cf= 0.7

the cf=0.7 indicates a evidence of 70% that hypothesis will be proven if the evidence above is confirmed.

When transferring this kind of representation into the rule based system used, the following set of rules was represented by **table 4.4**.

Table 4.4 - Logical combinations of evidence within a single rule.

```
if statement is 'OR condition'
and  cf1 = Cf1
 and cf2 = Cf2
then cf = max (cf1,cf2)
 and command reset cf1
 and command reset cf2
 and cf1 = cf
 and uncertainty has been evaluated

if statement is 'AND condition'
and  cf1 = Cf1
 and cf2 = Cf2
then cf = min (cf1,cf2)
 and command reset cf1
 and command reset cf2
 and cf1 = cf
 and uncertainty has been evaluated
```

If multiple rules support the same conclusion, when for instance both rules appear to be applicable, and they both support the same conclusion, this could be expressed by:

Rule 1:

If (e1) then (c)   ct(conclusion)= ct1

Rule 2:

If (e2) then (c)   ct(conclusion)= ct2

In this case, the reasoning system for getting a composite certainty can be combined in different ways depending the conditions established by the certainty factor individually. **Table 4.5** shows the representation used to get a conclusion inferred from the combinations between the two rules. It is important to observe that when one certainty is +1 and the other is -1 then condition assumed is that ctotal = 0.

As we can see from the two reasoning system, the rules will be processed as a group of two conditions every time. If we have more than two conditions, the rules

Table 4.5 - Combinations of evidence when multiple rules support the same conclusion.

```
if  cf1 >= 0
 and cf2 >= 0
then cf = cf1 + cf2 - cf1 * cf2
 and command reset cf1
 and command reset cf2
 and cf1 = cf
 and uncertainty has been evaluated

if  cf1 < 0
 and cf2 > 0
then cf = ( cf1 + cf2 ) / ( 1 - min ( -1 * cf1 , cf2 ) )
 and command reset cf1
 and command reset cf2
 and cf1 = cf
 and uncertainty has been evaluated

if  cf1 > 0
 and cf2 < 0
then cf = ( cf1 + cf2 ) / ( 1 - min ( cf1 , -1 * cf2 ) )
 and command reset cf1
 and command reset cf2
 and cf1 = cf
 and uncertainty has been evaluated

if  cf1 < 0
 and cf2 < 0
then cf = cf1 + cf2 + cf1 * cf2
 and command reset cf1
 and command reset cf2
 and cf1 = cf
 and uncertainty has been evaluated
```

will be divided into pairs and the conclusion will be the input for the next one group

4.2.5.5 KNOWLEDGE REPRESENTATION CONSIDERING THE DIAGNOSTIC PROCEDURE STAGE

A very interesting feature of the system is that it is possible using this methodology to establish the main reasons for the occurrence of any defect, even if the system detects that there is no possibility that the procedure will fail. Using this information it is possible to initiate an optimization procedure in which the system will advise the user of the main modifications to be made. Intuitively, the modifications can be performed and new diagnostics generated until a better solution can be reached. For instance, suppose that the system reaches the following conclusion:

if plate material is carbon manganese steel
and hardness value > 325
then risk of microstructure to fail is likely

Considering this conclusion, a fault analysis can be considered according to the rule statement expressed by the following structure:

if condition is Any_condition
and cause of Any_condition is This_fault
then fault is This_fault

This rule statement will allow the determination of the fault diagnosis, for instance,

if condition is susceptible microstructure
and cause of susceptible microstructure is high cooling rate
then fault is high cooling rate

and conclusion can be inferred, for example,

if fault is high cooling rate
then conclusion includes decrease cooling rate

Having identified the fault, report libraries can be used to advise the modifications to be taken, for example:

if conclusion includes decrease the cooling rate
and preheat temperature is insufficient
then action includes increase the preheat temperature
and report from file rep001

```
and   if    conclusion includes decrease the cooling rate
      and   welding process is GMAW
      and   arc energy < 1.5kJ
      then  action includes increase the arc energy level
      and   report from file rep002
```

The report's content (rep001, rep002, etc) is based on the information generated and will advise the user of appropriate new values for welding parameters (ie. which would decrease the cooling rate (vr_{85})). Actions could be:

* increase the preheat temperature

* increase arc energy

* decrease the thickness

* change plate material

4.3 VALIDATION TESTS

A very important phase in the development of an expert systems is validation. This post-knowledge representation test will verify the applicability and limitations of the developed system. Also it can show the incoherence present which could lead to incorrect decisions. Validation may encourage new development and further implementations.

In this specific case, tests were divided in two different stages. In a first stage, all knowledge was tested individually to verify the coherence. Tests concerning the characterization of the HAZ under thermal influence were performed in order to assess the correctness of the model used. Simulated results were compared with practical situations involving different welding conditions. The influence of uncertainty of individual knowledge was further evaluated. The applicability of this methodology to the determination of hydrogen presence under welding conditions and the welding stress further induced by hazardous conditions were also estimated.

In a second stage, the whole system was tested for situations involving a vast range of different welding conditions, within the limits of the system. Results generated under the present model were further compared with practical situations involving data from present work and also with values published in the literature.

4.3.1 FIRST STAGE - VALIDATION OF INDIVIDUAL KNOWLEDGEBASE

The effect of welding conditions on the properties of HAZ hardness was evaluated by using individual knowledge-base and this will be described in the next sections.

4.3.1.1 PREDICTED HAZ HARDNESS VALUE - SIMULATED RESULTS

Hardenability of steels can be characterized by investigating the variation of maximum hardness developed in the coarse grained HAZ (CGHAZ). It is necessary in this case, to have the capability of accurately estimating the hardness value from a knowledge of cooling rate and chemical composition.

Many formulae have been proposed for the prediction of HAZ hardness and on the present study three different methodologies were employed; ie those proposed by Suzuki, Yurioka and Düren. These equations cover a vast range of chemical composition and are claimed to be appropriate for the assessment of hardness value of carbon-manganese steel and high strength low alloy steels.

Suzuki (1985) proposed a formulae (equation 2.10) which was tested for 70 steels with chemical composition in the following ranges: c≤0.33 ; 0.48<mn<2.06; si≤0.65; cu<0.47; cr<1.06; ni<2.06; mo<0.66; v<0.07; nb<0.06; ti<0.02; b<0.002. Düren (1990) proposed an approach using equation 2.9. The range of chemical compositions in this case should be limited to c< 0.22; cr<0.5; al<0.06 and this formulae should not be applied to titanium or boron containing steels since it does not take into account the influence of these elements. Düren's prediction is claimed to be more reliable for the hardness assessment of short cooling time situation ($t_{8/5}$ under 12 seconds). Yurioka (1990) proposed a more general formulae (equation 2.11) which is valid for most of ferritic steels whose compositions are within the range c≤0.8, si≤ 1.2; mn≤2; cu≤0.9, ni≤10.

All of these formulae take into consideration the effect of hardenability and cooling time during welding. This represent a more comprehensive approach than that previously proposed by Dearden and O'Neill (highlighted in Düren (1990)) which predict the hardness of the HAZ by considering only the influence of carbon equivalent. Research to establish a more generic approach that can predict with accuracy the real hardness will continue and more use is likely to be made of mathematical modelling techniques, eg. Bahdeshia (1989). The approaches described above were considered to represent a range of reliable predictive methods and it was felt that their use in validating the expert systems was justified.

Validation trials were carried out by using the expert system described earlier to predict hardness values and comparing the results obtained with those derived from the equations proposed by Yurioka, Suzuki and Düren. Conditions were established using different welding conditions in order to cover a vast range of applications. The simulated results were considered using three different plate material C-Mn steels with carbon equivalents (IIW) of 0.35% (BS 1501-141/360), 0.45% (BS 4360/40B) and 0.56% (BS 1501-151/430) with chemical composition presented in **table 4.6**. The effect of preheat variation, arc energy, thickness and chemical composition on the hardness preview was evaluated. **Tables 4.7 - 4.9** show the results obtained using different parameters. Alternative assessments based on preheat evaluation, peak temperature, cooling time and cooling rate between 800-500°C were also determined and the results are shown in the same tables.

Simulation of a vast field of parameter variation was attempted in order to verify the hardness prediction in the HAZ using the three equations. The method used to determine the predicted hardness value initially checks for the validity range of each model. The final HAZ hardness was determined by the mean hardness from the individual empirical values. The standard deviation between the results of the various predictions was also recorded and gives an indication of the agreement between the different methods used. However, where one of the empirical methods does not apply for the chemical range specified, values are not allocated. If none of the formulae apply for the chemical range specified the system will advise the 'impossibility' of determination of an empirical HAZ hardness value. In this particular situation the system will not proceed with an attempt to use the result in HICC determination. It has been observed, however, that for the range of materials used, hardness can always been determined from the Yurioka methodology since this is far more comprehensive than the other formulae for ferritic steels. **Figures 4.17 - 4.19** show the influence of welding conditions on HAZ hardness predicted by different equations at distinct levels of heat input, thickness and preheat temperature.

4.3.1.2 EFFECT OF HEAT INPUT AND PREHEAT TEMPERATURE ON HAZ HARDNESS BY COMPARISION OF MEASURED AND SIMULATED RESULTS

In a report published by Swetnam (1984) carried out at Cranfield Institute of Technology, a series of tests were carried out on 40mm thick C-Mn steel (BS-4360-GR 55E) with a chemical composition as shown in **table 4.10**, in order to verify the influence of heat input and preheat temperature on HAZ hardness. Preheat temperatures of 15°C, 60°C, 100°C, 150°C and 250°C were used for single bead trials and welds were deposited at heat inputs of 1.0 kJ/mm, 1.5 kJ/mm and 2.0 kJ/mm. Variation in maximum HAZ hardness was recorded close as possible to the fusion line but located entirely within the coarse-grained region of the HAZ. Each hardness survey was carried out using a Vickeres Hardness Testing Machine with an indenting load of 10kg.

In order to determine the validity of the estimated HAZ hardness prediction equations, the same welding conditions were used in a simulated welding trial, and predictive HAZ hardness were determined through the application of Yurioka, Suzuki and Düren equations, as described before. Experimental and predictive results are summarised in **table 4.11**. The mean hardness was considered as the average of the three values obtained.

The curves shown in **figure 4.20** express the maximum HAZ hardness measured by Swetnam (1984) as a function of preheat temperature and heat input for single pass welds. Predictive hardness values obtained by using Yurioka, Düren and Suzuki are also plotted and the results can be compared.

Figure 4.21 illustrates the comparison between the actual and calculated hardness value using different equations.

4.3.1.3 HICC PREDICTION MODEL - COMPARED RESULTS USING DIFFERENT ASSESSMENTS

Models have been proposed for the prediction of HICC. Some of these models consider the hardness prediction as a parameter that gives an indication of HICC susceptibility, other models consider the hydrogen control method. This later methodology predicts a safe preheat temperature that can prevent the occurrence of this defect, and is derived usually by the combined influence of plate material thickness, hydrogen presence level, joint design and carbon equivalent. The Welding Institute has developed a nomogram that take into consideration the influence of these parameters.

In the expert system developed in the present work two models were considered for HICC risk prediction as described in chapter 4; these were the hardness prediction and the TWI preheat determination approach. The two approaches do not always provide the same conclusion and under different conditions one method may be more precise than the other. This fact is recognised in normal practice; for example, it is commonly reported (AWS D1.1, 1988) that carbon and carbon-manganese steels are susceptible to HICC if their hardness exceed 350 VPN, or if the steel is microalloyed then the limit may be extended to a hardness value exceeding 400 VPN. The TWI preheat prediction is reported to work well for steels with low carbon equivalent but is not as reliable for higher carbon values (Düren, 1990). In view of these differences the 'most appropriate' approach must be selected by a 'human expert' and a knowledge based computer system should be able to mimic this choice. The system developed here considered both approaches and a decision system was established to select the best approach in terms of evidence, considering the following statement:

- if both methods agree in their prediction the evidence for the occurrence of HICC has a high chance of being correct.

- if the methods disagree more evidence will be necessary in order for the system to reach reliable conclusion.

To illustrate these points and considering a fixed hydrogen level of 13ml/100gr concentration, a correlation between the hardness and hydrogen control method was evaluated. **Tables 4.7 - 4.9** shows a series of simulated results generated by using both methods for materials with IIW carbon equivalent levels of 0.36%, 0.45% and 0.56% respectively.

In another trial, hydrogen level concentration was hypothetically changed and **table 4.12** shows simulated results obtained. **Figure 4.22** shows plotted conditions obtained from this trial and illustrate the influence of hydrogen level on the predicted preheat temperature (using the TWI nomogram assessment) for different materials.

4.3.1.4 ASSESSMENT OF WELD STRESS PREDICTION MODEL USING UNCERTAINTY ANALYSIS INFLUENCE

The welding stress is generally a function of the joint design and is influenced by welding conditions. The restraint level associated with large thicknesses under high heat input conditions can give rise to a critical welding situation. Low heat input level can also be considered critical since they may result in fast cooling rates, the formation of critical microstructure, and the generation of a high stress concentration.

It is recognized that heat input, plate material thickness, welding design and restraint level of the joint play an important role in the welding stress prediction characteristics. A model which considered the influence of the main parameters and uncertainty approach was considered here. Each parameter was analysed separately and then the influence of these parameters when interacting with each other was considered. This approach considers an informal representation since there is no simple empirical model to determine the welding stress influence on weldments. The strategy acts in a very subjective way, only predicting the possibility of weld stress presence without determining its real value (this is similar to the approach normally adopted by the human expert).

Table 4.13 shows results for different welding conditions when using an uncertainty network propagation model according to the network established in **figure 3.11**. The influence of each element was converted into a number representing the confidence factor generated from that information. The final result was translated approximately in terms of possibility representing the 'risk of welding stress presence' under the chosen welding conditions.

4.3.1.5 ASSESSMENT OF HYDROGEN PRESENCE USING UNCERTAINTY ANALYSIS INFLUENCE

Hydrogen is a critical parameter influencing the occurrence of cold cracking. The hydrogen level will influence the directions to be taken when specifying a welding procedure. Hydrogen can originate from different sources, but moisture in the consumables or plate material is the most common source of hydrogen. Hydrogen can be measured relatively easily, but this is not often feasible at the procedure development stage. A knowledge based system which that takes into account the main factors affecting the hydrogen presence was therefore included in this system.

Hydrogen presence was evaluated by checking the welding conditions (consumables and material) when hydrogen level was not known. The evaluation method considered the influence of particular factors with 'certain' implications and the effect of using an uncertainty evaluation model propagation. The results are expressed in terms of a hydrogen content and a confidence level determined by the evaluation. Simulated results were generated for a range of different welding situations, which in real practice should be defined by the user. **Table 4.14** summarizes the results obtained in this case.

4.3.2 SECOND STAGE - VALIDATION OF THE SYSTEM

In order to validate the assessment of HICC using the current system, a series of trials were carried out to compare practical results from various sources with those predicted. Real data comprised values obtained from the literature or experimentally determined values from parallel work (mostly from restrained fillet weld cracking test CTS (Controlled Thermal Severity)). A series of different classes of C and C-Mn steels were analysed. Also the tests were extended to evaluation of lean alloy steels and HSLA steels under the original methodology and an extended approach was developed to evaluate alloy steels. In the first part, the expert systems predictions were compared with work published from the literature. In second and third trials, results were compared with research results from other work being carried out at CIT and involving alloy steels. In the third part, a series of welding procedure specifications provided from different sources were compared with predicted results.

4.3.2.1 ASSESSMENT OF HICC FOR C-Mn STEELS.

A series of trials were conducted using empirical results obtained from a study published by Hart (1991). This work entailed a study of the relative effect of compositional parameters, specially carbon, manganese, nickel, molybdenum and vanadium in carbon-manganese steels. The plate material thickness used was 20 mm and 50 mm and the elements were statistically balanced in order to obtain different ranges of chemical composition, which weight (%) of the steels are summarized **table 4.15**. The work was carried out using a restrained fillet weld cracking test (CTS) and bead-on-plate (BOP) tests with implant samples. The cracking tests were carried out using shielded metal arc welding (SMAW), with a weld hydrogen level of about 10 - 12 ml/100gr deposited metal. The welding consumables selected for the investigation were mild steel basic coated electrodes (AWS E7018). Welding conditions for the 4 mm electrodes employed consisted of 180 A/23 V. The risk of HICC presence was denoted by a crack/no crack factor (C/NC).

The same welding conditions were simulated using the expert system based on the methodology previously described. The severity of the CTS test was represented by considering welding subject to a high restraint level. The characterization of the microstructure was evaluated by considering the predicted HAZ hardness value determined using the equations discussed above. A check procedure determined automatically the validation of each equation, from the chemical composition was used. The Suzuki's equation was considered the basic equation in circumstances where it could be applied. For materials with chemical composition out of its range of application, the Yurioka and Düren equations were used and the final value determined by the mean value.

The results of the individual CTS tests simulated/experimental for each steel are summarised in **tables 4.16 - 4.17** for a 20mm thickness and arc energy from 0.7 to 5.0 kJ/mm. Hart reported that on four of the steels (1, 11, 15 and 21) no cracking was observed with the 20 mm plate even at the lowest arc energy practicable (approximately 0.7 kJ/mm). In this case, to establish a crack/no crack boundary for these steels, CTS tests on 50 mm thick plate was carried out and **table 4.18** summarise the comparative results obtained from empirical and simulated conditions for these tests. **Figure 4.23** shows the plotted critical arc energies representing the boundary between crack/no crack (simulated and empirical conditions) for the materials tested (CE_{iiw}) in different welding conditions. **Figure 4.24** illustrate the comparison between the actual and calculated critical arc energies for these conditions.

4.3.2.2 ASSESSMENT OF HICC - LEAN ALLOY STEELS

A series of experimental lean alloy steels was subjected to a CTS tests at Cranfield Institute of Technology (Healy, 1992). These non-standard steels has been used by steelmakers with controlled alloy additions to provide alternative means of achieving adequate strength in both normalised and accelerated cooled plates. The plate material thickness considered range from 15 mm to 50 mm, and the chemical composition and mechanical properties of the material tested are given in **table 4.19**. The material was welded using a restrained fillet weld cracking test (CTS) and bead-on-plate tests with implant samples. The cracking tests were carried out using shielded metal arc welding (SMAW), with a weld hydrogen level of about 10-15 ml/100gr deposited metal, except for steel number 7 (Ys=690 MPa), which the hydrogen level was kept under 5 ml/100gr. The critical arc energy for the boundary crack/no crack over each steel was determined. Also, the correspondent critical HAZ hardness value for the crack section was measured using a Vickers 10 load.

Using the same approach described in previous section to compare predicted/experimental results, the welding conditions used for the CTS test were simulated by the expert system. The severity of the CTS test were represented by considering a welding subject to a high restraint level. The characterization of the microstructure condition were evaluated by considering the predicted HAZ hardness value determined under the use of the equations discussed before. A series of simulation were carried out in order to determine the critical arc energy correspondent to the boundary crack/no cracking. The correspondent predicted hardness for each welding condition was recorded.

The results of the individual CTS tests simulated/experimental for each steel are summarised in **table 4.20**.

Figure 4.25(a) shows the plotted critical arc energies representing the boundary between crack/no crack (simulated and empirical conditions) for the materials tested (CE_{IIW}). **Figure 4.25(b)** summarises the results for critical arc energy predicted and experimental. **Figure 4.26** shows a comparision between the results using Boothby and Hart predictive methods for the same set of steels.

4.3.2.3 ASSESSMENT OF HICC - HIGH-STRENGTH LOW-ALLOY STEELS

High-strength low-alloy (HSLA) steels, also referred to as microalloyed steels, can be defined as steels possessing a yield strength of at least 43 kPa/mm^2. Strength is achieved by microalloying or special thermomechanical processing or a combination of both. The more common types of these steels are of the C-Mn with additions of Nb and/or V to increase the strength through grain refinement and precipitation hardening. Several steels have been developed which use additions of Ti and B together with controlled rolling and controlled cooling which results in extremely fine grain sizes and high strength with low carbon content. Important to the processing of these steels is careful control of the nitrogen content and the aluminium level. Many of the developments originated with pipeline steels in the early 1970's.

The HSLA steels shows a particular behaviour when welded, occasioned by its generally low CE. In order to estimate the assessment of HICC, a set of steels were welded using a restrained fillet weld cracking test (CTS). The chemical composition, properties and thickness of the plate materials are summarised in **table 4.21**. The cracking tests were carried out using shielded metal arc welding (SMAW), with a weld hydrogen level of about 10-15 ml/100gr deposited metal. The coarse HAZ hardness and the proportion of faces cracked from a total of six measurements was recorded from different welding conditions.

The actual results were compared with predictive values for the crack/no crack boundary by using a conventional methodology (Hardness Control approach) and a Critical Stress Control approach. In the Hardness Control, the preheat and critical arc energy were determined for the limit crack condition. In case of Critical Stress Control, the weldability of the steels were evaluated by measuring an index represented by the ratio of the lower critical stress and yield strength. It is assumed if the ratio of LCS and YS is one or greater than one, the steel can be safely welded under the welding conditions and hydrogen levels employed during the implant test. The LCS, in case, were evaluated considering the most appropriate equation for the material being welded as discussed earlier. The results between actual and predicted conditions are summarised in **table 4.22** (Laws,1992).

Table 4.6 - Chemical composition of C-Mn steels tested.

	C%	Si%	Mn%	P%	S%	Cr%	Mo%	Ni%	Cu%	Al%	Ce%
BS-1501/151 Grade 430	0.16	0.00	0.50	0.050	0.05	0.25	0.10	0.30	0.30	0.00	0.35
BS-4360 Grade 40B	0.20	0.50	1.50	0.050	0.00	0.00	0.00	0.00	0.30	0.00	0.45
BS-1501/141 Grade 360	0.25	0.35	1.20	0.030	0.045	0.25	0.10	0.30	0.30	0.00	0.56

Table 4.7 - Results obtained from C-Mn steel* (ce=0.35%) under different welding conditions (simulated results).

No	th	HI	T_{pk}	$t_{8/5}$	$vr_{8/5}$	T0	$T0_{ev}$	HARDNESS ** HV10					HICC*** APPROACH	
	mm	kJ	°C	s	°C/s	°C	°C	Hvd	Hvs	Hvy	Hv	σ	TWI	HDN
1	15	0.50	754	3.0	98.5	100	0	315	394	359	355	40	N	≈Y
2	15	0.70	873	5.9	50.6	100	0	255	332	304	297	38	N	N
3	15	0.80	919	7.7	38.7	100	0	238	307	281	275	34	N	N
4	15	0.90	959	9.7	30.6	100	0	226	285	263	258	29	N	N
5	15	1.10	1025	14.6	20.5	100	0	211	248	237	232	19	N	N
6	15	1.30	1076	20.4	14.6	100	0	201	217	221	213	10	N	N
7	25	0.50	582	3.0	98.5	100	20	313	394	359	355	40	N	≈Y
8	25	0.80	740	4.8	54.9	100	0	270	350	321	313	40	N	N
9	25	0.90	781	5.4	48.8	100	0	261	339	311	303	39	N	N
10	25	1.10	852	6.6	44.7	100	0	247	321	294	287	37	N	N
11	25	1.30	910	7.9	37.8	100	0	237	305	280	274	34	N	N
12	25	1.50	959	9.1	32.8	100	0	230	292	268	263	31	N	N
13	25	1.70	1000	12.5	23.8	100	0	216	262	246	241	23	N	N
14	15	0.50	675	2.1	140.7	0	0	346	427	382	385	40	N	Y
15	15	0.70	802	2.9	100.5	0	0	315	396	361	357	40	N	≈Y
16	15	0.90	895	5.6	52.9	0	0	259	336	308	301	38	N	N
17	15	1.10	967	8.4	354	0	0	233	299	274	268	33	N	N
18	15	1.30	1023	11.8	25.3	0	0	219	268	249	245	25	N	N
19	25	0.60	556	2.5	117.2	0	46	330	410	371	370	40	Y	Y
20	25	0.80	660	3.4	87.9	0	0	302	383	351	345	40	N	N
21	25	1.00	744	4.2	70.3	0	0	282	363	333	326	40	N	N
22	25	1.20	812	5.1	58.6	0	0	266	346	317	309	40	N	N
23	25	1.40	870	5.9	50.2	0	0	255	331	304	296	38	N	N
24	25	1.60	918	6.8	43.9	0	0	246	319	292	285	36	N	N

Keys:

* BS 1501-451 Grade 430

** Hardness prediction: Hvd (Düren); Hvy (Yurioka); Hvs (Suzuki); Hv (mean value).

*** Diagnostic: TWI (TWI nomogram); HDN (Hardness approach)

N/Y : No/Yes HICC tendency prediction

Table 4.8 - Results obtained for C-Mn steel* (ce=0.45%) using several welding conditions.

No	Th	HI	T_{pk}	$t_{8/5}$	$vr_{8/5}$	T0	$T0_{ev}$	HARDNESS ** HV10					HICC *** APPROACH	
	mm	kJ	°C	s	°C/s	°C	°C	Hvd	Hvs	Hvy	Hv	σ	TWI	HDN
1	15	0.50	754	3.0	98.5	100	142	487	437	441	455	27	Y	Y
2	15	0.70	873	7.2	41.3	100	116	391	386	383	386	4	Y	Y
3	15	0.80	919	9.5	31.5	100	103	361	362	357	360	2	Y	Y
4	15	0.90	959	11.8	25.3	100	82	337	343	334	338	4	N	N
5	15	1.10	1025	16.4	18.1	100	33	300	314	302	305	7	N	N
6	15	1.30	1076	21.1	14.1	100	0	273	295	281	283	11	N	N
7	25	0.50	582	3.0	98.5	100	173	487	437	441	455	27	Y	Y
8	25	0.80	740	4.8	61.5	100	145	435	414	415	421	11	Y	Y
9	25	0.90	781	5.4	54.7	100	137	422	407	407	412	8	Y	Y
10	25	1.10	852	6.61	44.7	100	121	400	392	390	394	5	Y	Y
11	25	1.30	910	7.9	37.8	100	106	382	378	375	378	3	≈Y	Y
12	25	1.50	959	9.1	32.8	100	81	366	366	361	364	2	N	≈Y
13	25	1.70	1000	14.7	20.2	100	52	312	323	312	315	6	N	N
14	15	0.50	675	2.1	140.7	0	142	527	448	454	476	43	Y	Y
15	15	0.70	802	2.9	100.5	0	116	489	438	442	456	28	Y	Y
16	15	0.90	895	6.9	43.4	0	82	396	389	387	390	4	Y	Y
17	15	1.10	967	10.1	29.5	0	33	354	356	350	353	3	Y	≈Y
18	15	1.30	1023	13.4	22.3	0	0	323	331	321	325	5	N	N
19	25	0.80	660	3.4	87.9	0	145	475	433	436	448	23	Y	Y
20	25	1.00	744	4.2	70.3	0	129	450	422	423	431	15	Y	Y
21	25	1.20	812	5.1	58.6	0	113	430	411	412	417	10	Y	Y
22	25	1.40	870	5.90	50.2	0	96	413	401	400	404	7	Y	Y
23	25	1.60	918	6.8	43.9	0	67	398	391	389	392	4	Y	Y
24	25	1.80	960	7.6	39.0	0	37	385	381	378	381	3	Y	Y
25	25	2.00	997	8.5	35.1	0	7	373	372	368	371	2	≈Y	≈Y
26	25	2.10	1013	13.1	22.7	0	0	325	333	323	327	5	N	N

Keys:

* BS 4360/Grade 40B

** Hardness prediction: Hvd (Düren); Hvy (Yurioka); Hvs (Suzuki); Hv (mean value).

*** Diagnostic: TWI (TWI nomogram); HDN (Hardness approach)

N/Y : No/Yes HICC tendency prediction

Table 4.9 - Results obtained for C-Mn steel* (ce=0.56%) using several welding conditions.

No	Th	HI	T_{pk}	$t_{8/5}$	$vr_{8/5}$	T0	$T0_{ev}$	Hardness** HV10					HICC*** APPROACH	
-	mm	kJ	°C	s	°C/s	°C	°C	Hvd	Hvs	Hvy	Hv	σ	TWI	HDN
1	15	0.9	895	6.9	43.0	0	156	485	473	485	481	6	Y	Y
2	15	1.1	967	10.1	29.5	0	137	462	449	462	457	7	Y	Y
3	15	1.3	1023	13.4	22.3	0	119	439	426	439	434	7	Y	Y
4	15	1.5	1069	16.6	18.0	0	102	417	405	417	413	6	Y	Y
6	15	1.7	1107	20.2	14.8	0	70	395	386	395	392	5	Y	Y
7	15	1.8	1124	22.6	13.2	0	54	381	375	381	379	3	Y	Y
8	15	2.0	1153	27.9	10.7	0	20	355	356	355	355	1	#Y	#Y
9	15	2.2	1179	33.8	7.7	0	0	333	340	333	335	4	N	N
10	15	0.9	229	11.8	25.3	100	146	451	437	451	446	8	Y	Y
11	15	1.1	1025	16.4	18.1	100	137	418	406	418	414	6	Y	Y
12	15	1.3	1076	21.1	14.1	100	119	389	382	389	386	4	Y	Y
13	15	1.5	1118	27.1	11.0	100	102	358	358	358	358	0	#Y	#Y
14	15	1.6	1136	30.9	9.6	100	87	343	347	343	344	2	N	N
16	15	1.8	1167	39.1	7.6	100	54	318	329	318	321	6	N	N
17	25	0.9	781	5.4	54.7	100	188	495	483	495	491	6	Y	Y
18	25	1.1	852	6.6	44.7	100	180	487	475	487	483	6	Y	Y
19	25	1.3	910	7.9	37.8	100	169	478	466	478	474	6	Y	Y
20	25	1.5	959	9.1	32.8	100	156	470	457	470	465	7	Y	Y
21	25	1.7	1000	14.7	20.2	100	144	430	417	430	425	7	Y	Y
22	25	1.9	1036	19.1	15.6	100	133	401	392	401	398	5	Y	Y
23	25	2.1	1067	23.6	12.6	100	123	375	371	375	373	2	Y	Y
24	25	2.4	1106	30.5	9.8	100	107	345	348	345	346	1	#Y	#N
26	25	2.5	1118	32.8	9.1	100	102	336	342	336	338	3	#Y	N
27	25	0.9	820	6.7	44.4	150	188	486	475	486	482	6	Y	Y
30	25	1.5	990	11.2	26.6	150	156	455	441	455	450	8	#Y	Y
31	25	1.7	1030	21.1	14.1	150	144	389	382	389	386	4	#N	Y
32	25	1.9	1064	26.7	11.2	150	133	360	360	360	360	0	N	#Y
33	25	2.1	1093	32.3	9.2	150	123	338	343	338	339	2	N	N

Keys:
* BS 1501-141/Grade 360
** Hardness prediction: Hvd (Düren); Hvy (Yurioka); Hvs (Suzuki); Hv (mean value).
*** Diagnostic: TWI (TWI nomogram); HDN (Hardness approach)
N/Y : No/Yes HICC tendency prediction

Table 4.10 - Chemical composition of base material tested (BS 4360/50E) in real condition.

Steel Type	C%	Si%	Mn%	P%	S%	Cr%	Mo%	Ni%	Cu%	Al%	Nb%	Ti%	V%	N%	Ce%
BS 4360-Gr.50E*	0.122	0.425	1.33	0.012	0.002	0.072	0.026	0.156	0.248	0.043	0.036	0	0	0.007	0.386

* - Fabrique de fer de Charleroi

Table 4.11 - Real and simulated HAZ hardness using empirical models for C-Mn steel (BS 4360/50E,th=40mm) welded in different preheats and arc energy conditions.

HI	T_0	HARDNESS MEASURED	HARDNESS PREDICTED			
			YURIOKA	Düren	SUZUKI	HV (mean)
(kJ/mm)	(°C)	(HV_{10})	(HV_{10})	(HV_{10})	(HV_{10})	(HV_{10})
1.0	15	384	328	355	349	344
1.0	60	382	317	343	341	333
1.0	100	371	305	331	332	322
1.0	150	349	290	316	319	308
1.0	250	293	257	277	287	273
1.5	15	351	298	324	326	316
1.5	60	351	287	312	316	305
1.5	100	334	276	300	307	294
1.5	150	310	263	285	293	280
1.5	250	266	239	246	264	249
2.0	15	321	277	302	308	295
2.0	60	325	267	290	298	285
2.0	100	309	258	278	288	274
2.0	150	295	248	263	276	262
2.0	250	258	229	224	251	234

Table 4.12 - Simulated results for C-Mn steels (CE = 0.45% and 0.56%, thickness = 25mm) welded with different hydrogen levels and arc energies.

No	HI	h_{level}	BS-4360 Gr 40B (CE=0.45%)				BS-1501/141 Gr 360 (CE=0.56%)			
			$T0_{av}$	HV*	HICC** APPROACH		$T0_{av}$	HV	HICC APPROACH	
-	kJ/mm	ml/100g	°C	HV10	TWI	HDN	°C	HV10	TWI	HDN
1	0.70	3	85	435	Y	Y	169	497	Y	N
2	0.70	6	152		Y	Y	196		Y	Y
3	0.70	10	153		Y	Y	197		Y	Y
4	0.70	15	166		Y	Y	202		Y	Y
5	0.90	3	42	424	Y	Y	151	492	Y	Y
6	0.90	6	136		Y	Y	187		Y	Y
7	0.90	10	137		Y	Y	188		Y	Y
8	0.90	15	148		Y	Y	194		Y	Y
9	1.10	3	0	419	Y	Y	137	487	Y	Y
10	1.10	6	120		Y	Y	178		Y	Y
11	1.10	10	121		Y	Y	180		Y	Y
12	1.10	15	134		Y	Y	185		Y	Y
13	1.30	3	0	405	N	Y	122	480	Y	Y
14	1.30	6	105		Y	Y	166		Y	Y
15	1.30	10	106		Y	Y	169		Y	Y
16	1.30	15	119		Y	Y	177		Y	Y
17	1.50	3	0	390	N	Y	108	474	Y	Y
18	1.50	6	79		Y	Y	153		Y	Y
19	1.50	10	81		Y	Y	156		Y	Y
20	1.50	15	105		Y	Y	166		Y	Y
21	1.70	3	0	380	N	Y	89	467	Y	Y
22	1.70	6	50		Y	Y	141		Y	Y
23	1.70	10	52		Y	Y	144		Y	Y
24	1.70	15	82		Y	Y	154		Y	Y
25	2.00	3	0	348	N	Y	49	442	Y	Y
26	2.00	6	5		N	Y	125		Y	Y
27	2.00	10	7		N	Y	128		Y	Y
28	2.00	15	41		Y	Y	138		Y	Y

Keys:

* - Predicted HAZ hardness

** Diagnostic: TWI (TWI nomogram); HDN (Hardness approach)

N/Y : No/Yes HICC tendency prediction

Table 4.13 - Examples of simulated welding stress evaluation using a reasoning mechanism based on uncertainty analysis (the values extracted refers to network in figure 3.11).

No	Th*	HI	Restr. level**	λ_{bm}	Gap	cs1	cs2	cs3	cs5	cs6	cs7	cs8	cs9	cs10***
	-	(kJ)	-	(%)	(mm)									
1	1.0	1.0	H	25	2	0.56	-0.14	0.54	0.69	-0.54	0.45	-0.56	-0.57	0.27
2	0.4	1.0	H	8	5	-0.42	-0.14	0.54	0.07	0.54	-0.33	0.42	0.54	0.57
3	0.4	1.0	S	20	5	-0.42	-0.14	0	-0.45	0.18	-0.33	0.42	0.26	-0.26
4	0.4	1.0	S	20	3	-0.42	-0.14	0	-0.45	0.18	-0.33	-0.56	-0.57	-0.76
5	0.4	1.0	S	30	3	-0.42	-0.14	0	-0.45	-0.54	-0.33	-0.56	-0.77	-0.87
6	1.0	1.3	M	25	2	0.56	-0.14	0	0.44	-0.54	-0.46	-0.56	-0.57	-0.23
7	0.4	2.0	N	30	3	-0.42	0.42	0	0	-0.54	-0.33	-0.56	-0.77	-0.77
8	0.4	2.0	H	30	3	-0.42	0.42	0.54	0.49	-0.54	-0.33	-0.56	-0.77	-0.57
9	1.0	2.0	H	30	3	0.56	0.42	0.54	0.79	-0.54	0.45	-0.56	-0.57	0.521
10	1.0	2.0	H	25	2	0.56	0.42	0.54	0.79	-0.54	0.45	-0.56	-0.57	0.52
11	1.0	2.0	H	15	5	0.56	0.42	0.54	0.79	0.18	0.45	0.14	0.55	0.91
12	1.0	2.0	H	8	5	0.56	0.42	0.54	0.79	0.54	0.45	0.42	0.77	0.95
13	0.4	2.0	H	8	5	-0.42	0.42	0.54	0.49	0.54	-0.33	0.42	0.54	0.76

* Relative thickness

** Restraint level: (H/M/S - High/Medium/Small)

*** cs10 : risk of high stress presence (range value -1 to +1)

Table 4.14 - Examples of an inference to derive the evidence of high hydrogen concentration level based on the welding conditions established (the values extracted refers to network in figure 3.10).

WELDING CONDITIONS

No	WELD PROC.	STAND-OFF	PLATE MATERIAL CONTAMINATION		CONSUMABLE CONTAMINATION		WELD. SITE			POSSIB. GAS LINE LEAKING	POSSIB. GAS LINE CONDENS.	ELECT. ORIENT.	GAS PURITY
		(mm)	CONT. (Y/N)	LEVEL	CONT. (Y/N)	LEVEL	LOCAL (EXT/ INT)	WIND COND.	COVER (ADEQ/ INADEQ)	(0 - 1)	(0 - 1)	(degree)	(%)
1	GMAW	25	y	medium	y	medium	ext	normal	-	0.0	0.2	60	95
2	GMAW	25	y	medium	y	small	ext	normal	-	0.0	0.2	60	95
3	GMAW	20	y	medium	y	medium	ext	normal	-	0.0	0.5	60	95
4	GMAW	25	y	high	y	high	ext	normal	-	0.0	0.2	60	95
5	GMAW	25	y	small	y	small	ext	excessive	adeq	0.0	0.2	60	95
6	GMAW	25	y	medium	y	medium	int	-	-	0.0	0.2	60	95
7	GMAW	20	y	medium	y	medium	ext	normal	-	0.5	0.5	60	85
8	GMAW	25	y	small	y	high	ext	normal	-	0.0	0.2	60	85
9	SMAW	25	y	medium	y	medium	ext	normal	-	--	--	60	--
10	SMAW	25	y	high	y	high	ext	normal	-	--	--	60	--
11	SMAW	30	y	small	y	small	ext	excessive	inad	--	--	60	--
12	SMAW	25	y	small	y	medium	int	-	-	--	--	60	--
13	SMAW	25	y	small	y	high	ext	normal	-	--	--	60	--
14	SMAW	18	y	small	y	small	ext	excessive	adeq	--	--	60	--

RESULTS (EVIDENCE FOR HYDROGEN PRESENCE)

No.	ch13	ch14	ch17	ch19	ch21	ch26	ch27	cfd2*
1	0.54	-0.27	-0.096	-0.032	0.15	0	0.119	0.56
2	0.54	-0.27	-0.096	-0.032	0.148	-0.18	-0.07	0.46
3	-0.18	-0.27	0	-0.032	-0.22	0	-0.177	0.41
4	0.54	-0.27	-0.096	-0.032	0.148	0.816	0.83	0.91
5	0.54	-0.27	-0.096	-0.032	0.15	-0.54	-0.47	0.26
6	0.54	-0.27	-0.096	-0.032	0.148	0	0.12	0.56
7	-0.18	-0.27	0.384	-0.032	0.03	0	0.02	0.51
8	0.54	-0.27	-0.096	-0.032	0.148	0.54	0.59	0.79
9	0.54	-0.27	--	-0.032	0.19	0	0.16	0.58
10	0.54	-0.27	--	-0.032	0.19	0.816	0.84	0.92
11	0.54	-0.27	--	0.096	0.22	-0.54	-0.43	0.28
12	0.54	-0.27	--	-0.032	0.17	0	0.14	0.57
13	0.54	-0.27	--	-0.032	0.19	0.54	0.61	0.81
14	-0.18	-0.27	--	0.096	-0.19	-0.54	-0.61	0.19

* - cfd2 - represents the evidence (confidence factor) that the hydrogen content in this case is high for the specific welding condition established.

Table 4.15 - Chemical composition of steels used in the theoretical simulation trials (Hart, 1991).

Steel identity	Plate thickness, mm	Element, wt%														* CE
		C	S	P	Si	Mn	Ni	Cr	Mo	V	Cu	Ti	Al	O	N	
1	20	0.07	<0.005	0.007	0.35	1.08	0.01	0.01	<0.01	<0.01	<0.01	0.005	0.047	0.003	0.009	0.25
	50	0.07	<0.005	0.006	0.31	1.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.003	0.047	0.003	0.009	0.24
2	20	0.18	<0.005	0.010	0.36	1.97	0.02	0.03	<0.01	0.01	0.01	0.004	0.050	0.003	0.010	0.52
	50	0.18	<0.005	0.008	0.32	1.93	0.02	0.02	0.01	<0.01	<0.01	<0.003	0.045	0.002	0.009	0.51
3	20	0.19	0.008	0.009	0.35	1.13	0.88	0.03	0.51	0.13	0.02	0.006	0.058	0.002	0.007	0.57
	50	0.18	0.006	0.007	0.32	1.07	0.86	0.02	0.49	0.14	0.01	<0.003	0.061	0.003	0.006	0.55
4	20	0.08	0.005	0.007	0.34	2.00	0.89	0.03	0.54	0.14	0.01	0.005	0.052	0.004	0.010	0.62
	50	0.07	0.005	0.007	0.33	1.98	0.87	0.02	0.53	0.14	0.01	<0.003	0.050	0.004	0.011	0.60
5	20	0.17	<0.005	0.008	0.26	1.03	0.86	0.01	<0.01	<0.01	0.01	0.003	0.041	0.004	0.009	0.40
	50	0.18	<0.005	0.007	0.26	1.04	0.85	0.01	0.01	<0.01	0.01	<0.003	0.036	0.004	0.008	0.41
6	20	0.08	<0.005	0.008	0.32	1.94	0.88	0.02	<0.01	<0.01	0.01	0.004	0.030	0.005	0.009	0.47
	50	0.08	<0.005	0.007	0.31	1.96	0.86	0.02	0.02	<0.01	<0.01	<0.003	0.021	0.003	0.009	0.47
7	20	0.07	0.006	0.008	0.30	1.11	0.02	0.02	0.50	0.14	0.01	0.004	0.044	0.003	0.008	0.39
	50	0.07	0.006	0.008	0.29	1.08	0.02	0.02	0.49	0.14	<0.01	<0.003	0.039	0.003	0.008	0.38
8	20	0.17	<0.005	0.008	0.29	1.99	0.02	0.03	0.51	0.15	0.02	0.003	0.038	0.003	0.009	0.64
	50	0.17	<0.005	0.008	0.27	1.93	0.02	0.02	0.50	0.14	0.01	<0.003	0.036	0.006	0.010	0.63
9	20	0.17	<0.005	0.007	0.25	1.01	0.01	0.03	0.48	<0.01	0.02	<0.003	0.045	0.003	0.005	0.44
	50	0.17	<0.005	0.008	0.25	1.03	0.01	0.03	0.49	<0.01	0.02	<0.003	0.044	0.003	0.006	0.45
10	20	0.07	<0.005	0.008	0.32	1.90	0.02	0.02	0.48	<0.01	0.02	<0.003	0.041	0.003	0.008	0.49
	50	0.08	<0.005	0.007	0.32	1.90	0.02	0.02	0.48	<0.01	0.02	<0.003	0.039	0.004	0.008	0.50
11	20	0.06	<0.005	0.006	0.34	1.05	0.82	0.01	<0.01	0.14	<0.01	0.003	0.042	0.002	0.007	0.32
	50	0.07	<0.005	0.006	0.34	1.06	0.82	0.01	<0.01	0.13	<0.01	<0.003	0.047	0.003	0.008	0.33
12	20	0.17	<0.005	0.009	0.33	1.92	0.84	0.02	<0.01	0.14	0.02	<0.003	0.052	0.004	0.008	0.58
	50	0.17	0.005	0.009	0.35	1.95	0.83	0.02	<0.01	0.14	0.02	<0.003	0.047	0.003	0.008	0.58
13	20	0.17	0.005	0.007	0.32	1.05	0.01	0.01	<0.01	0.14	0.01	<0.003	0.046	0.003	0.008	0.38
	50	0.18	<0.005	0.007	0.31	1.03	0.01	0.01	<0.01	0.13	0.01	<0.003	0.049	0.003	0.008	0.38
14	20	0.08	0.005	0.008	0.37	1.91	0.02	0.02	<0.01	0.13	<0.01	<0.003	0.048	0.003	0.008	0.43
	50	0.07	0.005	0.007	0.37	1.92	0.02	0.02	<0.01	0.13	<0.01	0.003	0.042	0.002	0.008	0.42
15	20	0.07	<0.005	0.006	0.31	1.01	0.83	0.02	0.45	<0.01	0.01	<0.003	0.038	0.003	0.008	0.39
	50	0.07	<0.005	0.009	0.33	1.00	0.83	0.01	0.46	<0.01	0.02	<0.005	0.041	0.004	0.008	0.39
16	20	0.17	0.006	0.009	0.33	1.98	0.86	0.02	0.49	<0.01	0.02	<0.003	0.041	0.002	0.010	0.66
17	20	0.11	<0.005	0.008	0.33	1.03	0.02	0.01	0.45	0.12	0.02	<0.003	0.043	0.003	0.008	0.40
18	20	0.15	<0.005	0.009	0.32	1.48	0.02	0.01	0.46	<0.01	0.02	<0.003	0.031	0.005	0.008	0.49
19	20	0.17	<0.005	0.009	0.32	1.90	0.32	0.01	0.01	<0.01	0.01	<0.003	0.039	0.003	0.008	0.51
20	20	0.07	<0.005	0.008	0.30	1.92	0.83	0.01	0.01	0.06	<0.01	<0.003	0.042	0.003	0.008	0.46
21	20	0.06	<0.005	0.006	0.28	1.01	0.82	0.01	0.19	0.10	<0.01	<0.003	0.036	0.003	0.007	0.34
	50	0.07	<0.005	0.008	0.26	1.00	0.83	<0.01	0.19	0.11	0.01	0.004	0.038	0.004	0.007	0.35

Nb <0.005, B <0.0005, Sn <0.01, Co <0.01 for all steels 1-21

*IIW carbon equivalent formula.

Table 4.16 - Compared cracking tendency results between simulated and real welding conditions for different types of steels.

20 mm plate and arc energies 0.7 to 3.0 kJ/mm																								
Steel Type	Eval. Met.*	Arc Energy, kJ/mm																						
		0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	3
1	Real Expt Hard	NC S NC		NC S NC																				
5	Real Expt Hard						C H C	 H 	 M 	C S NC		C/NC S NC			NC N NC									
6	Real Expt Hard					C H ≈NC				NC H NC		NC M NC	NC M NC		NC S NC									
7	Real Expt Hard		C H ≈NC	C H NC	NC S NC																			
9	Real Expt Hard												– M NC		– S NC	C S NC	C/NC S NC		NC N NC					
10	Real Expt Hard		C H C		C H ≈C			C H ≈NC	C H NC		NC H NC		NC M NC		– M NC		– S NC							
11	Real Expt Hard	NC N NC																						
13	Real Expt Hard			C H ≈C		C H ≈NC	– S NC			C S NC	NC S NC													
14	Real Expt Hard					C H ≈NC			C M NC	NC S NC														
15	Real Expt Hard		NC H ≈NC	NC H NC		 M NC	NC S NC																	
17	Real Expt Hard		C H ≈C					C/NC M NC	C M NC	– S NC	NC S NC													
18	Real Expt Hard									C H C						C H ≈NC		C M NC	NC M NC	NC M NC	– S NC			
19	Real Expt Hard										C H C					C H ≈C				C H NC	– M NC	C M NC	NC S NC	NC S NC
20	Real Expt Hard	C H C	C H ≈C			NC H ≈NC			C H NC		NC M NC	NC S NC												
21	Real Expt Hard	NC S NC	NC S NC			NC S NC																		

* - Methods of Cracking Evaluation:

Real : Real CTS evaluation.
Expt.: Expert system risk evaluation.
Hard.: HICC evaluation considering HAZ hardness prediction.
C/NC : Crack/No Crack presence
H/M/S: High/Medium/Small cracking tendency using a predictive method.

Table 4.17 - Compared cracking tendency results between simulated and real welding conditions for different types of steels.

20 mm plate and arc energies 2.0 to 5.0 kJ/mm																					
Steel Type	Eval. Met.*	Arc Energy, kJ/mm																			
		2.0	2.2	2.3	2.4	2.6	2.7	2.8	3.0	3.1	3.3	3.5	3.7	3.9	4.0	4.2	4.3	4.4	4.6	4.7	4.9
2	Real Expt Hard	C H ≈NC	NC H NC		NC H NC	NC M NC	- S NC				NC S NC										
3	Real Expt Hard	C H C		C H C			C H ≈C			NC H NC		NC S NC			NC N NC						
4	Real Expt Hard	C H C		NC H C				C H NC		NC H NC		NC M NC		- S NC							
8	Real Expt Hard	C H C				C H ≈C				C H ≈C	C H ≈C	NC H ≈NC			NC M NC		- S NC				NC N NC
12	Real Expt Hard	- H C							- H ≈NC		- M NC		NC S NC								
16	Real Expt Hard				C H C				C H C	NC H C		C/NC H NC						NC H NC		- S NC	

\- Methods of Cracking Evaluation:

Real :	Real CTS evaluation.
Expt.:	Expert system risk evaluation.
Hard.:	HICC evaluation considering HAZ hardness prediction.
C/NC :	Crack/No crack presence
H/M/S:	High/Medium/Small cracking tendency using a predictive method.

Table 4.18 - Compared cracking tendency results between simulated and real welding conditions for different types of steels.

Steel Type	Eval. Meth.	50 mm plate and arc energies 0.6 to 1.6 kJ/mm									
		0.6	0.7	0.8	0.9	1.0	1.1	1.3	1.4	1.5	1.6
1	Real Expt Hard	NC S NC	NC S NC				NC S NC				
11	Real Expt Hard		C/NC S NC		NC S NC		NC S NC			NC S NC	
15	Real Expt Hard		C H ≈NC			C H NC		NC M NC			NC S NC
21	Real Expt Hard		NC M NC	NC S NC		NC S NC					

\- Methods of Cracking Evaluation:

Real :	Real CTS evaluation.
Expt.:	Expert system risk evaluation.
Hard.:	HICC evaluation considering HAZ hardness prediction.
C/NC :	Crack/No crack presence

Table 4.19 - Chemical composition and properties of modified steels tested.

Steel Type	C%	S%	P%	Si%	Mn%	Ni%	Cr%	Mo%	Cu%	Nb%	Al%	Ti%	V%	Thick (mm)	YP (MPa)
50D	0.19	0.016	0.015	0.42	1.35	0.02	0.022	0.002	0.06	0.028	0.022	-	0.004	25	350
50D (Mod.)	0.12	0.006	0.015	0.31	1.15	0.01	0.01	0.03	0.02	0.01	0.02	0.001	0.006	30	≈350
50E (Mod.)	0.14	0.003	0.014	0.35	1.31	-	-	-	0.02	0.03	0.051	-	-	30	350
50D (Mod.)	0.11	0.002	0.015	0.44	1.18	0.19	0.11	0.04	0.24	0.01	0.04	-	-	50	≈350
50D (Olac)	0.07	0.001	0.004	0.27	1.45	0.40	0.01	0.03	0.19	-	0.07	-	0.01	25	≈350
50D (Q&T)	0.11	0.002	0.010	0.34	1.35	0.30	0.07	0.02	0.23	0.016	0.023	-	-	15	≈500
50D (Q&T)	0.11	0.003	0.008	0.26	0.89	1.18	0.46	0.38	0.15	0.002	0.071	-	0.01	50	≈690

Table 4.20 - CTS results (Actual and simulated results) for modified alloy steels.

Steel Type	Thick	CE	Critical Arc Energy (measured)	Critical HAZ Hardness (measured)	HART (Calculated)		BOOTHBY (Calculated)		Conventional Methodology (calculated)		T0 (Calc.)
					Critical HAZ Hardness	Critical dt_{85}	Critical HAZ Hardness	Critical dt_{85}	HAZ Hardness	dt_{85}	
-	(mm)	(%)	(kJ/mm)	(HV 10)	(HV 10)	(s)	(HV 10)	(s)	(HV 10)	(s)	(°C)
50D	25	0.43	2.6	413	421	5.78	433	6.1	297	16.0	0
50D (Mod.)	30	0.32	1.5	384	400	3.05	375	2.6	317	3.6	0
50D (Mod.)	50	0.37	1.5	376	394	4.14	-	-	289	9.1	46
50E (Mod.)	30	0.36	2.3	381	411	3.52	389	4.17	306	5.9	0
50D (Olac)	25	0.35	<0.9	355	361	4.00	424	1.96	292	5.0	0
50D (Q&T)	15	0.39	1.3	380	393	4.88	388	4.93	317	6.2	0
50D (Q&T)	50	-	1.5	370	378	2.01	-	-	-	-	-

Table 4.21 - Chemical composition and properties of HSLA steels tested.

Designation	C%	S%	P%	Si%	Mn%	Ni%	Cr%	Mo	Cu%	Nb%	Al%	Ti%	V%
Superelso 500 (Creusot Loire)	0.09	0.0005	0.008	0.31	1.13	0.48	0.18	0.24	0.30	<0.01	0.02	0.005	0.05
55FMZ (Svenskt Stal)	0.09	0.001	0.012	0.30	1.29	0.25	0.01	0.07	0.08	<0.01	0.04	0.011	0.04
HSLA 80 (Lukens Steel)	0.06	0.003	0.012	0.31	0.60	0.87	0.75	0.02	1.15	0.036	0.024	0.004	0.004
450EMZ (British Steel)	0.08	0.001	0.011	0.29	1.23	0.50	0.02	0.17	0.02	0.004	0.028	0.004	0.046
RQT501 (British Steel)	0.12	0.005	0.012	0.23	1.335	0.03	0.01	0.10	0.03	<0.01	0.04	<0.005	0.044

Table 4.21 (Cont.)

Designation	Steel Type	Mechanical Property Data		Plate Thickness (mm)	CE %
		YS (MPa)	Cv(J) & -40C		
Superelso 500 (Creusot Loire)	Quenched & Tempered	564	214	30	0.42
55FMZ (Svenskt Stal)	Quenched & Tempered	505	267	30	0.35
HSLA 80 (Lukens Steel)	Precipitation Hardening	640	136	24	0.57
450EMZ (British Steel)	Quenched & Tempered	460	299	50	0.37
RQT501 (British Steel)	Quenched & Tempered	560	200	30	0.35

Table 4.22 - Compared cracking tendency for simulated and real results using HSLA steels welded in different welding conditions.

Steel	Th	Energy	HAZ HARDNESS		CRACKING TENDENCY				
			PREDICT.	MEASUR.	HARD. APPR.	CTS		LCS	
						Prop.	Real	Index	Crack
	mm	kJ/mm	HV 10	HV 10	-	-	-	-	-
RQT 501	30	1.2	308	341	≈NC	6/6	C	0.81	C
		1.6	288	296	NC	0/6	NC	0.87	C
		2.1	270	301	NC	0/6	NC	0.92	C
		2.3	264	280	NC	0/6	NC	0.93	C
55FMZ	30	1.1	288	324	NC	4/6	C	0.94	C
		1.5	269	321	NC	4/6	C	1.00	NC
		1.6	266	318	NC	6/6	C	1.02	NC
		1.9	256	297	NC	2/6	C	1.05	NC
		2.1	250	275	NC	4/6	C	1.07	NC
		2.4	243	246	NC	0/6	NC	1.10	NC
		2.6	239	267	NC	1/6	C	1.12	NC
450EMZ	50	1.2	286	303	NC	4/6	C	1.05	NC
		1.6	270	284	NC	4/6	C	1.12	NC
		2.0	257	258	NC	3/6	C	1.17	NC
		2.5	246	242	NC	2/6	C	1.23	NC
HSLA80	24	1.1	288	272	NC	2/6	C	0.69	C
		1.7	264	255	NC	3/6	C	0.76	C
		1.8	251	249	NC	2/6	C	0.77	C
		2.6	224	240	NC	1/6	C	1.13	NC

CHAPTER 5

DISCUSSION

The discussion is divided into three parts; the first concerns general aspects of the expert system structure design developed here; in the second part results from individual knowledge base validation are examined and the third part discusses the results of the whole system when compared with practical results.

5.1 GENERAL ASPECTS OF THE EXPERT SYSTEM DESIGN

In this section general aspects involving the design of the system are discussed.

5.1.1 ASPECTS INVOLVING AUTOMATIC CHECKING OF WELDING PROCEDURE SPECIFICATIONS

It is recognised by Thielsch (1966) that any analysis involving the assessment of welding procedure specifications needs to consider aspects involving

- welding process characteristics;
- energy input;
- base metal defects or compositions;
- material selection and properties;
- welding environment (joint design, fit-up, temperature, restraint, etc).

Weld defects and specially cracks are generated by poor specifications of welding conditions. The aim of the present work was to examine the procedure variables and predict the likelihood of cracking. The scope of the work was limited to demonstrating the feasibility of HICC risk prediction and although most welding procedures likely to encounter this defect are multipass welds. In this case the welding procedure analysis has been based on the first root pass. The reasons for this restriction are:

(1) most of the weld cracking-tests that have been developed are root- or first-pass cracking tests.

(2) Experience has shown that weld cracking is most likely to occur in the root pass

(3) As reported by **Davidson (1989)**, root cracking is enhanced because

  (a) the root pass is the first weld pass so that the preheat temperature is usually at the specified minimum, and there is no build-up of interpass temperature;

  (b) the energy input is usually lower than for the fill passes and;

  (c) high restraint and stress concentration usually exist. For example, an analysis of various weld-groove geometries has shown that elastic stress concentration factors ranged from 1.5 to 8 in the weld root but were only 1.5 at the toe of the last pass at the weld face.

As a consequence of the critical welding conditions in the root pass, it has been observed that the maximum HAZ hardness is higher in this condition than for multi-pass welding. **Swetnam (1984)**, for example, working with C-Mn steel, compared the maximum hardness range between first-pass and multi-pass welds. The results, reproduced here in **figure 5.1**, shows a higher hardness tendency in one pass welding than in multi-pass (it has been recognized that the hardness shows a straight correlation with the magnitude of cracking tendency, especially cold cracking).

One exception to these arguments is the situation regarding the final pass of a multipass weld. As described by Davidson (1989) for multi-pass welds, the HAZ may also exhibit cracking because,

(1) the beneficial effects of tempering from subsequent passes (tempering of the martensite) are absent and the interpass temperature (which aids diffusion of hydrogen out of the region) is not maintained, and

(2) the cooling rate of the last pass may be high if it is a cosmetic or repair pass which is applied when the nearly completed weldment is locally preheated (often only to the specified minimum preheat temperature used initially). The filler passes generally cool more slowly due to the build-up of interpass temperature from the multiple weld passes.

Thus, welding procedures that are developed to prevent cracking in the root pass are usually adequate and may be overly conservative for the remaining passes in the weldment. In a "watch-dog" welding procedure, as is the case of this project, the decision to concentrate only in the first pass seems to be adequate.

5.1.2 SYSTEM STRUCTURE

When developing expert systems of the type described it is necessary to consider the effect of changes in the knowledge base as new information becomes available. Systems need to be designed with enough flexibility to allow future users to incorporate or modify the knowledgebase when it becomes necessary. In this case the knowledgebase structure is an important factor to be considered when developing expert systems applications. The modularity implemented in this system was adopted as a means of addressing this problem.

In case of this project, the system structure was divided in several modules which perform different tasks as described in section 4.2. It is believed that the use of such a structure gives some important benefits for example;

- improved system flexibility by merely integration of new modules to the pre-existent structure;

- particular knowledge was developed and tested separately until all the tasks were performed as required;

- improved maintainability; since all the modules work independently. The knowledgebase can be updated and modified at any time without affecting the whole system structure. In this particular situation, it was observed that the use of a rule based system as a form of knowledge representation can simplify the maintenance aspect of the system. The structure of a simple rule being represented in a plain english can be easily interpreted and updated.

The modularity concept applied in this work contains an important feature. The current system was designed to check the soundness of a welding procedure, and was dedicated to HICC. As an essentially metallurgical defect, HICC is highly influenced by transformations inside of HAZ during cooling. A special module was designed to analyze all of thermal aspects involving the HAZ and to derive its properties based on real welding conditions. This kind of structure can easily be extended to other kind of metallurgical defects which are influenced by the thermal cycle as is the case, for instance, of hot cracking and microfissures, stress-relief cracking, strain-age cracking, lamellar tearing, etc (Savage, 1966). Obviously these defects have different basis, but the determination of HAZ properties is an important factor to be considered when assessing their likely occurrence. Additional modules specific to each defects should be added more easily and integrated to the present structure.

It was also observed that the development of the system required special attention to the system interface. At the minimum, an interface capability should be able to execute an external program, and return values to the running knowledge system application. This allows the external program to query the user or even consult a database when it is requested. To really get the most out of this type of knowledge based system it is felt that a user should be able to interface to files of a powerful database. Most users seeking to utilize such a system will not wish to operate two separate applications and duplicate data entry. It is not productive for users to have to continually answer questions about information that is already sitting in datafiles within the same computer system. It is envisaged that a fully configured interface would allow the expert system itself to send a fairly extensive list of parameters to an external environment performing sophisticated multiple queries to a relational database.

These aspects were considered in the present system design. The interface developed here (expert system shell/database system -XiPlus/dBase III Plus), offers the potential to fully explore both system to perform functions that are normally expected on its field of application. The use of relational database concept provides a powerful way to improve database organization with benefits in terms of maintenance and operation. However, two problems were observed in the use of the interface in the present work. The first problem refers to computational memory limitation, which needs to be very well managed to get the full efficiency of the system. The second problem relates to the computational processing speed. As a consequence, when accessing external programs, the operational time to execute a program was increased as expected. These problems can be avoided by ensuring that memory is cleared by the programme after a database consultation and by using higher specification hardware (a 286 portable computer was used for most of this work; the improved processing speed and memory handling capabilities of a 486 system would be beneficial in this respect).

5.1.3 INFERENCE CONTROL STRATEGY

Reasoning by the exercising of inference rules can proceed in different ways according to different control procedures, and this forms the basis of forward and backward chaining strategy. The strategy in forward reasoning is to work from the data and reason toward establishing the proper conclusion. Another pattern is to hypothesize each conclusion, one at a time, and then collect and examine all the necessary evidence that would confirm or deny the conclusion. This method of reasoning is called backward chaining. Backward chaining is usually favoured when the number of rules is large and forward chaining could lead to a combinatorial explosion. In practice, forward and backward chaining are often integrated and an interactive convergence process is used to join the opposite lines of reasoning together at some intermediate point to yield a problem solution.

In essence the choice between different strategies will depend essentially on the system structure and objectives. In case of this project careful attention was given to the user interface. The objective was to produce a welding procedure using the least number of questions to the user yet still considering all possible options. It has been observed that in many cases an excessive number of question and answer session in order to collect all the input data may frustrate the user and make him critical of the system. In this case the use of backward chaining was felt to be effective in reducing the number of questions. On the other hand, the essence of forward chaining is to devise questions that discard large numbers of possible answers at each step so that the correct answer can be ascertained quickly. The use of forward chaining alone could generate an excessive number of questions due of the great number of variables involved in welding procedure analysis or even combinatorial explosion, but its selective binary decisions could simplify the way in which the system could reach the final conclusion.

Considering these aspects, the combined use of backward and forward chaining strategies was expected to be beneficial from the point of view of exploring the advantages of both strategies and this was observed in the case of welding procedure evaluation. The use of both system strategies generate an improved ability to handle the rules, increasing the system flexibility by improving the decision system and speeding up the computer processing by avoiding unnecessary steps.

5.1.4 DECISION MECHANISM BASED ON UNCERTAINTY ANALYSIS

The use of reasoning mechanism to represent uncertainty can be analyzed by the influence of two different aspects: simple reasoning situations where the final conclusion was separated from evidence by one reasoning step and a more typical situation involving multi-step reasoning. The use of conditional probability can be assessed by first looking at the conditions established in a simple reasoning step inference. It has been recognized that uncertainty is an important aspect to be considered in knowledge based systems, not only as an alternative method of knowledge representation but also as a mechanism of decision analysis. This is the typical case of risk analysis for example (Gregory, 1988). Mechanisms to evaluate uncertainty have been proposed in chapter 4, and most of these rely on the probabilistic basis. The use of conditional probability for reasoning with uncertainty provides the necessary mechanism to deal with automatic reasoning systems when pieces of evidence independently bear upon a conclusion. Also, its use makes it possible to distinguish between strong pieces of evidences supporting the same conclusion.

All of these aspects were considered in this project. Typical situations arose during knowledge representation which suggested the need to express different strength of evidence, as described in chapter 4. An approach based on the 'Bayesian conditional probability model' was first considered as a means to represent uncertainty. Despite the apparent advantages of using conditional probability approach, Marcellus (1989) proved that reasoning strictly from probability is difficult and cumbersome especially when several pieces of evidence support the same conclusion (a common case in rule based systems). For this reason, most expert systems abandon reasoning from conditional probability and this approach was also discounted in this project. Instead, a scheme of approximate reasoning was implemented. The calculation other than the probability was used to quantify how strongly underlying implications support conclusions. So, the certainty of the evidence was roughly equivalent to the probability of evidence, and the certainty of the implication is similar to the conditional probability of the conclusion given that the evidence is true (similar scheme of conditional probability based on Bayes' rules - $p(a)p(b/a)=p(b)p(a/b)$).

It was observed that this kind of reasoning mechanism was flexible enough to represent the different strengths of competitive evidence whilst retaining the most important aspects of a probabilistic system. The definition of confidence and implication factors established in each rule statement simulate the autonomous and more subjective way in which a human expert works, without being restrained by the formalism used in probabilistic representation. Despite the advantages, it has been reported that the approximate reasoning based on conditional probability suffers from the deficiency that if the reasoning gets very complicated, the expert breaks down too (Marcellus, 1989). This was not observed in the present project.

Considering the techniques used to represent the uncertainty, different procedures can be used to embody different patterns of evidence. The use of logical combinations of evidence based on fuzzy logic (see chapter 4) provides the necessary strategy to combine information within a single rule or even with multiple rules in a typical inference network. The decision mechanism in this case considers the varying strengths of two rules supporting the same conclusion by determining a composite certainty result. This technique is based on the fact that when two rules of moderate certainty each support the same conclusion, it becomes much more certain. On the other hand, when two rules point in the opposite directions, the stronger one 'wins out', but its influence is diminished. Despite the theoretical problems, systems based on fuzzy logic do seem to work reasonably well in practice, as is the case of EMYCIN for example (Winstanley, 1990).

This discussion has concentrated on simple reasoning situations where the final conclusion was separated from evidence by one reasoning step. A more typical situation is to have a network in which the final conclusions are affected by many evidentiary bases representing the multi-step reasoning in an inference network. As the procedure for assigning a certainty to a conclusion given any pattern of evidence was already defined, the uncertainty processing in this case consisted of working up in the network from the base nodes and propagating certainty factors up to the highest nodes by using the combination rules. The reasoning mechanism was updated immediately any time a new piece of information was acquired. It was found that this procedure was the most economical way for the system to maintain its information, since only one composite certainty was stored for every conclusion in the network.

The performance of the approaches in the welding knowledge domain is discussed in the next section.

5.1.5 THE ROLE OF UNCERTAINTY IN WELDING INFORMATION

Many areas of unreliability and uncertainty in engineering derive from the inability of engineers to identify and assimilate all the information appropriate and necessary to their task. Such information is abundant but without understanding, it can be used incorrectly to the detriment of engineering analysis. Inadequate weld quality can arise from the lack of such understanding or misuse of knowledge.

It has been recognised that a large proportion of welding defects in construction or fabrication work have been a result of inadequate attention to design rather than poor workmanship (Hicks, 1988). Whilst such defects can detract from the performance of the structure, the design can also prove inadequate due to inappropriate welding procedure specification. As Hicks (1988) states, "the growing attention to quality assurance in design as well as in production illustrates the significance now attached to this matter".

In the course of assessing welding defects, uncertainty can arise from different sources during experimental or practical work and the welding engineer needs to be able to deal with this. The presence of uncertainty does not invalidate the knowledge but knowing how to identify and process it is essential to complement the knowledge. The use of reasoning with uncertainty can provide a disciplined framework within which information can be organised and processed for decision making. Some advantages of this kind of assessment are;

- knowledge and data keep changing and it is therefore important to devise means by which the knowledge base can keep thoroughly up to date;

- by handling the confidence factor associate with each piece of evidence, heuristic facts can be represented in a more organized way;

- to some extent, lack of a facility to analyze comprehensively service performance of welded joint has inhibited improvement in the quality of design. It has lead to both excessively conservative design and to unreliability. In the past, defect assessment has been constrained by the lack of knowledge-based methodologies and technical validation. To the practising engineer defect assessment has been more of an art than a science in that its practical execution relied to a degree on subjective inputs by knowledgeable specialists.

Reasoning with uncertainty was implemented in this work as a method of dealing with lack of information and facilitate the decision making process. In the case of welding defect assessment, and more specifically HICC susceptibility, it was observed that these considerations are very important, since it is uncommon for all the aspects of the problem to be completely defined. Two particular knowledge domains were identified in this project where it was felt that the uncertainty approach could be very useful. These were weld stress analysis and hydrogen presence assessment.

5.1.6 ASSESSMENT OF WELD STRESS PREDICTION MODEL USING UNCERTAINTY ANALYSIS

Welding stress is induced by a combination of conditions during welding execution. However, its evaluation is recognized to be extremely difficult and models developed have been limited only for some specific situations. The process of calculating stress distribution requires the input of the loads and the physical dimensions of the joint associated members. Methods of analyzing the welding stress by the use of finite elements analyses require a powerful computing facility capable of handling several gigabytes of data and presenting the results in an usable form.

Considering these aspects, an approach which examines the influence of the main parameters and is supported by a decision system based on the uncertainty analysis was adopted in this project (as described in section 4.3.1.4). The strategy acts in a very subjective way, only predicting the possibility of weld stress presence without determining its real value (this is similar to the approach normally adopted by the human expert).

A series of simulated conditions were generated when using different welding conditions and results can be seen from **table 4.13**. According to these results, the risk associated with welding stress changes from a high level (thick material, high arc energy, high restraint level and poor joint profile) to a small level when conditions are optimized. The results show the effect of variation of welding conditions on the welding stress level and reflect the influence of different parameters according to the knowledge base established. Final output is a result of the combination between implications and certainty factors processed according to the welding stress analysis network. It was observed that results present a good coherence between particular parameters and the final output. From the present condition it was observed that the system was able to predict the expected influence of change of thickness and the restraint level. Obviously this situation will be influenced by the arc energy level, weld profile and fit-up. For instance, the results show that the use of a thick plate material under a high restraint level is not as serious as the use of a thinner material under the same conditions if a material with improved ductility can be used. This is reflected by the implication of the parameters and the propagation of this effect according to the uncertainty evaluation. The evaluation was not as precise as was expected probably because it was analyzed according to the implications of specific parameters. The determination of a real value of welding stress is not the objective of this work, but the knowledge of its presence is required for prediction of the risk of HICC.

5.1.7 APPROACH USED TO ASSESS THE HYDROGEN PRESENCE USING UNCERTAINTY ANALYSIS

Hydrogen can be measured relatively easily, but this is not often feasible at the procedure development stage. Instead, a knowledge based system which takes into account the main factors affecting the hydrogen presence was included in this system. The evaluation method implemented was based on the influence of particular factors with 'certain' implications and the effect of using an uncertainty evaluation model propagation. The results representing the influence of welding conditions (**table 4.14**) are expressed in terms of an evidence (value between 0 and 1) of hydrogen presence.

The approach was felt to be very important since it represents the strength of each particular evidence on the whole decision system by using implication factors to correlate it with the hypothesis. The influence of each parameter is induced by confidence factors associated with pieces of information provided by the user. This procedure enables the small influence of one parameter to be measured in terms of its effect on the final conclusion.

The method of inducing a result even if direct knowledge of hydrogen level is not available is very important. Knowledge extracted from the user can be added to the database of the whole welding condition; this information can later be accessed in the advisory system in order to optimize the welding procedure.

5.2 VALIDATION OF THE WELDCARE KNOWLEDGE BASE SYSTEM

A very important phase in the development of an expert systems is validation. This post-knowledge representation test will verify the applicability and limitations of the system. Also it can show any incoherence which could lead to incorrect decisions. Validation even may encourage new development and further implementations.

The next section discusses the results obtained during the validation of the system. In this specific case, all knowledge was tested individually to verify the coherence and the WELDCARE system as a whole was tested against known results from existing welding procedures and welding test results.

In this system the knowledge base consisted of,

- Physical and empirical models and,
- Rules (Based on consultation with experts).

It was possible to evaluate the models independently but the interaction of these with the rules and the treatment of uncertainty could only be tested by comparing the output of the system as a whole with known results.

The following section (6.2) discusses the results of the validation of the main knowledge base models.

5.2.1 PREDICTED HAZ HARDNESS VALUE - SIMULATED RESULTS

Validation trials were carried out, and the results of this stage are described in section 4.3.1.1. From the results obtained and illustrated in **figures 4.17 - 4.19** it can be seen that with different welding conditions the HAZ hardness prediction using the equations tested shows a very close range of agreement when using plate materials with carbon equivalent above 0.45%. The standard deviation of hardness, in this case, was kept within a reasonable range of around 10 -15 HV10. However, the hardness prediction using the Yurioka methodology shows an increased deviation from the other techniques when using a material with carbon equivalent of 0.35% (in this case the standard deviation of hardness increased to around 25-30 HV10). This result could be expected since the Yurioka method takes into consideration the presence of additional elements (eg boron and nitrogen) while the other approaches do not. From these results the evaluations are more appropriate for materials with higher carbon equivalent. However the prediction of HAZ hardness with a standard deviation of 25-30 HV10 can be considered a reasonable result and gives a good indication of the hardness level present in the HAZ. Obviously more results compared with practical evaluation need to be considered in order to assess the realistic effect of these model in the present work.

Further investigation of the results shows a significant increment in HAZ hardness value with the increase of carbon equivalent values. Also, variations in welding conditions that cause an increase in cooling rate showed an expected increase in the predicted HAZ hardness as verified. This situation was particularly influenced by the effect of energy input, peak temperature and the thickness of the plate. Arc energy level influence the metallurgical aspects of HAZ. The use of low arc energy input minimizes the extent of the HAZ, and weld metal properties are enhanced through production of fine grain structure. Increase in cooling rate should be expected in this case, with an increase in HAZ hardness prediction. However, it is recognised (Welding Handbook, 1976) that for a given preheat temperature, increasing the energy input causes an increase in the time of exposure to temperatures near the peak temperature causing as a consequence a decrease in the cooling rate. The use of large weld passes (high energy input) can benefit from the metallurgical aspects of reduced cooling rates in the welding of hardenable ferrous base metals, with an expected decrease in HAZ hardness level as predicted.

Aspects involving metallurgical features of the joint need to be considered as well as the effect of plate thickness and weld geometry. Plate thickness influence is complex because the heat flow pattern changes markedly from a two-dimensional flow for very thin plates to a three-dimensional flow for very thick plates. This change explains in a qualitative mode the influence of plate thickness on cooling rates. From the validation tests it was observed **(figures 4.17 - 4.19)** that an increase of plate thickness from 15 to 25 mm resulted in an increase in the HAZ hardness as expected. It is important to point out here that the classification between two dimensional and three dimensional heat flow was determined in this project by the determination of the relative thickness as recommended by AWS (Welding Handbook, 1976).

Based on these general results obtained using theoretical models, it is reasonable to assume that the models used are in general agreement with what was expected and this was particularly true for materials with a higher carbon equivalent. Supported by this assessment the use of any of these equations could give a reasonable confident value of hardness when used inside of the valid range of chemical composition. Meanwhile, for a full assessment of the hardness prediction method, simulated results need to be compared with real situations and this will be discussed in the next section.

5.2.2 VALIDATION OF THE SYSTEM BY COMPARING THE EFFECT OF HEAT INPUT AND PREHEAT TEMPERATURE ON HAZ HARDNESS

A full analysis of any system or knowledge based systems needs to be tested against practical results in order to assess its validity. In previous discussions the results of testing the ability of the equations to predict HAZ hardness on an individual basis was examined and in this section the same equations were compared with practical results.

As described in section 4.3.1.2, a series of tests were carried out by Swetnam (1984) using a 40 mm thick C-Mn steel (BS-4360-Gr 55E). Heat input and preheat temperature were changed in order to verify their influence on CGHAZ hardness. Simulated welding trial were developed and predictive HAZ hardness were determined through the application of Yurioka, Suzuki and Düren equations.

As illustrated in figures 4.20 - 4.21, the predicted conditions were compared with the real hardness value for each hardness predictive method. By analyzing individual conditions expressed by figure 4.21.a (Yurioka), figure 4.21.b (Düren) and figure 4.21.c (Suzuki), linear regression analysis can be generated for each particular condition. Predicted results in this case can be corrected using the prediction to a more realistic situation.

The linear regression equation for the relationship between experimental and calculated hardness values was derived and the accuracy of the prediction was checked further by calculating the coefficient and standard error of determination, R^2 and P, respectively. The standard error is defined as

$$P=\sqrt{\frac{\Sigma[H_{max}(\mathrm{exp})-H_{max}(calc)]^2}{n}} \tag{5.1}$$

where n is the number of readings. The following regression equations were obtained by using the above formulas for calculating H_{max}:

a. Suzuki equation:

$$H_{max}(\mathrm{exp})=-90.27+1.37H_{max}(\mathrm{calc}) \tag{5.2}$$

$R^2=0.986$; $P=6.64$

b. Yurioka equation:

$$H_{max}(exp)=-43.59+1.34H_{max}(calc) \tag{5.3}$$

$R^2=0.980$; $P=7.96$

c. Düren equation:

$$H_{max}(exp)=10.43+1.07H_{max}(calc) \tag{5.4}$$

$R^2=0.983$; $P=7.36$

The hardness calculated from the equations does not vary significantly, but all three equations underestimate the real hardness value shown by the values of slope and intercepts. The Suzuki equation and the Düren equation give better correlation with the experimental results. Since R^2 values were kept close, these formulas can be ranked on the basis of standard error of determination and in this case, from the present conditions the results were:

H_{max}(Suzuki) > H_{max}(Düren)> H_{max}(Yurioka)

The Suzuki formula appears to be more acceptable for prediction of the maximum HAZ hardness in C-Mn steel (BS-4360 - Gr. 50E). However from the results obtained it can be seen that there is a constant variation between real value and predictive value from the welding conditions established. From these trials, the Yurioka approach gave the most representative assessment of real hardness value when compared with the other methods for the specific material used. However, the prediction still gives a small standard error (P=7.96), (of the same order as other predictive methods considered in this work). Since Yurioka's equation can be applied to a wider range of steels than Suzuki and Düren, and considering the correlation with the real hardness, the Yurioka method offers an alternative way of HAZ hardness evaluation for materials that are not completely assessed by the other methodologies (as is the case of HSLA steels and lean alloy steels). Obviously, the linear regression equation obtained above can only be applied to carbon-manganese steels. In the case of other types of material, new correlations with the real value need to be determined.

An important factor to be considered in this comparison between real hardness and predictive values is that it applies to a carbon manganese steel with a carbon equivalent (Ce_{IIW}) of 0.386%. When comparing the results obtained for real measurement with simulated conditions previously described in section **5.4.1**, it can be seen that the hardness value obtained for a material with a carbon equivalent of 0.35% are in the same range of values obtained for the practical situation. In this case it seems reasonable to use the same regression equation. However for materials with higher carbon equivalent (0.45% and 0.56%), the results suggest that these considerations can not be applied, since the predictive hardness value in this case presents a slightly close range of variation when using a material with smaller carbon equivalent. In this case, comparative results with empirical values need to be considered in order to check the validation of the equations considered in this work.

5.3 VALIDATION OF THE WELDCARE SYSTEM

The following section discusses the validation of the complete WELDCARE system. This involved the comparision of risk evaluation performed by the system and the known results from established procedures & welding trials.

5.3.1 HICC PREDICTION MODEL - COMPARED RESULTS USING DIFFERENT ASSESSMENTS

The discussion so far has been concerned with the validation of individual knowledge that predicts the thermal aspects of the welding joint. The main feature considered is the prediction of HAZ hardness. Since this condition is a result of a combination of a series of welding conditions involving arc energy, chemical composition, cooling rate, etc, its knowledge can give an indication of HAZ properties.

Hardness prediction has been used as a guide to estimate the presence of defects in welding, specially HICC susceptibility. However, at the present stage discussions are still being carried out in order to validate this assumption (Yurioka (1990) claims that the hardness control approach is appropriate for a certain class of material, especially carbon manganese steels). For other classes of material, such as high strength and low alloy steels (HSLA), the methods used to determine hardness need to take into consideration the influence of microalloy elements and in this case Yurioka equation seems to provide a good indication of the magnitude of hardness under at any particular welding condition.

In an attempt to determine the weld soundness with respect to HICC susceptibility, the TWI nomogram (based on hardness control approach) has also been used. This technique has been applied very successfully, specially for certain class of C-Mn steels with Ce_{IIW} lower than 0.45%. This methodology predicts a safe preheat temperature that should prevent the occurrence of this defect, and is derived usually by the combined influence of plate material thickness, hydrogen presence level, joint design and carbon equivalent.

To illustrate these points and considering a fixed hydrogen level of 13ml/100gr concentration, a correlation between the hardness and hydrogen control approach was evaluated. A series of results for both methods were generated using materials with Ce_{IIW} of 0.36%, 0.45% and 0.56% respectively, as seen from **tables 4.7-4.9**. It was observed from these results that both methods correlate very well for hardness values over 375 VPN or under 340 VPN. For values between 340-375 VPN there is some discrepancy in the predictions. This can be explained by the hydrogen level concentration which will have a more significant effect on the TWI approach than on the hardness approach.

The influence of hydrogen is a determinant aspect in the HICC prediction. In order to assess its influence a series of results were obtained in welding with different hydrogen level concentrations. The results were determined in terms of safe predicted preheat temperature in order to avoid HICC when using the hydrogen control method. As seen from **figure 4.22** the safe predicted preheat temperature changes with the hydrogen concentration. It can be observed that the safe preheat temperature increases with the hydrogen concentration as expected. This can be explained by the fact that in this case more time will be necessary to allow hydrogen to escape to atmosphere during the cooling thermal cycle. The use of higher preheat provides the necessary condition to avoid hydrogen to be entrapped inside of HAZ which can cause HICC.

From the results obtained it is observed that, the hardness control technique is insensitive to the hydrogen variation and correlation with hydrogen control method in this case does not conform very well. As would be expected the hardness value is not affected by the hydrogen level, since the approach does not take into consideration the presence of hydrogen. It has also been reported that with a low-hydrogen level, hardnesses of 400 HV could be tolerated without cracking (Lundin, 1990). Such hardness may not be tolerable in service where there is an increased risk of stress corrosion cracking, brittle fracture initiation, or other risks for the safety or serviceability of the structure (AWS D1.1, 1988). From this point of view, the hardness control method can be used as an accurate guide for cold cracking prediction when using controlled hydrogen electrodes. Outside of this range, more information concerning the welding conditions needs to be established, in order to determine the weld stress level presence.

Based on all aspects discussed above, the decision system discussed in section 5.1.4 was implemented for assessing the risk of HICC presence this considering the influence of the two models (hardness and TWI approach) as described in section 4.2.1.3. This decision system was implemented in the present structure and was used as the guideline for the welding procedure specification check.

5.3.2 ASSESSMENT OF HICC - VALIDATION OF THE SYSTEM

Current approaches used for HICC detection have some limitations. The hydrogen based approach (such is the TWI nomogram) is limited to C-Mn steels and fits well for material with carbon content inferior to 0.2%. Over this limit the results reported from the literature are not very consistent. On the other hand, the straight hardness control approach can be used for a greater range of steels, including HSLA steels. However, due to the fact that this method does not consider the influence of hydrogen concentration level, its evaluation is restricted in welding situations where hydrogen presence is a potential risk. In the WELDCARE system, a decision system that selects the best of both approaches was used. The decision mechanism was supported by the use of confidence factors associated with each piece of information and evidence was processed according to the uncertainty analysis model already described. The decision analysis was based on the following type of statement for instance:

- if both methods agree in their prediction then evidence of HICC susceptibility is high (CF=0.9); where CF denotes hypothesis belief given observed evidence;

- if the methods disagree in their predictions then conclusions will be derived after the analysis of more evidence, such as HAZ properties, general welding conditions, etc. The CF in this case will be generated also by combined evidence from different sources.

The system using this approach was tested against practical results and the discussion at this stage will concentrate on the validation results obtained through a series of trials carried out comparing practical results from various sources with those predicted, as described in section 4.3.2. The tests included a range of wide materials with different chemical compositions and included C-Mn steels, experimental lean alloy steels and HSLA steels. The discussion is divided in three parts (following the format of the results section). In the first part, the expert systems predictions were compared with work published from the literature. In second part, results were compared with research results from other work being carried out at Cranfield Institute of Technology and involving alloy steels. In the third part, a series of welding procedure specification provided from different sources were compared with predicted results.

5.3.2.1 CARBON MANGANESE STEELS

A series of trials were conducted using empirical results obtained from a study published by Hart (1991). This work entailed a study of the relative effect of compositional parameters, specially carbon, manganese, nickel, molybdenum and vanadium in carbon-manganese steels. The same welding conditions were simulated using the expert system and the diagnostic was based on the decision mechanism discussed above.

The results of the individual CTS tests simulated/experimental for each steel are summarised in **tables 4.16 and 4.17** for a 20mm thickness and arc energy from 0.7 to 5.0 kJ/mm. Hart reported that on four of the steels (1, 11, 15 and 21) no cracking was observed with the 20 mm plate even at the lowest arc energy practicable (approximately 0.7 kJ/mm). In this case, to establish a crack/no crack boundary for these steels, CTS tests on 50 mm thick plate was carried out and **table 4.18** summarise the comparative results obtained from empirical and simulated conditions for these tests.

As seen from **figure 4.23**, critical arc energies representing the boundary between crack/no crack (simulated and empirical conditions) was plotted for the materials tested (Ce_{IIW}) using different welding conditions. A clear boundary between crack/no crack can be easily recognised from the plotted conditions. In all welding conditions used, it was observed that there was a small 'no-cracking tendency' with the use of high arc energy. This factor does however need to be balanced against the increase of welding stress, despite the microstructure advantages resulted from a slow cooling rate. Considering separately each group, a very close correlation between predicted and empirical results can be observed for steels using arc energies from 0.7 to 3 kJ/mm and 20 mm thickness. In this case the predicted critical arc energy is closer to the 45° line compared with other results and also shows good correlations with the experimental results as in **figure 4.24.a**. It was also observed that the cracking zone was basically the same for predictive and experimental conditions. For materials with higher carbon equivalent (0.52%- 0.66%) and arc energies (2.0 to 5.0 kJ/mm), see **table 4.17**, more scattered results were obtained. In this case the predicted critical arc energies were considerably higher than the experimental ones, as seen in **figure 4.24.b**. Only in one case was the predicted and experimental value exactly the same (steel 12- CE=0.58%). In this case the predictive cracking zone was higher than the experimental one. Finally for the last group, plate material with thickness of 50 mm, there is a tendency of lower predicted critical arc energy than that found experimentally and the cracking zone for the predicted values was slightly higher than the experimental results, as can be seen from **figure 4.24.c**.

Hart (1991), carried out a series of multiple linear regression analyses on the critical hardnesses and critical cooling times for cracking composition. As a consequence he determined two different equations relating hardness and cooling time for the critical condition:

a) Equation Predicting Critical Hardness, HV_{crit}

$$HV_{crit} = 833.65\ (CCP_4) + 334.69 \tag{5.5}$$

where

$CCP_4 = C - 0.0321Mn - 0.3157V - 0.0202Ni - 0.0415Mo - 3.8055C^2 + 0.3776CMn + 0.5418CMo + 0.2504NiV(CP_4)$

and,

$$CP4 = C - \frac{Mn}{31} - \frac{V}{3} - \frac{Ni}{50} - \frac{Mo}{24} - 3.8C^2 + \frac{CMn}{3} + \frac{CMo}{2} + \frac{NiV}{4}$$

b. Equation Predicting Critical Cooling Time, Δt_{crit}

$$\log\Delta t_{crit} = 3.661(CCP_5) - 0.129 \qquad (6.6)$$

where

$CCP_5 = C + 0.0341Mn - 0.5875V + 0.3099Ni + 0.1566Mo - 0.3208Ni^2 + 0.6184MnV - 0.587VMo(CP_5)$

and,

$$CP4 = C + \frac{Mn}{29} - \frac{V}{2} + \frac{Ni}{3} + \frac{Mo}{6} - \frac{Ni^2}{3} + \frac{MnV}{2} - \frac{VMo}{2}$$

Based on these results, it is suggested that the two equations predicted by Hart could be incorporated in the WELDCARE system and used as a complementary check procedure for C-Mn steels which do not comprise with the validity field established by the approach used in this project. On the whole comparison with Hart's results showed that the WELDCARE system gave a good indication of cracking tendency.

5.3.2.2 LEAN ALLOY STEELS

A series of experimental lean alloy steels was subjected to a Controlled Thermal Severity tests (CTS) at Cranfield Institute of Technology (Highs, 1992). These non-standard steels have been used by steelmakers with controlled alloy additions to provide alternative means of achieving adequate strength in both normalised and accelerated cooled plates. The plate material thickness considered was in the range from 15 mm to 50 mm, and the chemical composition and mechanical properties of the material tested are given in **table 4.19**. The material was welded using a restrained fillet weld cracking test (CTS) and bead-on-plate tests with implant samples. The cracking tests were carried out using shielded metal arc welding (SMAW), with a weld hydrogen level of about 10-15 ml/100g deposited metal, except for steel number 7 (Ys=690 MPa), for which the hydrogen level was kept under 5 ml/100g. The critical arc energy for the boundary crack/no crack for each steel was determined. Also, the correspondent critical HAZ hardness value for the crack section was measured using a Vickers 10 kg load.

Using the approach described in previous section to compare predicted/experimental results, the welding conditions used for the CTS test were simulated by the expert system. The severity of the CTS test were represented by considering the weld to be subject to a high restraint level. The likely microstructure condition was evaluated by considering the predicted HAZ hardness value determined from the equations previously discussed. A series of simulations were carried out in order to determine the critical arc energy corresponding to the boundary crack/no cracking. The corresponding predicted hardness for each welding condition was recorded.

The results of the individual CTS tests simulated/experimental for each steel are summarised in **table 4.20**.

Figure 4.25.a shows the plotted critical arc energies representing the boundary between crack/no crack (simulated and empirical conditions) for the materials tested (Ce_{IIW}). **Figure 4.25.b** summarises the results for critical arc energy predicted and experimental using materials with different thickness.

The results show that the crack free zone from the predicted conditions seems to be smaller than the experimental ones. These seem to be a consequence of the critical predicted hardness, which was lower than the experimental results. Only for one condition was the predicted hardness higher, and this was probably due to the high nickel content in this particular steel (Ni=0.4%). The lower hardness prediction affected the whole HAZ cracking prediction since it plays a very important role in the model. In this case, the predictive model was more conservative than the real. The prediction of a small HAZ hardness implies a less susceptible microstructure to fail, and as a consequence the tolerance against hydrogen presence level is higher. The combination of all these factors will provide a prediction of a higher cracking tolerance, as verified. Another aspect to be considered is that apparently the thickness does not have a significant effect on the prediction model. It was observed that the use of higher thickness cause as a consequence a decrease in the critical heat input. These results could be expected, since an increase in the plate material thickness generates a higher cooling rate.

Considering the importance of hardness prediction, a further analysis was undertaken to find a model that would better conform with the empirical results. Hart (1991) and Boothby (1982) have offered some equations to predict critical hardness and critical cooling time for the boundary crack/no crack presence. These equations were tested for the present set of steels. **Table 4.20** summarises the results obtained for all methodologies tested. The comparison between the predicted hardness with the experimental values, are shown in **figure 4.26**.

From the results it can be seen that critical hardness proposed by Hart (1991), showed very close correlation with the empirical value. In this case the predicted critical hardness from the Hart work is closer to the 45° correlation line than that predicted by Boothby. However, for the same welding conditions, the Suzuki equation do not fit the present set of steels, due to the variation of chemical composition, as explained before.

Based on these results, it may therefore be worthwhile to incorporate Hart's critical hardness and cooling time prediction model for use in case of "lean" alloy steels. Obviously, the use of this prediction model to other steels would need to be carefully analyzed.

5.3.2.3 HIGH-STRENGTH LOW-ALLOY STEELS

To compare the applicability of the approach for HICC assessment discussed above, high-strength low-alloy (HSLA) steels were tested at CIT (Laws, 1992) using a restrained fillet weld cracking test (CTS), as described in section 4.3.2.3. The cracking tests were carried out using shielded metal arc welding (SMAW), with a weld hydrogen level of about 10-15 ml/100gr deposited metal. The coarse HAZ hardness and the proportion of faces cracked from a total of six measurements was recorded from different welding conditions.

The actual results were compared with predictive values for the crack/no crack boundary by using a conventional methodology (Hardness approach). The Hydrogen based approach (TWI nomogram) was not used in this validation test since its applicability does not extend to HSLA steels. Instead the Critical Stress Control approach (see chapter 3) was applied. In the Hardness Control approach the preheat and critical arc energy were determined for the limit crack condition. In case of Critical Stress Control, the weldability of the steels were evaluated by measuring an index represented by the ratio of the Lower Critical Stress (LCS) and Yield Strength (YS). It is assumed if the ratio of LCS and YS is one or greater than one, the steel can be safely welded under the welding conditions and hydrogen levels employed during the implant test. The LCS, in case, were evaluated considering the most appropriate equation for the material being welded as discussed earlier.

Based on results between actual and predicted conditions summarised in **table 4.22**, it was verified that under the use of a conventional methodology for the steels examined, only the type BS RQT 501 shows some similarity with the actual result. This was to be expected from the predicted HAZ hardness value that in this case was around 308 HV for an arc energy of 1.2 kJ/mm. For the other steels tested, no cracking tendency was predicted even with a very low arc energies. This result was in contradiction to the actual measurement. Another fact noticed was that the hardness prediction as a whole show the same tendency observed for the C-Mn steels. The predicted value was often lower than the actual hardness. If a corrective regression equation correlating the predictive and actual HAZ hardness value were determined the predictive method could be modified to present a better result.

From the results obtained, it is evident that the conventional method of HICC prediction using the Hardness Control approach does not work well for this kind of steels. This approach considers that if the HAZ hardness is kept below a certain critical hardness the risk of cracking is greatly reduced (Lundin, 1990). However, since modern steels usually present low CE's, these kind of steels might crack even if the carbon equivalent is low. This was specially verified for steel BS 450EMZ (CE=0.37%) with a mean HAZ hardness under 300 Hv, and with a higher cracking tendency. This effect could possibly be reduced by the use of the present expert system methodology, where a combined effect between the preheat evaluation and the HAZ hardness prediction are analyzed under the HICC effect. However, the use of IIW nomogram does not apply for this class of steel. In this case the evaluation would be expected to lead a false conclusion.

The alternative use of LCS approach shows a cracking tendency for the steels HSLA 80 and RQT 501. For the others steels no cracking tendency was predicted, even when welded under a very low arc energy. The LCS considers the influence of the YS, and in the case of steels 55FMZ and 450EMZ, the remarkable lower yield strength of these steels when compared to HSLA-80 strongly influenced the no-cracking prediction. Differently, the HSLA 80 shows a clear cracking tendency when arc energy is under values about 1.7 kJ/mm. This condition shows the same tendency as the measured results. In the case of steel RQT 501, the predicted cracking tendency does not conform well with the real results. The reason for this fact was the system used to evaluate the LCS, which in this case was adopted as the same used for HSLA 80 (based on the yield strength). However, due to the fact that the chemical composition of both steels are different the approximation adopted in this case was the main reason for the discrepancy observed.

Considering all the aspects analyzed, it is reasonable to affirm that the conventional approach (preheat evaluation and hardness approach) do not fit well for the prediction of HICC cracking tendency for HSLA steels. The use of LCS shows a reasonable result if the steels being analyzed conform with the class of steels for which procedure are kept in the knowledgebase.

5.4 SUMMARY

The integration of an expert system shell and a relational database enabled a practical system for weld procedure risk evaluation to be developed. Rules derived from experts and models from published work were incorporated in to knowledge base and uncertainty analysis was applied to the less well defined knowledge domains.

The validity of both the models and the full system have been tested and within the scope of the work (HICC detection in C/Mn steels) good predictive accuracy was obtained.

5.4.1 LIMITATIONS OF THE SYSTEM

Some limitations have been identified during the development and application of the system. It was observed that the use of an expert system shell may limit the capability of the system in terms of handling large amount of data. This limitation was very critical during development of the system, since every real application is usually associated with a great deal of information, which will support each decision. The use of an external database has shown to improve this capability, but on the other hand this may generate a limitation in terms of computer memory capability. To overcome this problem, special attention was needed in the area of memory management in order to get the most out of the system.

The limitations of the expert system shell could be minimised by using more powerful softwares. Alternative software has been examined and it is believed that POP-11 matches most of the requirements for the development of similar large applications in AI and specifically in expert systems. This software combines powerful language developments and a vast capacity for database organization. This later facility associated with the use of relational database management could have extensive application in the welding procedure analysis field. It was also found that the use of POPLOG, a management environment system that combines the power of languages such as POP-11, Prolog and Lisp, could increase the potential application of expert systems in this area (POPLOG has an inbuilt facility to communicate with external languages, and in most cases, applications developed in other software can be automatically translated to POPLOG environment).

In case of the present project, automatic knowledge transfer from one system to another was originally envisaged, but further investigated that this was not viable with XiPlus. However, due to the form of knowledge representation used (rule based system) and the completeness of the knowledge represented the system could be rewritten in another language by transcribing all the rules represented in the XiPlus system.

CHAPTER 6

CONCLUSIONS AND FUTURE RESEARCH

6.1 SUMMARY OF CONCLUSIONS

Knowledge elicitation is an important aspect of expert system application development and the time required by this phase affects the cost-effectiveness of these systems. Also, the performance of the expert system in terms of the systems reliability, validity and utility depends on the reliability, validity and accuracy of the elicited knowledge. It is thus of great concern that knowledge elicitation poses a significant bottleneck to the process of building expert systems. In this work the use of a conceptual framework methodology similar to that proposed by Garg-Janardan (1988) provided the guidelines regarding the process and content knowledge to be elicited, and the sequence and format in which this should be done. Elicitation of knowledge in such a structured format significantly reduced the time required to analyze the elicited data. The access of structured knowledge can also provide improvement in the maintainability of the knowledge base. Following the HICC knowledge elicitation, the identification of main domain, sub-domains and invariant parts of the knowledge engineering was helpful in transferring the knowledge to the expert system. The identification of classes of evidence containing variables involved in HICC analysis was useful in attributing the confidence and implication factors between evidence and conclusions for each piece of information. The identification of these variables facilitated the implementation of a decision analysis mechanism based on a fuzzy logic approximation. As a result of these procedures, the expert system was much easier to construct and also to maintain.

The validation stage of the system by comparing practical results with simulated results for a vast range of lean alloy steels has shown the accuracy of the knowledge and the validity of the conceptual framework structure for knowledge elicitation.

6.2 CONCLUSIONS

The following conclusions may be drawn from this work:-

(1) A practical expert system for risk evaluation of welding procedures has been built and demonstrated; the use of expert systems is feasible for risk evaluation of welding procedures. It was observed however that its use needs to concentrate on a relatively small domain. Large domains may result in errors that can give misleading results.

(2) The predictions obtained from the system have been validated by reference to experimental results and published work.

(3) The combination of a relational database and an expert system shell system operation increases the flexibility of expert system operation and improves the user interface.

(4) The combined use of a relational database and an expert system shell led to some computer memory management problems.

(5) A combination of backward chaining and forward chaining is appropriate for welding procedure evaluation; the use of this control strategy is the most appropriate way to analyze a welding procedure using the least number of questions yet considering all possible options.

(6) Uncertainty analysis is important in this type of expert systems (ie. when all knowledge is not completely clear). The use of reasoning mechanism under

uncertainty by combining rules can simplify the decision system and also facilitates the representation of heuristics facts.

(7) When reasoning with uncertainty, it was observed that the use of fuzzy logic provides the potential for an effective decision analysis mechanism by representing the probabilistic aspects of each piece of evidence (represented by the uncertainty mechanism) for the whole process. This approach to risk analysis mechanism is an efficient way to establish degrees of dependency between different pieces of evidence affecting the same conclusion (The results obtained from validation of the system indicate the applicability of such mechanism).

(8) Investigation of the methods used for cold cracking evaluation shows that a combination of different methods based on hardness control approach associated with the use of uncertainty analysis was required to obtain the best prediction of HICC risk. The use of this approach allow the system to be applied to a more vast range of materials than the conventional methods in use. The expert system developed here incorporated the selection of the 'most appropriate' rules and could perform better than a human expert in this respect.

6.3 SUGGESTIONS FOR FUTURE WORKS

There are many aspects of this research which could be further explored:-

(1) The extension of the present methodology to the checking of other defects. Obviously this would need a new knowledge base, but it could easily be integrated with the knowledge already in the system. In case of defects with metallurgical origins, as is the case of hot cracking, stress cracking, lamellar tearing, etc, modules containing information about thermal aspects of the HAZ for instance can be integrated with new knowledge bases. The development of

the expert system in separate modules provides the facility to combine new knowledge with that already existing.

(2) New materials and electrodes could be added to the data-base. This should be a relatively easy process that would require very little theoretical modification to the models. Welding in the overhead position could also be incorporated with some additional theoretical analysis. (If new classes of materials such as high strength alloy steels are incorporated this could require revisions to the present system).

(3) An important extension could be the incorporation of additional welding processes, such as SMAW, FCAW and GTAW. A separate model would have to be developed for each additional process. Ideally, these process models would be developed using the same techniques presented in this research. Also, additional models would have to be developed to select which welding process to use in a given situation, based on economic requirements, physical requirements or both factors.

(4) Another aspect to be considered could be the extension of the database management system to integrate the welding procedure specification (WPS) with procedure qualification records (PQR). The adaptation of the present database management system could be based on the concept of relational database by establishing frames between PQR and WPS. A system of this type could be very useful for the completeness of the integrated welding information.

(5) The interaction between databases, welding procedures and welding defect analysis could be integrated by using separate modules covering particular areas of interest. This would probably be easier using POP-11 or POPLOG software.

(6) The system could be developed as a training aid since it allows procedure errors

to be simulated and gives guidance on the likely cause of defects.

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APPENDIX A

The appendix A shows some parts of the knowledge elicited.

RULE SHEET: 1

DOMAIN PROBLEM:
Hydrogen Induced Cold Cracking

INPUT USER:

OBJECTIVE:
Verify the effect of high hardness giving the possibility of HICC presence.

SOURCE OF RULE (full reference / named authority / other):
a. 'Theories of Hydrogen Cracking' MSc. Handout , Mat 226 (250).
b. 'Metallurgy of Welding', J. F. Lancaster.
c. 'Welding Steels without Hydrogen Cracking', F.R. Coe.

STATEMENT(S) OF RULE:

This is a widely used empirical method of determining the possibility of HICC - the rule is dependent on a knowledge of hardnes (VPN) values of the steel in question, and also, to make use of this rule, the steel must fit into one of 5 categories. This is because hardness relationships with steels outside of this selected group are not sufficiently consistent to enable generalised empirical rules to be made. Traditionally steels with hardness less than 350 VPN are regarded as being relatively safe from HICC. Those over 350 VPN are susceptible. The higher the value, the greater the possibility. No data is yet available to categorise varying VPN's over 350.
Rules could be established by the following conditions:

(i) the material is mild steel, and its VPN > 350.
(ii) the material is medium carbon, and its VPN > 350.
(iii) the material is low carbon manganese steel, and its VPN > 350.
(iv) the material is medium carbon manganese steel, and its VPN > 350.
(vi) the material is microallyed steel, and its VPN > 400.

HEURISTIC FACT:
In general for carbon manganese steel:
if hardness > 350 then microstructure is susceptible to failure and HICC is potentially present if hydrogen presence is over acceptable limit and weld stress is present.

RULE SHEET: 2

DOMAIN PROBLEM:
Risk of Hydrogen Induced Cold Cracking

INPUT USER:

OBJECTIVE:
Verify the possibility of HICC presence in a WPS

SOURCE OF RULE (full reference / named authority / other):
a. 'Theories of Hydrogen Cracking' (see rule sheet 1)
b. 'Weldability of Steels', K.G. Richards (Publ. TWI)
c. 'Metallurgy of Welding', Lancaster.

STATEMENT(S) OF RULE:

This rule is supported by four conditions, all of which are interdependent and all of which must be in existence for the rule to be true. It true, the rule will inform the 'user' that HICC is likely to occur.
The HICC is likely if:
(i) the microstructure is susceptible;
AND (ii) diffusible hydrogen is present;
AND (iii) the temperature of the parent plate, during welding, falls below a critical level;
AND (iv) a tensile stress is created in the parent plate.

Each condition becomes a sub-domain according to the logic tree.

The above rule is applicable to all carbon, and carbon-manganese steels, and also low carbon microally steels.

RULE SHEET: 3

SUB-DOMAIN PROBLEM: 1
Susceptible microstructure

INPUT USER:

OBJECTIVE:
Verify the risk of HICC due to the microstructure being susceptible to failure under a specific welding condition.

SOURCE OF RULE (full reference / named authority / other):
(See rule sheet 2)

STATEMENT(S) OF RULE:

This rule is related to the hardness of the microstructure. One is considering, in effect, the hardness of the HAZ when assessing the susceptibility of the microstructure to the HICC. The hardness is made up of 3 classes which consider: the hardening effect of various elements, the effect of cooling on the hardenability, and the effect of grain growth on the hardenability.

The rule is true if all of the following are true:

(i) there is a high level of hardenability;
AND (ii) there is a risk of a high cooling rate;
AND (iii) there is a risk of a high grain growth rate.

RULE SHEET: 4

PROBLEM SPACE: 1
High hardenability

INPUT USER:

OBJECTIVE:
Verify the risk of HICC due to high level of hardenability.

SOURCE OF RULE (full reference / named authority / other):

(see sheet 2)

STATEMENT(S) OF RULE:

This rule is true if one of the following is true:

(i) there is a risk of HICC from high amount of individual elementes;
(ii) there is a risk of HICC from high amount of combinations of elements;
(iii) there is a risk of HICC from low amount of individual elements.

Each of the 3 clauses becomes a sub-problem space invariant parts.

RULE SHEET: 5

INVARIANT PART: 1/1
High amount of individual elements.

INPUT USER:

OBJECTIVE:
Verify the risk of HICC due to high amount of individual elements.

SOURCE OF RULE (full reference / named authority / other):

Paper TWI - 'HAZ hardenability and boron', Brownrigg, Chang and Glover, 1983.

STATEMENT(S) OF RULE:

The rule is true if one of the two clauses is true:

(i) high boron;
OR (ii) high carbon.

Clauses:

(i) High boron is true if:

(i) there is a low level of oxygen, ie O2 $< 0.0013\%$;
AND (ii) there is a low level of nitrogen, ie N2 $< 0.01\%$;
AND (iii) there is a low level of sulphur, ie S $< 0.05\%$;
AND (iv) there is boron presence, ie B $> 0\%$.

OR

(i) there is a low level of boron, ie B > 5ppm

(ii) High carbon is true if:

(i) there is a level of carbon, C $> 0.25\%$;
AND (ii) there is a level of manganese, Mn $> 1.00\%$.

RULE SHEET: Rule sheet 6

INVARIANT PART: 2/1
High proportions of combinations of elements.

INPUT USER:

OBJECTIVE:
Evaluate the risk of HICC from high proportions of combinations of elements.

SOURCE OF RULE (full reference / named authority / other):
(1) M.Sc. Handout, Mat 250 + Mat 157 + Mat 160.
(ii) Affix here references about CE.

STATEMENT(S) OF RULE:
This rule encompasses the carbon equivalent formulae. The most widely used formulas, Ceq(IIW) and P^{cm}(Ito-Bessyo) have been used here.
The following clauses must be satisfied for the above rule to be true:

(i) there is a risk of HICC on carbon, carbon-manganese steels only if Ce^{iiw} value exceed 0.37%;

OR (ii) there is a risk of HICC on microalloyed steels if P^{cm} exceed 0.20%.

In other words, if Ce^{iiw} or P^{cm} exceed their respective maximums then HICC is increasingly likely - there will then be a need to take corrective actions for avoidance.

RULE SHEET: Rule sheet 7

INVARIANT PART: 3/1
Low proportions of individual elements.

INPUT USER:

OBJECTIVE:
Evaluate the risk of HICC from low proportions of individual elements.

SOURCE OF RULE (full reference / named authority / other):
(1) BS 5135 - appendices.

STATEMENT(S) OF RULE:
This rule deals with the incidence of sulphur in the parent plate.

Risk of HICC if:

(i) sulphur exists below a value of 0.008%.

The low sulphur increases the risk of HICC by making the microstructure more hardenable. The effect has been shown to exist in a limited number of cases; an increased CE value may be assumed, if sulphur is of a low magnitude, to take account of its hardening effect.

RULE SHEET: Rule sheet 8

PROBLEM SPACE: 2
Cooling rate.

INPUT USER:

OBJECTIVE:
Evaluate the risk of HICC due to a fast cooling rate in a specific range.

SOURCE OF RULE (full reference / named authority / other):
(1) 'Metallurgy of Welding' - J.F. Lancaster.

STATEMENT(S) OF RULE:
This rule is supported by all of the following , ie rule is true if:

(i) there is insufficient heat generation from process parameters;
(ii) there is insufficient preheat temperature;
(iii) there is insufficient interpass temperature.

Preheat is effective in reducing cooling rate, and thereby modifying the thermal transformations, and in reducing weld and HAZ hardness. It will also contribute to reducing the maximum sensitivity to hydrogen embrittlement and will allow hydrogen to diffuse out of the weld and HAZ.
NB: Post weld heat treatment in the subcritical range has the effect of reducing the hardness and strength of alloy steel weld deposits, and (in thickness over about 30 mm) increasing the ductility and the fracture toughnes of the joint as a whole. Impact strength may however be reduced in part because of the reduction in yied strength.
ostructure more hardenable. The effect has been shown to exist in a limited number of cases; an increased CE value may be assumed, if sulphur is of a low magnitude, to take account of its hardening effect.

RULE SHEET: Rule sheet 9.

INVARIANT PART: 1/2
Insufficient heat generation from process parameters.

INPUT USER:

OBJECTIVE:
Evaluate the risk of HICC from insufficient heat generation from process parameters.

SOURCE OF RULE (full reference / named authority / other):
(1) No particular source - any weld procedure manual will give information relating to these parameters.

STATEMENT(S) OF RULE:
This rule is concerned with supplying adquante arc energy and is dependent on the following conditions.
The rule will succeed if:

(i) the arc current supplied to the workpiece is too low;
(ii) the arc voltage supplied to the workpiece is too low;
(iii) the arc travel speed is too high;
(iv) the wrong leg length has been specified - ie the size is not achievable in order that sufficient heat may be generated.
(v) the wrong polarity has been used (electrode -DC best heat input).

<u>RULE SHEET:</u> Rule sheet 10.

<u>INVARIANT PART:</u> 2/2
Insufficient preheat.

<u>INPUT USER:</u>

<u>OBJECTIVE:</u>
Evaluate the risk of HICC from insufficient preheat temperature specification.

<u>SOURCE OF RULE (full reference / named authority / other):</u>
(1) 'Welding steels without hydrogen cracking' - F.R. Coe
(2) 'MSc thesis' T. Garrido.

<u>STATEMENT(S) OF RULE:</u>
This rule is concerned with evaluate adequate preheat temperature and dependent on the following conditions. The adequate preheat temperature can be determined by the use of Nomogram of IIW and the rule will succeed if:

(i) the user preheat temperature is smaller than preheat temperature evaluated

RULE SHEET: Rule sheet 11.

INVARIANT PART: 3/2
Insufficient interpass temperature.

INPUT USER:

OBJECTIVE:
Evaluate the risk of HICC from insufficient interpass temperature specification.

SOURCE OF RULE (full reference / named authority / other):
(1) 'Welding steels without hydrogen cracking' - F.R. Coe
(2) 'MSc thesis' T. Garrido.

STATEMENT(S) OF RULE:
This rule is concerned with evaluate adequate interpass temperature and dependent on the following conditions. The adequate interpass temperature can be determined considering that its value will be the same as the preheat temperature evaluated. The rule will succeed if:

(i) the user interpass temperature is smaller than interpass temperature evaluated

RULE SHEET: Rule sheet 13.

PROBLEM SPACE: 3
High rate of grain growth.

INPUT USER:

OBJECTIVE:
Evaluate the risk of HICC from a high rate of grain growth.

SOURCE OF RULE (full reference / named authority / other):
(1) No particular source - any reference relating to welding metallurgy, ie 'Metallurgy of Welding' J.F. Lancaster.

STATEMENT(S) OF RULE:
This rule is true if one of the following is true:

(i) there is an unacceptably high risk of grain growth due to:

(a) length heat input
OR (b) excessive high heat input

OR (ii) there is insuffficient additions of grain refiners to the weld metal. This would be overcome by making additions to the weld metal via the electrode or via the consumable wire.

RULE SHEET: Rule sheet 12.

SUB-DOMAIN PROBLEM: 2
Hydrogen presence.

INPUT USER:

OBJECTIVE:
Evaluate the hydrogen presence.

SOURCE OF RULE (full reference / named authority / other):
(1) No particular source - any reference relating to welding metallurgy, ie ’Metallurgy of Welding’ J.F. Lancaster.

STATEMENT(S) OF RULE:
This rule may be satisfied in one to two ways. Hydrogen may be introduced into either the HAZ or into the weld metal:

(i) excess of amount hydrogen in HAZ;
(ii) excess of amount hydrogen in weld metal.

In the overwhelming majority of cases, the problem of hydrogen is confined to the HAZ - seldom is the problem associated with the weld metal, but it cannot be overlooked. The reason for this is based on the fact that the weld metal transforms into ferrite first before the HAZ, and since hydrogen is not soluble within ferrite, it transforms to the HAZ which remains austenitic for a longer time, and hydrogen is fully soluble here.

RULE SHEET: Rule sheet 14.

PROBLEM SPACE: 1/2
Excess of hydrogen presence in HAZ.

INPUT USER:

OBJECTIVE:
Evaluate the risk of HICC due to excess of hydrogen in HAZ.

SOURCE OF RULE (full reference / named authority / other):
(1) No particular source - any reference relating to welding metallurgy, ie 'Metallurgy of Welding' J.F. Lancaster.

STATEMENT(S) OF RULE:
This rule is true if one of the following is true:

(i) there is a risk of HICC from a source of hydrogen from the arc atmosphere;
OR (ii) there is a risk of HICC from a source of hydrogen from hydrocarbon and moisture.

RULE SHEET: Rule sheet 15.

INVARIANT PART: 1/1/2
Source of hydrogen from arc atmosphere.

INPUT USER:

OBJECTIVE:
Evaluate the risk of HICC from source hydrogen from arc atmosphere.

SOURCE OF RULE (full reference / named authority / other):
(1) No particular source - any reference relating to welding metallurgy, ie 'Metallurgy of Welding' J.F. Lancaster.

STATEMENT(S) OF RULE:
An intermediate explanatory note is 'ineffective arc shielding'.
The main rule is true if one of the following it is true:

(i) there is entrainment of hydrogen which is inherent in the welding process which has been adopted:
    (a) excess amount of hydrogen in the gas bottles (is not pure enough);
  OR (b) moisture has been drawn from the gas lines (condensation);

OR (ii) there is an excessive amount of standoff (ie distance between workpiece and torch) which reduces the effectiveness of the shielding gas atmosphere
    (a) too great for GMA process;
  OR (b) too great for GTA process.

OR (iii) there may be a danger of hydrogen entrainment if welding is carried at on site
    (a) excess wind speed (blow away shielding gas)
  OR (b) inadequate cover: no cover, or leaking.

OR (iv) there may be incorrect electrode orientation which will permit hydrogen entrainment.

RULE SHEET: Rule sheet 16.

INVARIANT PART: 2/1/2
Source of hydrogen from hydrocarbon and moisture.

INPUT USER:

OBJECTIVE:
Evaluate the risk of HICC from hydrocarbon and moisture.

SOURCE OF RULE (full reference / named authority / other):
(1) No particular source - any reference relating to welding metallurgy, ie 'Metallurgy of Welding' J.F. Lancaster.

STATEMENT(S) OF RULE:
This rule may be satisfied if one of the following is true;

(i) there is a risk of HICC from a source of hydrogen from the plate material:
  (a) source from paint;
OR (b) source from rust;
OR (c) source from dust;
OR (d) source from degreasing fluid.

OR (ii) there is a risk of HICC from a source of hydrogen from the consumables:
  (a) source from moisture on electrodes;
  (b) source from rust on wire;
  (c) source from oil on wire;
  (d) source from moisture in flux;
  (e) source from moisture in flux-cored-wire;
  (f) source from oil from wire feed mechanism.

RULE SHEET: Rule sheet 17.

SUB-DOMAIN PROBLEM: 3
Critical temperature.

INPUT USER:

OBJECTIVE:
Evaluate the risk of HICC from weld metal and HAZ reaching critical low temperatures.

SOURCE OF RULE (full reference / named authority / other):
(1) No particular source - any reference relating to welding metallurgy, ie 'Metallurgy of Welding' J.F. Lancaster.

STATEMENT(S) OF RULE:
The general rule is dependent on one of 3 factors:

(i) there is a risk of HICC due to insufficient heat input from preheating
    (a) either insufficient heat from blowtorches
OR (b) insufficient heat from electric elements

(ii) there is a risk of HICC due to insufficient heat input form interpass
    (a) either insufficient heat from blowtorches,
OR (b) insufficient heat from electric elements.

(iii) there is a risk of HICC due to insufficient conservation of existing heat
    (a) the insulation blankets are not thick enough,
OR (b) the blankets are not being used;
OR (c) the blankets are not being used in the most efficient manner.

RULE SHEET: Rule sheet 18.

SUB-DOMAIN PROBLEM: 4
Weld stress.

INPUT USER:

OBJECTIVE:
Evaluate the risk of HICC from residual tensile stress presence in the weld.

SOURCE OF RULE (full reference / named authority / other):
(1) No particular source - any reference relating to welding metallurgy, ie 'Metallurgy of Welding' J.F. Lancaster.

STATEMENT(S) OF RULE:
This rule is supported by 2 conditions which need to be present:

(i) a residual stress risk due to material properties;
OR (ii) a residual stress risk due to joint design.

RULE SHEET: Rule sheet 19.

PROBLEM SPACE: 1/4
Residual stress-material properties.

INPUT USER:

OBJECTIVE:
Evaluate the risk of HICC due to residual stress - material properties.

SOURCE OF RULE (full reference / named authority / other):
(1) No particular source - any reference relating to welding metallurgy, ie 'Metallurgy of Welding' J.F. Lancaster.

STATEMENT(S) OF RULE:
This rule is dependent on one of the three conditions:

(i) there is a risk of HICC due to lateral contraction stresses;
OR (i) there is a risk of HICC due to angular rotational stresses;
OR (ii) both the above.

RULE SHEET: Rule sheet 20.

PROBLEM SPACE: 2/4
Residual stress - joint design.

INPUT USER:

OBJECTIVE:
Evaluate the risk of HICC due to residual stress - joint design.

SOURCE OF RULE (full reference / named authority / other):
(1) No particular source - any reference relating to welding metallurgy, ie 'Metallurgy of Welding' J.F. Lancaster.

STATEMENT(S) OF RULE:
This rule is dependent on one of the three conditions:

(i) there is a risk of HICC due to lateral contraction stresses;
OR (i) there is a risk of HICC due to angular rotational stresses;
OR (ii) both the above.

APPENDIX B

This appendix presents part of the computer program for the database management. It allows the integration expert system/database (XiPlus/dBase III Plus).

```
comment  *****************************************************************
     and   *  Integration Expert System/external database.
     and  *****************************************************************

when query startup
then do form "Blank entire screen"
 and do form "Dbase: Introduction"
 and do form "Dbase: database contents"
 and check startup

if   dbase commands filename is Known
 and dbase search filename is Also_Known
 and dbase results filename is Established
 and dbase filename is Determined
then updates are nonexistent
 and startup is complete

when startup is complete
then command reset file [dbase commands filename]
 and report to file [dbase commands filename] use [dbase filename]
 and command dosq copy matdata.dbf save.dbf
 and check reporting

comment ************************************************************
     and  The main rules to add, modify and delete database records, etc
     and  ************************************************************

if   current action is to add a new record to the database
then do form "PROCEDURE: new chemical composition of mb"
 and report to field output in "Dbase: Show dbase commands" from file new1.rpt
 and do form "Dbase: Show dbase commands"
 and report to file [dbase commands filename is] from file new1.rpt
 and force updates are outstanding
 and reporting is completed

if   current action is to modify an existing record
 and character is not na
 and the user says this is the right record
then report to field output in "Dbase: Show dbase commands" from file replace1.rpt
 and do form "Dbase: Show dbase commands"
 and report to file [dbase commands filename is] from file replace1.rpt
 and force updates are outstanding
 and reporting is completed
because
   and Looking at 'standard,class and number ' causes the database to be
   and read to get the first matching record.
   and Asking whether 'the user says this is correct' steps through successive
   and matching records until the user finds the right one.
   and Then we ask for the new standard,new class and new number .
```

```
if   current action is to delete an existing record
 and character is not na
 and the user says this is the right record
then report to field output in "Dbase: Show dbase commands" from file delete1.rpt
 and do form "Dbase: Show dbase commands"
 and report to file [dbase commands filename is] from file delete1.rpt
 and force updates are outstanding
 and reporting is completed

if   current action is to apply the changes to the database
 and updates are outstanding
then report to file [dbase commands filename] pack
 and report to file [dbase commands filename] quit
 and do form "Dbase: Entering dbase III Plus"
 and do program dbase access using ( dbase commands filename , space needed to get dbase in )
 and force updates are applied
 and reporting is completed

if   current action is to apply the changes to the database
 and updates are nonexistent or applied or discarded
then do form "Dbase: No updates to apply"
 and reporting is completed

if   current action is to discard any changes not yet applied to the database
then do form "Dbase: Discard changes"
 and force updates are discarded
 and reporting is completed

if   current action is to restore the database file to its original state
then command dosq copy save.dbf matdata.dbf
 and do form "Dbase: Changes undone"
 and force updates are discarded
 and reporting is completed

if   current action is to finish with this application
 and updates are applied or discarded or nonexistent
then reporting is completely finished

if   current action is to finish with this application
 and updates are outstanding
 and the user's decision is to exit anyway
then reporting is completely finished

if   current action is to finish with this application
 and updates are outstanding
 and the user's decision is "not to exit yet"
then reporting is completed

comment **************************************************************
   and Finding the right record to modify or delete.
   and **************************************************************
```

```
if   dbase has been read
then no matching records have yet been read
 and do program get dbase goodies using ( dbase results filename , next cells ) giving ( character , c , mn
     , si , p , ni , cr , mo , cu , al , v , nb , w , ti , s , b , rmin , rmax , reys , elm )

default next cells is f1.y1

when result of dbase access is Anything
 and result of dbase access is not ok
then do form "Dbase: Problem calling dbase"
 and command reset app

when character is na
 and no matching records have yet been read
then force the user says this is rather unexpected
 and do form "Dbase: No matching records"
 and reporting is completed

when character is na
 and matching records exist
then force the user says this is rather unexpected
 and do form "Dbase: No more matching records"
 and reporting is completed

when the user says this is "not the right record"
 and next cells is Next
 and successor of Next is Successor
then do form "Dbase: Getting next matching record"
 and command reset data
 and command reset agenda
 and command reset the user says this
 and force next cells is Successor
 and force matching records exist
 and do program get dbase goodies using ( dbase results filename , next cells ) giving ( character , c , mn
, si , p , ni , cr , mo , cu , al , v , nb , w , ti , s , b , rmin , rmax , reys , elm )
 and ask the user says this


if   current action is to modify an existing record or to delete an existing record
 and standard is Standard
 and number is Number
 and class is Class
then command reset file [dbase search filename]
 and report to file [dbase search filename] from file find1.rpt
 and do form "Dbase: Searching database"
 and do program dbase access using ( dbase search filename , space needed to get dbase in )
 and dbase has been read

when dbase has been read
then command reset forms
 and do form "Blank entire screen"
```

```
when current action is to modify an existing record
then modify\delete is modify

when current action is to delete an existing record
then modify\delete is delete

comment ************************************************************
    and After applying updates, reset the commands file.
    and ************************************************************

when updates are applied or discarded
then command reset file [dbase commands filename]
 and report to file [dbase commands filename] use [dbase filename]

comment ************************************************************
    and Having done the current action, what next?
    and ************************************************************

when reporting is completed
 and dbase search filename is Search filename
 and dbase commands filename is Commands filename
 and dbase results filename is Results filename
 and dbase filename is Filename
 and updates are Anything
then command reset data
 and dbase search filename is Search filename
 and dbase commands filename is Commands filename
 and dbase results filename is Results filename
 and dbase filename is Filename
 and updates are Anything
 and do form "Blank entire screen"
 and check reporting
because We only keep the things we are interested in

when reporting is completely finished
then do form "Dbase: Goodbye"
 and command dosq del [dbase commands filename is]
 and command dosq del [dbase results filename is]
 and command dosq del [dbase search filename is]
 and command load kb "Introduction to the example applications"

comment ********************************************************************
    and * facts                                                *

fact successor of f1.y1 is f2.y2

fact successor of f2.y2 is f3.y3

fact successor of f3.y3 is f4.y4

fact successor of f4.y4 is f5.y5

fact space needed to get dbase in = 512
```

```
comment ******************************************************
    and  Intercept ESC from any form or question.
    and  ******************************************************

fact "hitting ESC key" is probably to exit

when key escape Any_identifier
 and "hitting ESC key" is probably to exit
then force "hitting ESC key" is definitely to exit
 and do form "Initial escape"
 and command reset "hitting ESC key"
because We want the user to be able to ESC from the "Initial escape" form
   and but if the user acknowledges the form, then ESC was unintentional.




comment ****************************************************************
    and  * This knowledge base sets up the various filenames needed,
    and  * to access the database in  dbase III Plus
    and  ****************************************************************

when query initialisation
then do form "Blank entire screen"
 and do form "Dbase: Introduction"
 and do form "Dbase: Introduction 2"
 and check initialisation

if  dbase commands filename is Anything
 and dbase search filename is Established
 and dbase results filename is Known
 and dbase filename is Set up
then command load kb "Reading a series" of mb records and updating the database
 and initialisation is complete

if  user's dbase directory is Established
 and user's xip directory is Asked
then dbase commands filename is concatenation ( user's dbase directory , "\hlpmod.prg" )
 and dbase search filename is concatenation ( user's dbase directory , "\hlpfind.prg" )
 and dbase results filename is concatenation ( user's dbase directory , "\hlpfind.txt" )
 and dbase filename is concatenation ( user's xip directory , "\myexamp\matdata" )

default user's xip directory is c:\xip

when user's dbase directory is Anything
 and user's dbase directory is not \dbase3
then do form "Dbase: Change dbase access directory"

default user's dbase directory is c:\db3
```

```
comment *****************************************************
      and  Intercept ESC from any form or question.
      and  *****************************************************

fact "hitting ESC key" is probably to exit

when key escape Any_identifier
 and "hitting ESC key" is probably to exit
then force "hitting ESC key" is definitely to exit
 and do form "Initial escape"
 and command reset "hitting ESC key"
because We want the user to be able to ESC from the "Initial escape" form
    and but if the user acknowledges the form, then ESC was unintentional.






comment ********************************************************
      and  This knowledge base resumes a previous procedure database.
      and  It does this by asking for the number of the procedure and loading
      and  the database that was created when the previous procedure
      and  was finished.
      and  *********************************************************

when query call
then command reset forms
 and do form "Blank entire screen"
 and check call

if   the xi plus database is loaded
 and "the name and location are correct"
 and the synopsis report has been output
then call is ready to be resumed

if   the xi plus database for this procedure is unavailable
 and the welding procedure database record is definitely correct
then do form "Resume: lost the information"
 and command load kb "Introduction to wda application"
 and call is impossible to resume
because We can't resume the call

when the welding procedure database record is incorrect
then command reset data
 and do form "Help Desk Banner"
 and command query call
because If the number is incorrect, all we need to do is to start again.
```

```
if   first item read from xi plus database file is Anything
then the xi plus database for this procedure is located
because The Xi Plus database file exists and it's not empty.

if   done first item read from xi plus database file
 and result of read comma delimited file is file not found
then the xi plus database for this procedure is unavailable

if   the xi plus database for this procedure is located
 and xi plus database filename is File
then command load data File , noprompt
 and the xi plus database is loaded
 and do form "Blank entire screen"
 and check call

if   "the name and location are correct"
then do form "PROCEDURE: main screen final"
 and do form "table1"
 and do form "PROCEDURE: thermal results"
 and do form "PROCEDURE: final conclusion"
 and the synopsis report has been output
because
    and Note that "call log file" is one of the identifiers read from the
    and Xi Plus database file: we don't work it out in this knowledge base

if   xi plus database filename with extension is Any_file
then first item read from xi plus database file is read comma delimited file ( xi plus database filename
with extension is , "a1.a1" )
because
    and Note that the .dbc file is NOT a comma-delimited file. This read is
    and just a way of seeing if the file is found or not.

fact xi plus database filename is concatenation ( path code , "ps" , file number is )

default path code is c:\xip\scc\dbc\

fact xi plus database filename with extension is concatenation ( path code ,"ps",file number is , ".dbc" )

if   numeric wp number = Any_number
then file number is Any_number

when "the name and location are incorrect"
then ask welding procedure database record is

when "the name and location are incorrect"
 and welding procedure database record is incorrect
then command reset data
 and do form "Help Desk Banner"
 and command query call
because We just start again from the beginning.
    and We've found an Xi Plus database file, but we don't seem to be
    and resuming the call that corresponds to the caller.
```

```
when "the name and location are incorrect"
 and welding procedure database record is definitely correct
then do form "Resume: lost the information"
 and command load kb "Introduction to wda application"

when call is ready to be resumed
then command reset call
 and command reset the xi plus database
 and command reset the name and location
 and command reset the synopsis report
 and command load kb "Introduction to wda application"

comment ** Intercept ESC from any form or question. **

fact "hitting ESC key" is probably to exit

when key escape Any_identifier
 and "hitting ESC key" is probably to exit
then force "hitting ESC key" is definitely to exit
 and do form "Initial escape"
 and command reset "hitting ESC key"
because We want the user to be able to ESC from the "Initial escape" form
    and but if the user acknowledges the form, then ESC was unintentional.
```

APPENDIX C

This appendix presents a summary of the papers previously published involving parts of this work.

Paper 1 - Fourth International Conference - Computer Technology in Welding, June 1992, Cambridge, UK

WELDCARE - Computer Prediction of Welding Defect at the Procedure Stage.

S C Costa, MSc (EFEI/Brasil)
J Norrish, MSc, C.Eng, F.Weld I (Head of Welding Group, Cranfield Institute of Technology)

SUMMARY

Weld defects are costly to rectify and the most effective method of preventing their occurrence is at the procedure specification stage. An attempt has therefore been made to evaluate the risk of defects being produced as the welding procedure proposal is being prepared.

The feasibility of the system has been demonstrated using an expert system shell and a common procedure database storage system. Knowledge base representation using production rules with a forward and backward control strategies were utilised. The potential of the system has been assessed for hydrogen induced cold cracking and the extension of the system to other risk factors is considered.

INTRODUCTION

A wide range of defects may arise during the course of normal fabrication operations and these may lead to rejection, costly rework or even inadequate service performance of the joint. In practice the final joint quality is often assessed after welding by a variety of non destructive examination techniques, the significance of any defects is estimated and the necessary corrective action taken.

A much more cost effective approach is to establish a welding procedure which gives acceptable joint quality prior to the commencement of production welding. This "Right First Time" approach is the basis of the common practice of establishing qualified welding procedures. Although welding procedures are an effective means of control their development is a time consuming and costly exercise which is best carried out by an experienced welding engineer.

Some progress has been made in the computerisation of procedure records (1)

Paper 2 - Welding and Metal Fabrication, ed. TWI, may 1991, pp. 186-190.

Computer prediction of welding defects at the procedure stage

by S C Costa and J Norrish*

An expert system approach has been developed to assess the likelihood of defects arising from the adoption of a selected welding procedure. This article explains the advantages of using such a system and describes a prototype system designed to minimise the risk of hydrogen induced cold cracking.

A wide range of defects may arise during the course of normal fabrication operations, and these may lead to rejection, costly rework or inadequate service performance of the joint. In practice, the final joint quality is often assessed after welding by a variety of non destructive examination techniques, the significance of any defects assessed and the necessary corrective action taken.

A much more cost effective approach is to establish a welding procedure which gives acceptable joint quality prior to the commencement of production welding. This 'right first time' approach is the basis of the common practice of establishing qualified welding procedures. Although welding procedures are an effective means of control, their development is a time consuming and costly exercise which is best carried out by an experienced welding engineer. Some progress has been made in the computerisation of procedure records[1]. This enables pre-existing procedures to be located easily and can be shown to decrease the cost of procedure storage and retrieval. It seems logical to extend the use of computers to procedure generation and defect assessment; work in these areas has been reported[2].

The object of the present work has been to demonstrate the feasibility of using an expert system approach to check for the likelihood of defective welds as a procedure proposal is entered into a computerised database system.

Expert systems

An expert system is defined as a computer system which emulates human expertise by making deductions from given information using the rules of logical inference. This concept was developed in the 1970s and has attracted great interest in many engineering applications.

Expert systems are an example of artificial intelligence (AI), and specific computer languages have been developed to deal with them. In fact, there are two possible approaches for developing such a system[3]. The system can be developed from first principles, using any suitable computer language, eg, Prolog or Lisp. The second method is to use a suitable expert system shell. These systems are generally regarded as knowledge engineering tools that include most of the elements necessary for building a complete expert system. This method is quicker, but offers certain restrictions in the system design and operation domain[3].

Risk of defects

The types of defect which occur in the fabrication of common engineering materials are fairly well established[4], and the experienced welding engineer will be aware of the techniques required for their avoidance. If it is required to use a computer based system to assess the risk of a defect, it is first necessary to establish a set of rules which may be used to determine the cause and the likelihood of the defect occurring. Establishing this set of rules is a complex and time consuming task which entails a process known as knowledge elicitation; this requires the experience of the welding engineer and published data to be organised in a manner suitable for use with a knowledge based system. The basic information required to define several modes of failure has been determined[5-6], but in order to demonstrate the feasibility of the approach in a realistic timescale hydrogen induced cold cracking (HICC) was chosen for further study in the present work.

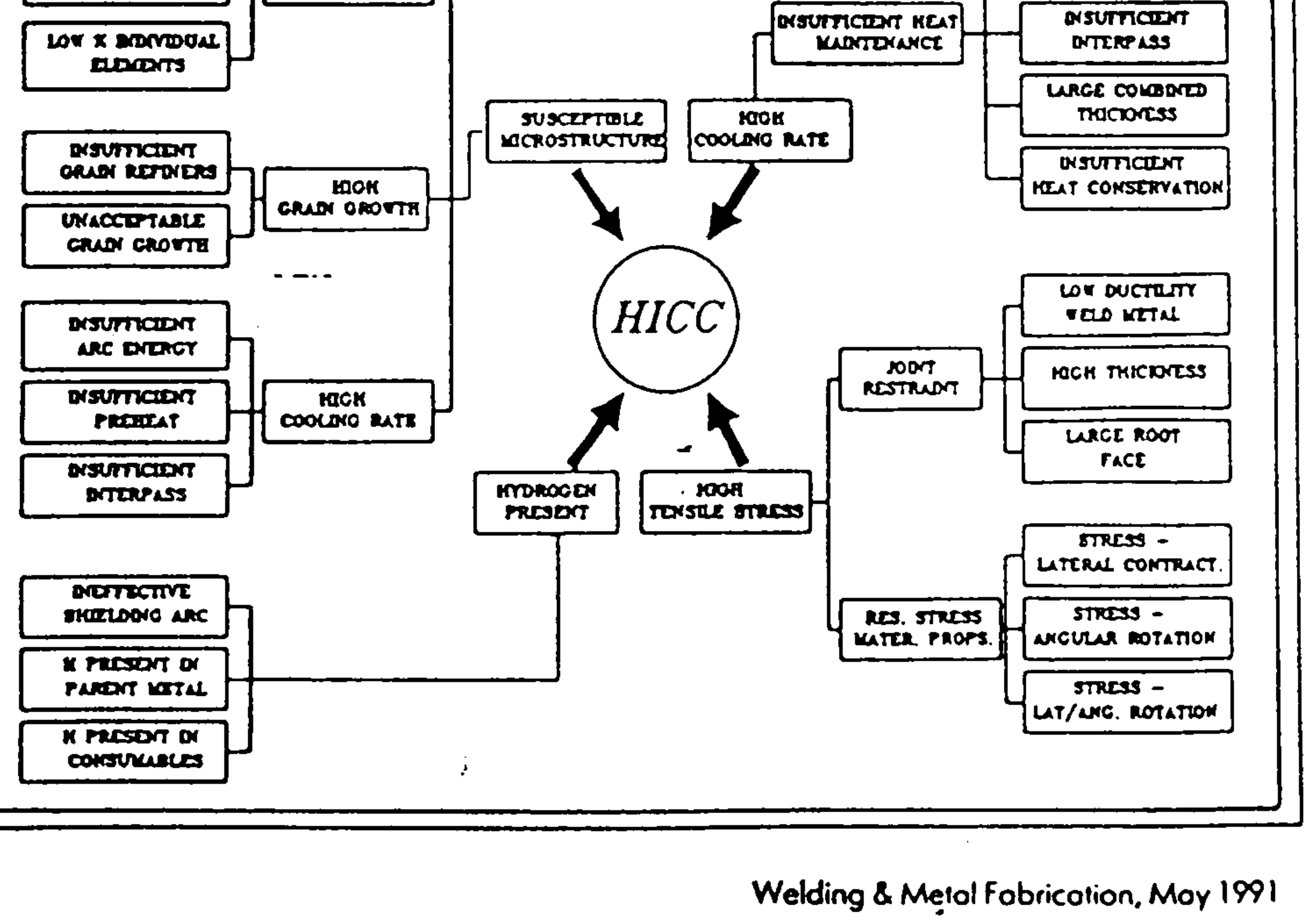
The risk of hydrogen induced cold cracking is a major concern in the fabrication of ferritic steels. For this reason many attempts have been made to establish appropriate methodologies to control the welding parameters to avoid HICC. It is known, for example, that hydrogen induced cold cracking is likely under the combined influence of susceptible microstructure, hydrogen presence and high stress. All of these aspects are naturally correlated with a series of secondary factors, such as the carbon equivalent of the material, the cooling rate after welding and the level of restraint, which in turn are dependent on the joint design and the welding parameters. The relationship between these factors and the risk of HICC is illustrated in fig 1.

The complexity of specifying a procedure which minimises the risk of this one defect is apparent, and gives some indication of the magnitude of the welding engineer's task. The aim of the system developed here is to assist the welding engineer to produce a 'low risk' procedure and not to 'de-skill' the task of procedure generation.

The prototype system

Taking the aspects above into consideration, a prototype system was designed as outlined in fig 2. The system is designed to receive information encoded in a welding procedure specification. The data is typed into fields on the entry

Fig 1. Hydrogen induced cold cracking influence factors



*Sebastião C Costa is a PhD student at Cranfield Institute of Technology and John Norrish is Head of Welding Group, Cranfield Institute of Technology, Bedford MK43 0AL.

Paper 3 - International Conference on Computerization of Welding Information IV, Orlando, Florida, Nov. 1992.

A COMPUTER BASED SYSTEM FOR THE EVALUATION OF WELDING PROCEDURES AT THE DESIGN STAGE.

S.C.Costa*, J.Norrish**

ABSTRACT

Weld defects are costly to rectify and the most effective method of preventing their occurrence is at the procedure specification stage. An attempt has therefore been made to evaluate the risk of defects being produced as the welding procedure proposal is being prepared.

The system developed during the current work presents the user with a blank welding procedure sheet and gives him complete freedom to input the welding parameters. When the required details are entered the knowledge based system evaluates the risk of "failure" of the proposed procedure and advises the user of the possibility of defects and corrective action. Using this information optimisation of the procedure is possible and an improved specification can be established.

The feasibility of the system has been demonstrated using an expert system shell and a common procedure database storage system. Uncertainty analysis was applied as a means of representing some of the "vague" knowledge involved and the effect of the uncertainty propagation into a risk evaluation network was analyzed.

The potential of the system has been assessed for hydrogen induced cold cracking. Results indicate that the use of such system can predict with some accuracy the occurrence of cold cracking. As a consequence reduced time should be required to establish a safe welding procedure specification, this in turn should greatly decrease the work load involved in welding experiments, saving manpower and material resources, and raising the quality level of the resultant joints.

INTRODUCTION

A wide range of defects may arise during the course of normal fabrication operations and these may lead to rejection, costly rework or even inadequate service performance

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* **EFEI, Itajubá, MG, Brasil.**

** **Head of Welding Group, Cranfield Institute of Technology, Cranfield, Beds, MK43 0AL, England.**

CHAPTER FIGURES

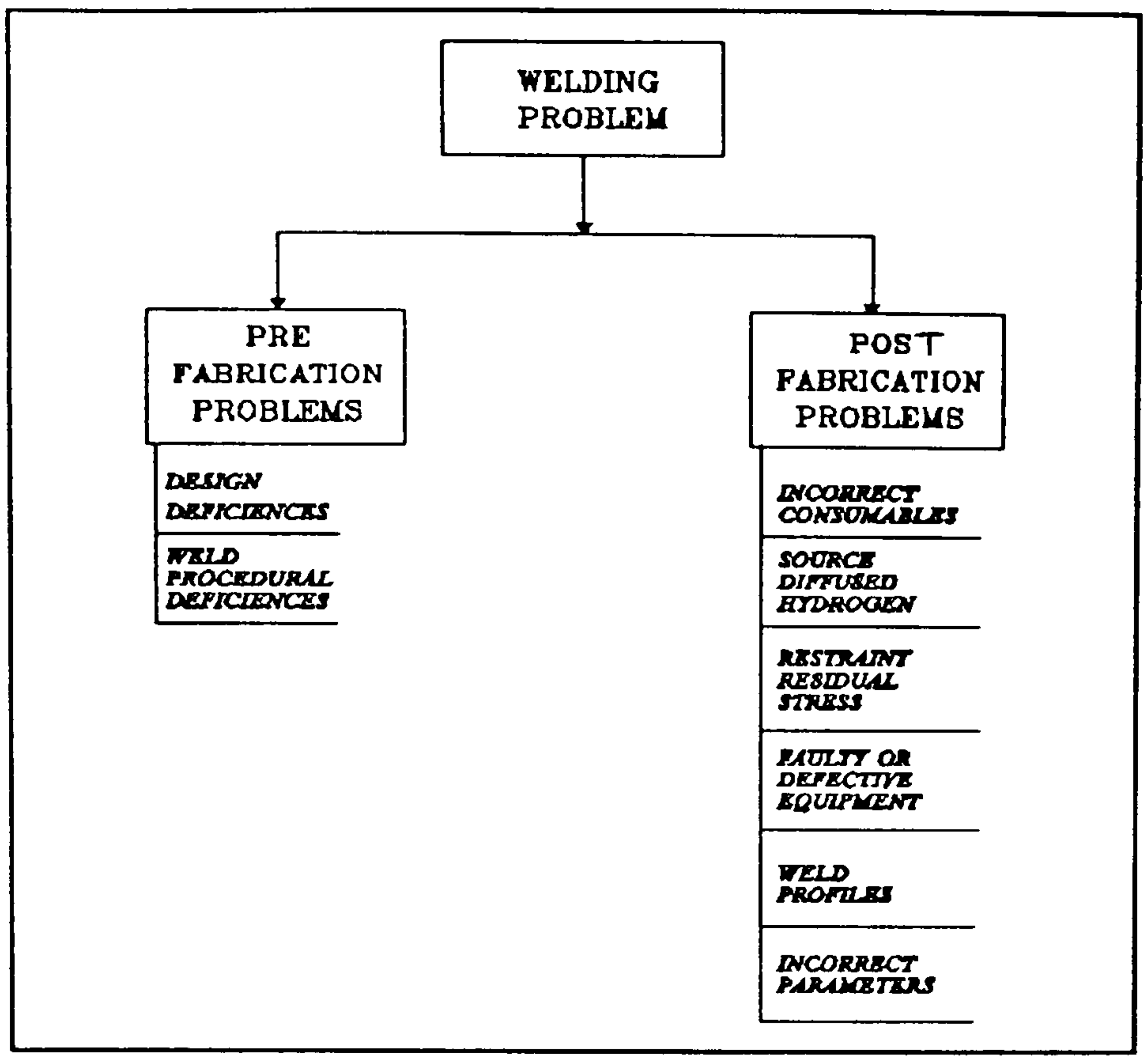


Figure 1.1 - Identification of welding problems.

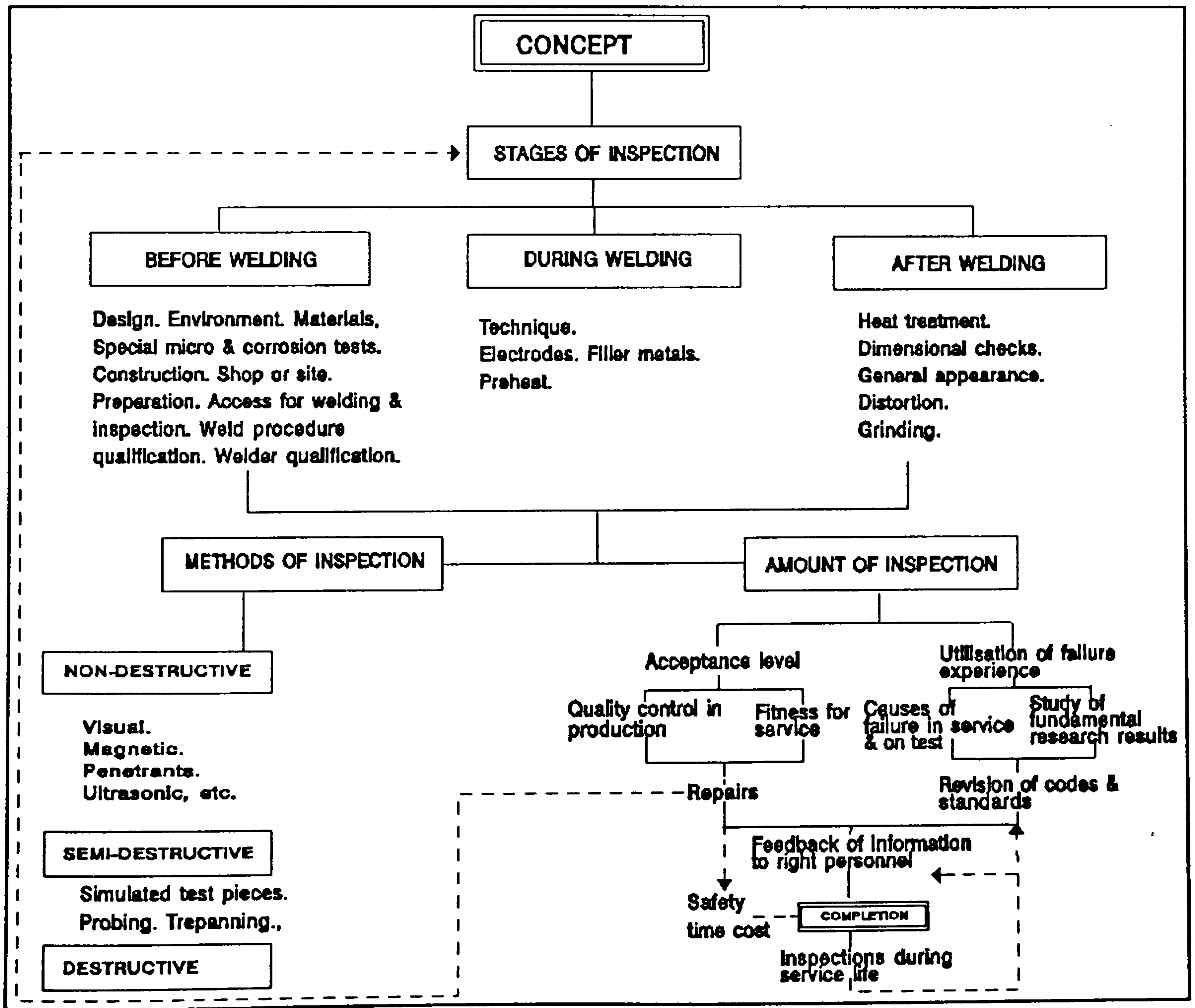


Figure 1.2 - Factors concerning inspection (Atkinson, 1970).

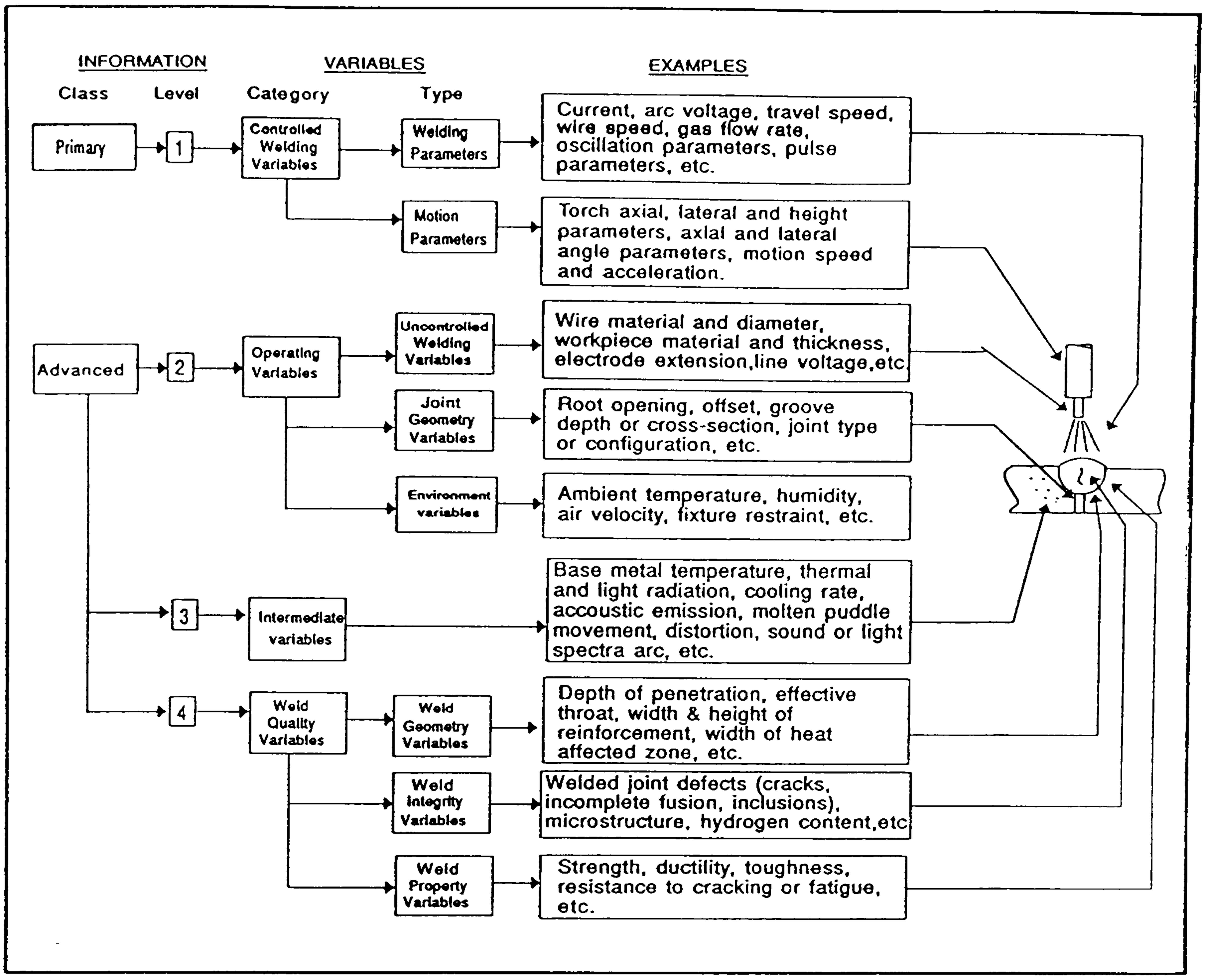


Figure 1.3 - Categorisations of variables of welding process.

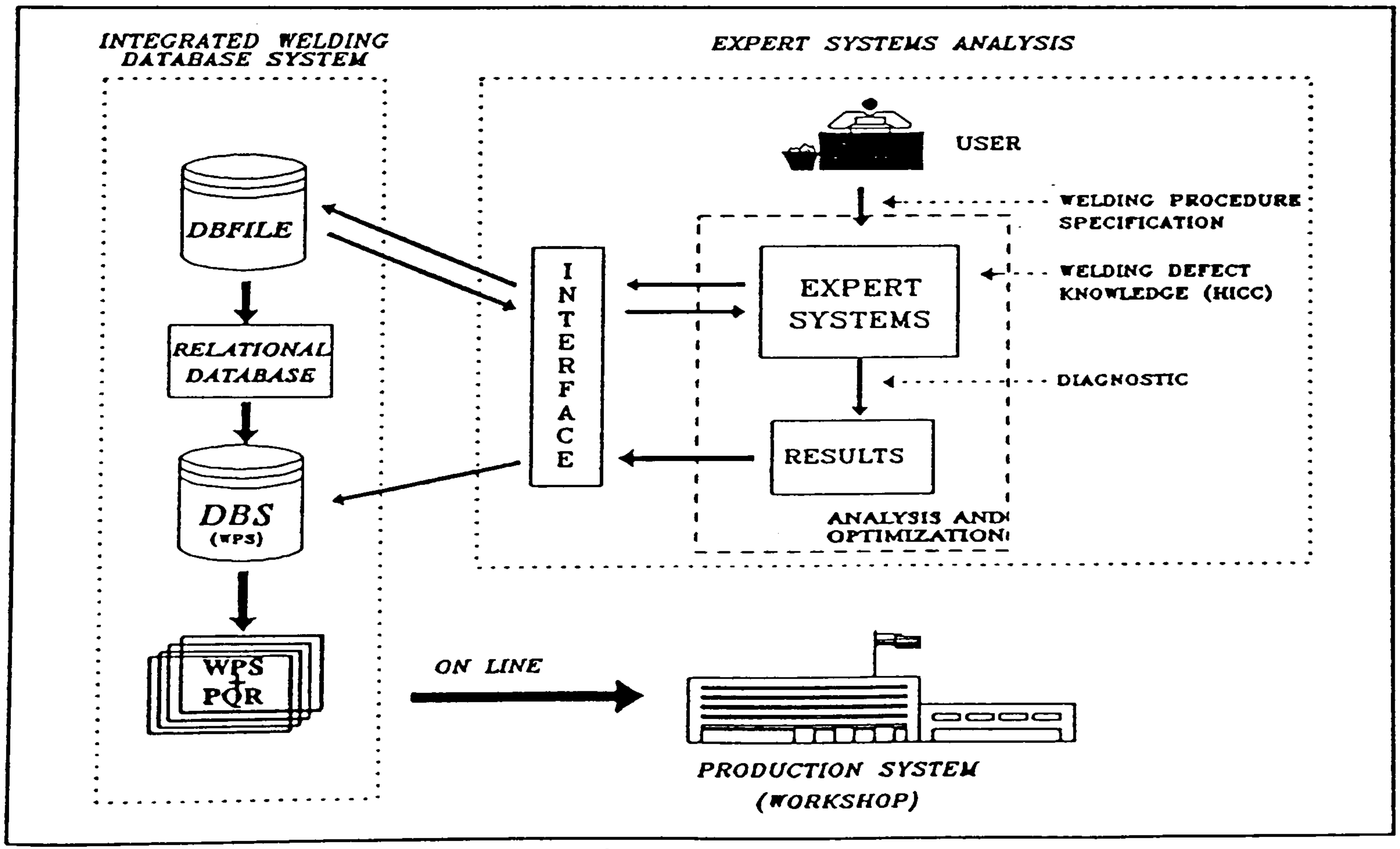


Figure 1.4 - Integrated welding design system.

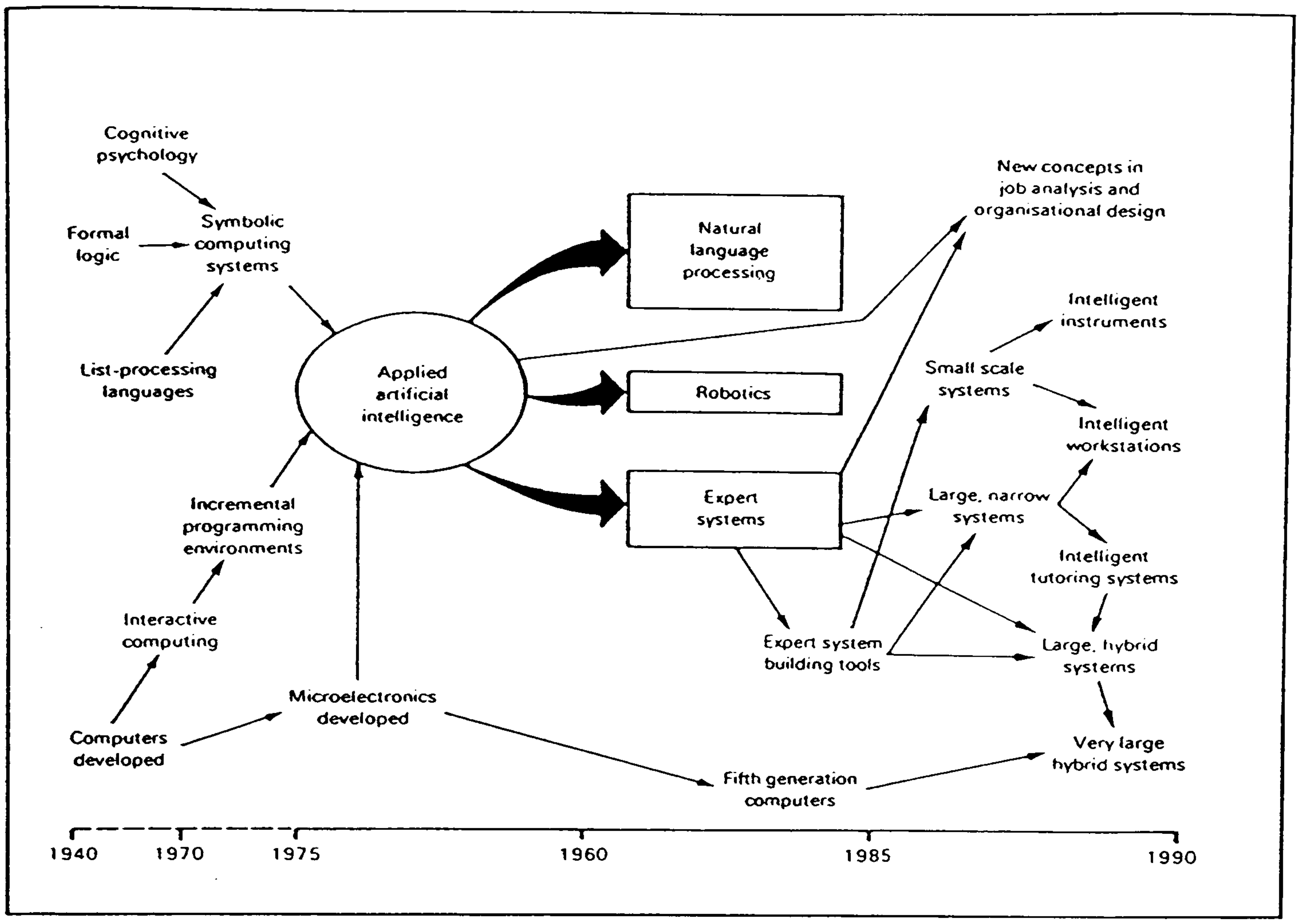


Figure 2.1 - Evolution of expert systems (Edward, 1988).

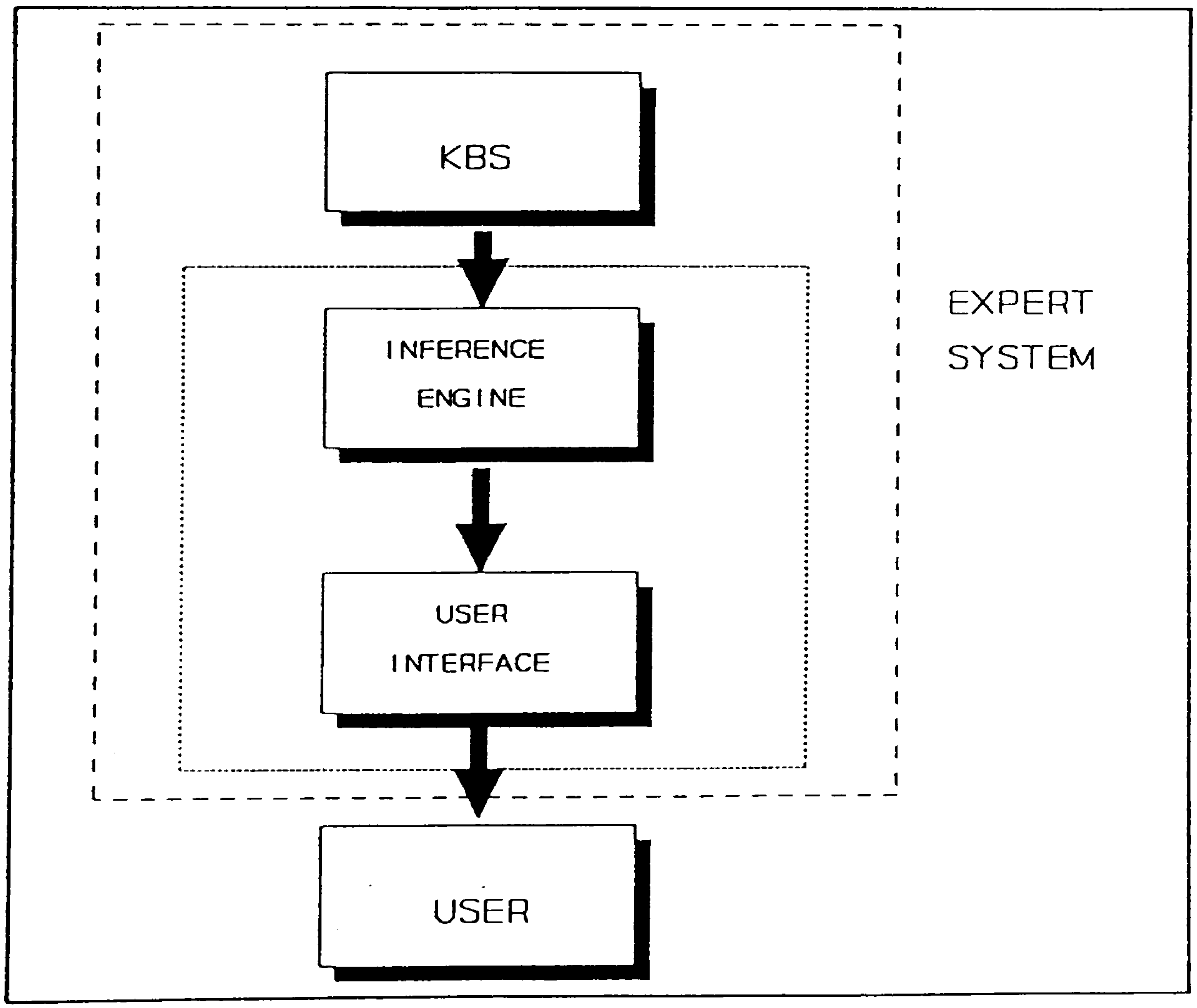


Figure 2.2 - Main structure of an expert system.

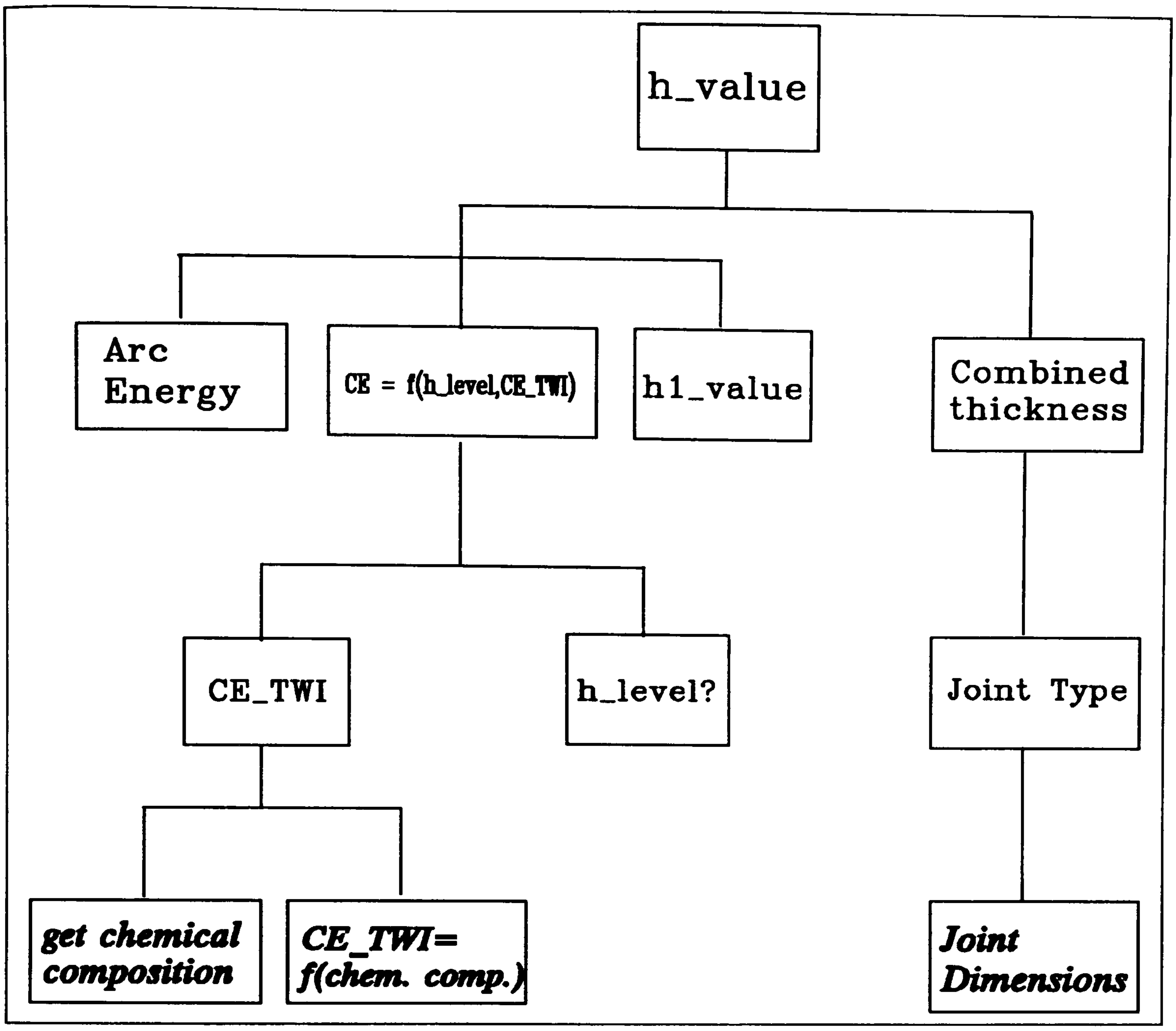


Figure 2.3 - A network representation.

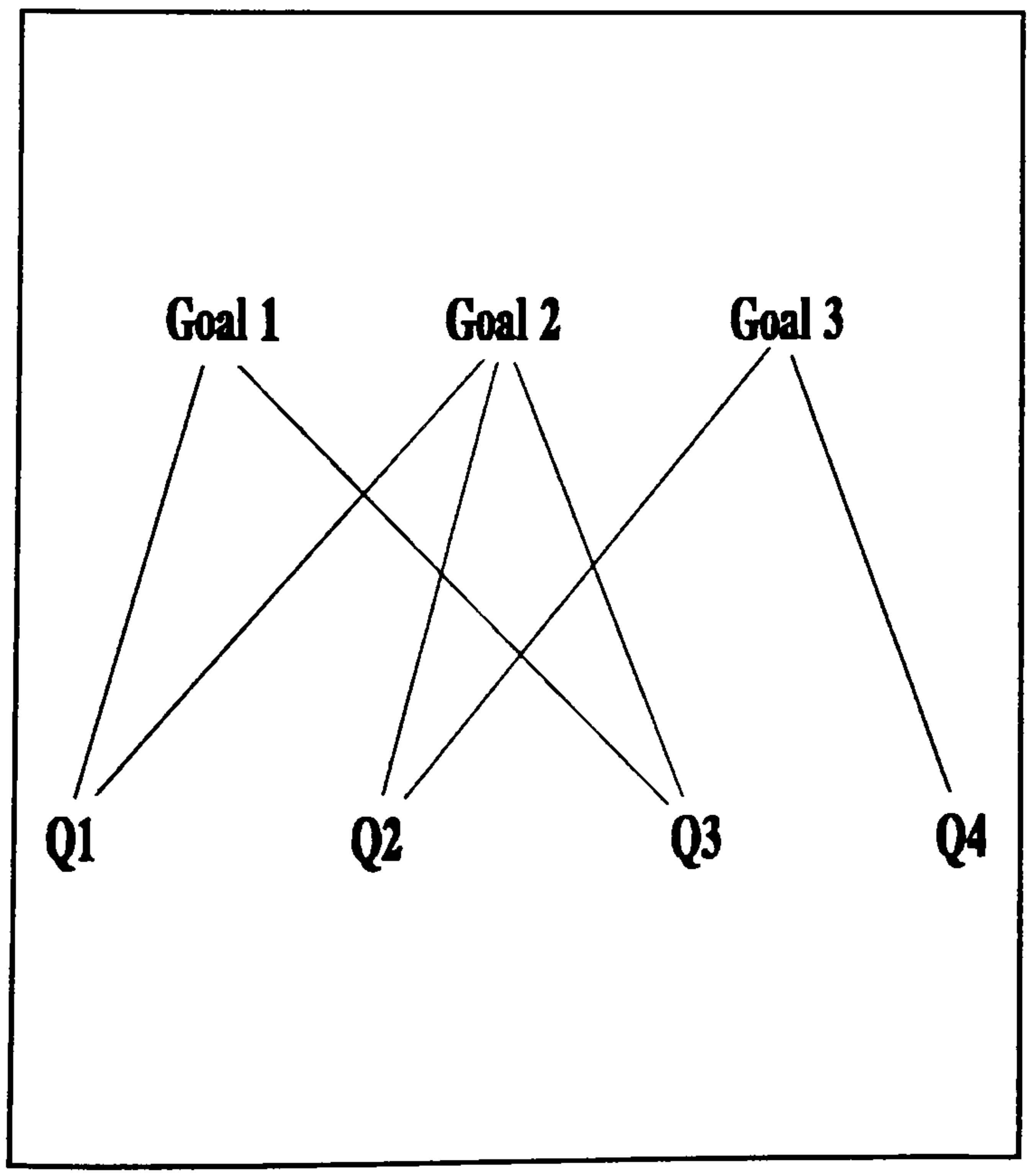


Figure 2.4 - Network representing inference control strategie.

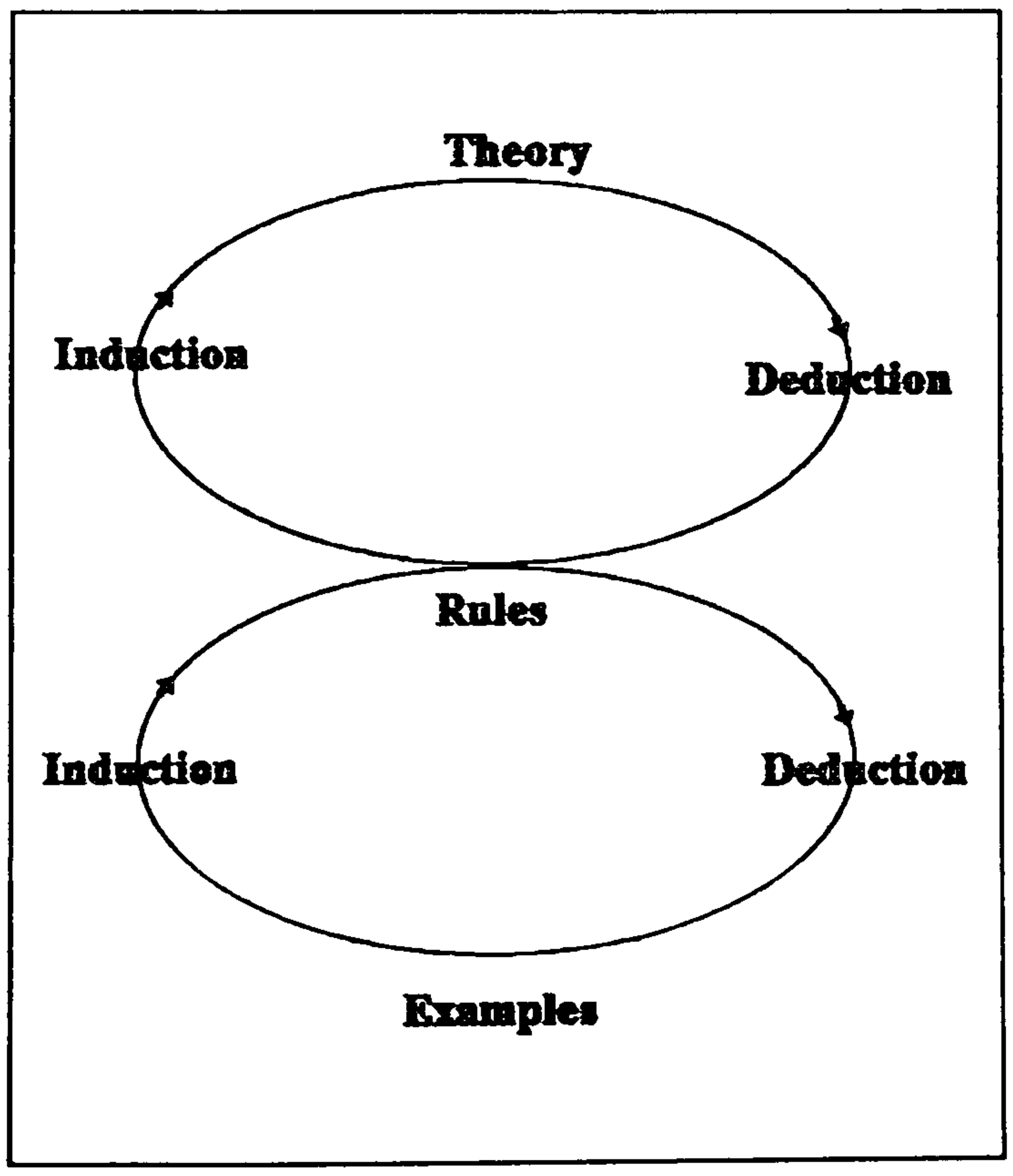


Figure 2.5 - Types of reasoning.

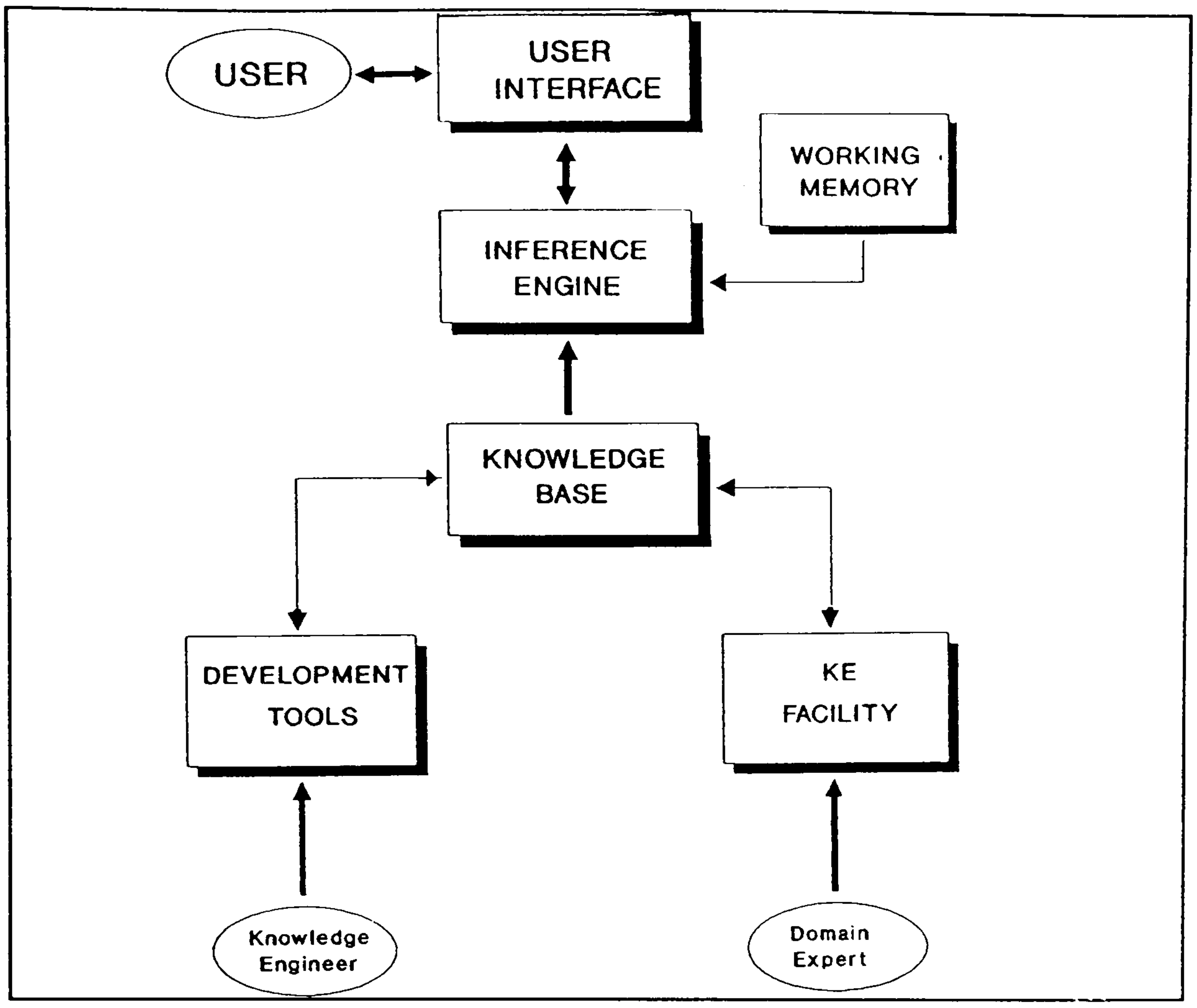


Figure 2.6 - Architecture of an expert system shell.

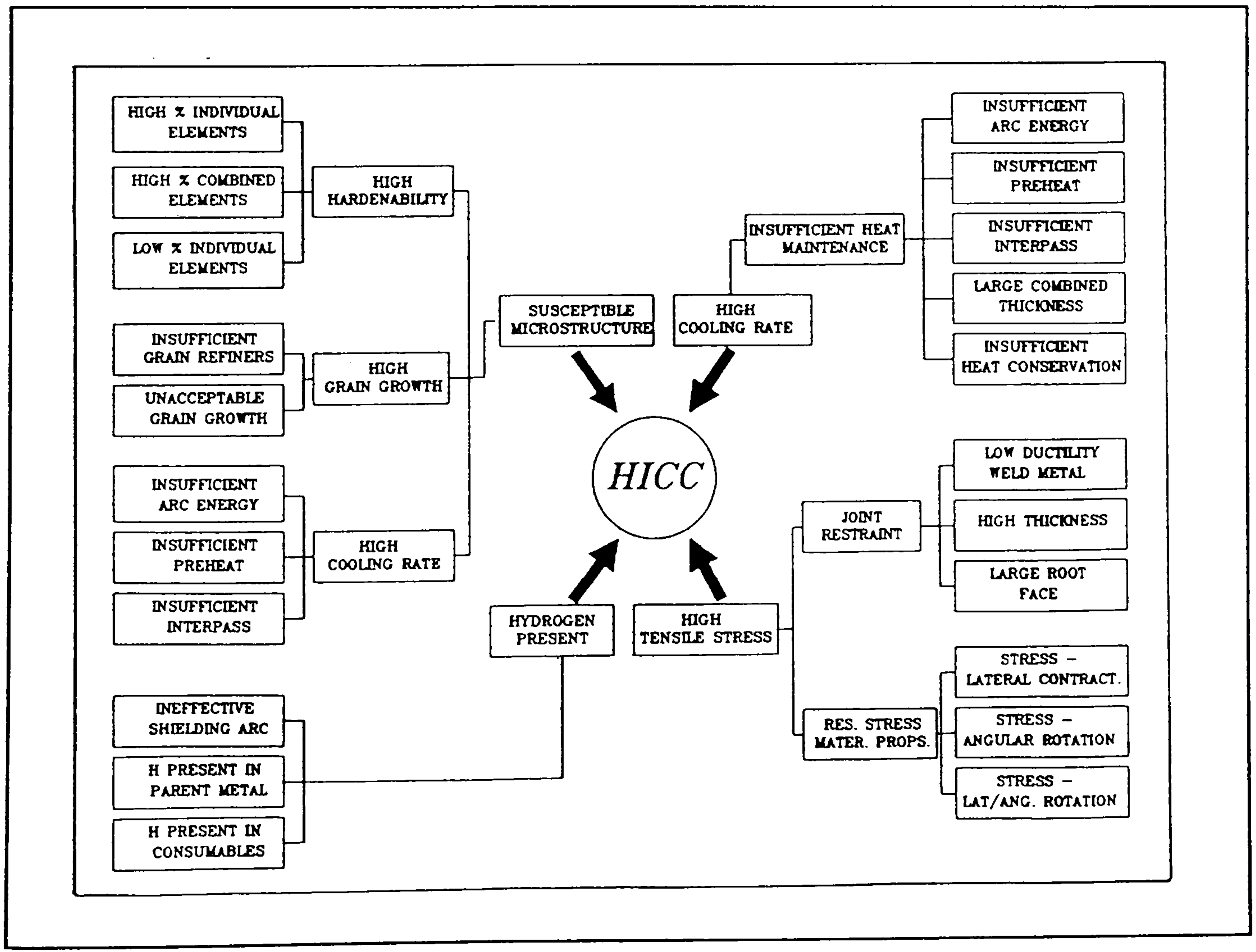


Figure 2.7 - HICC influencing factors.

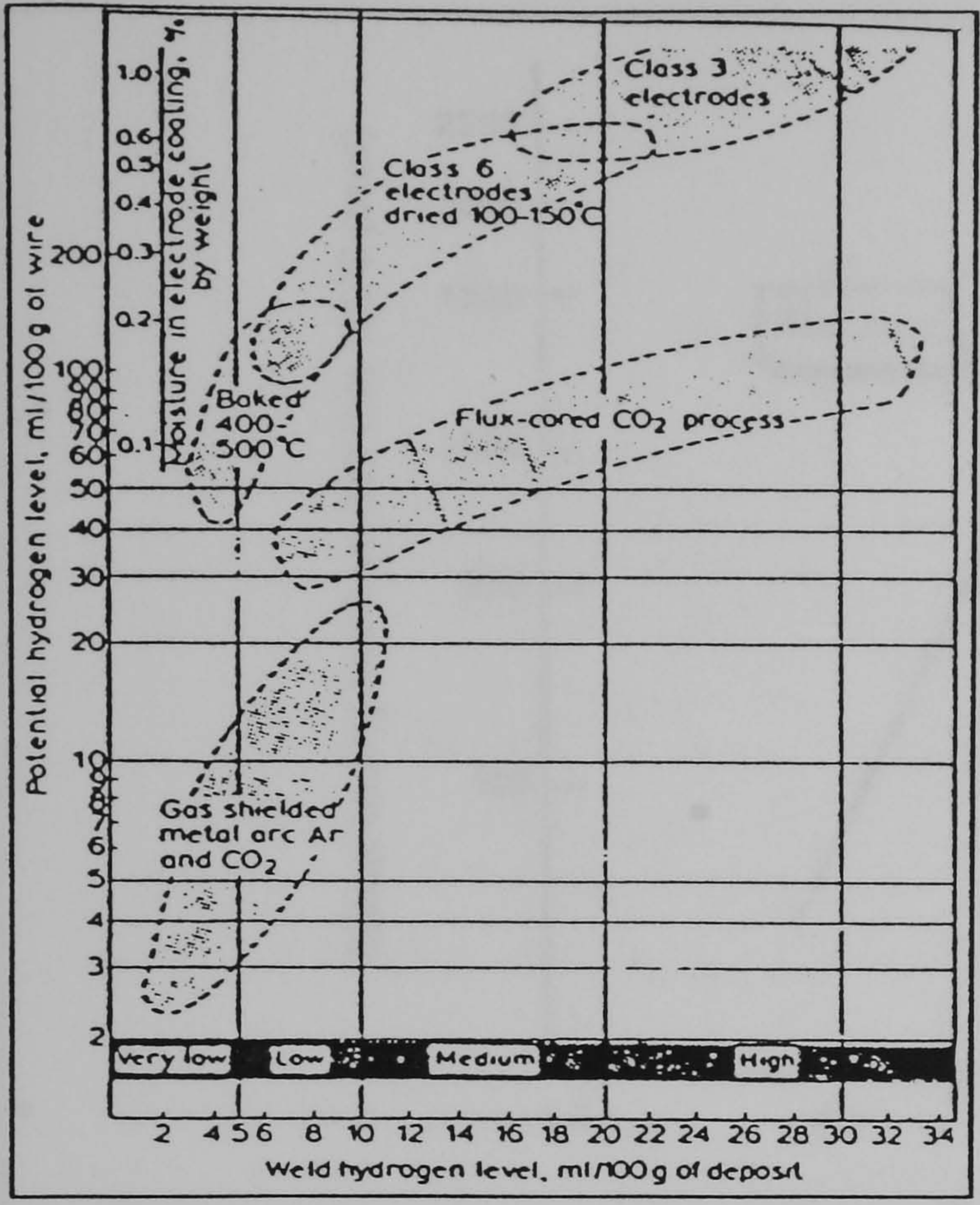


Figure 2.8 - Range of hydrogen contents expected in various welding processes (Lundin, 1990).

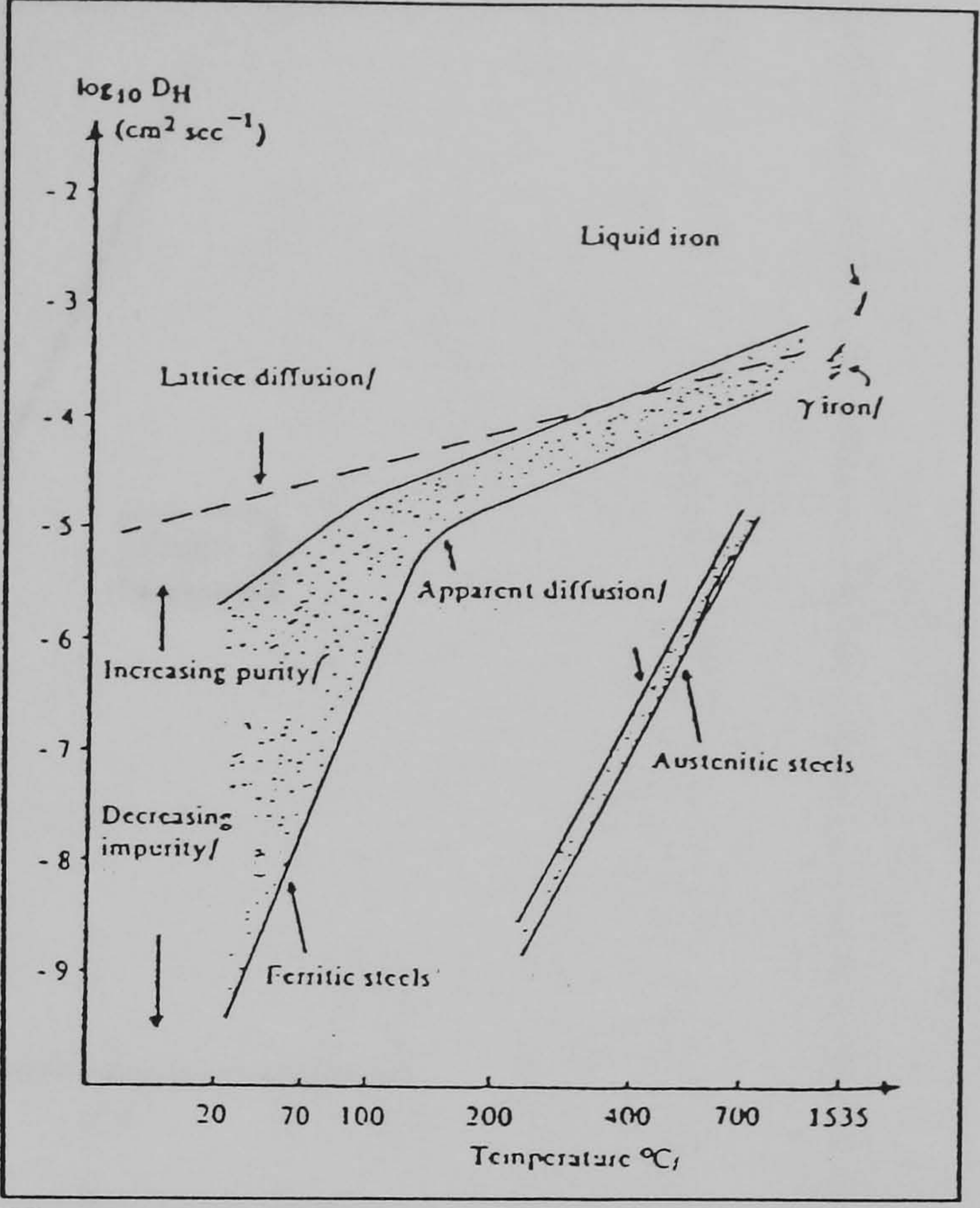


Figure 2.9 - Variation in the hydrogen diffusivity coefficient with temperature (Coe, 1973).

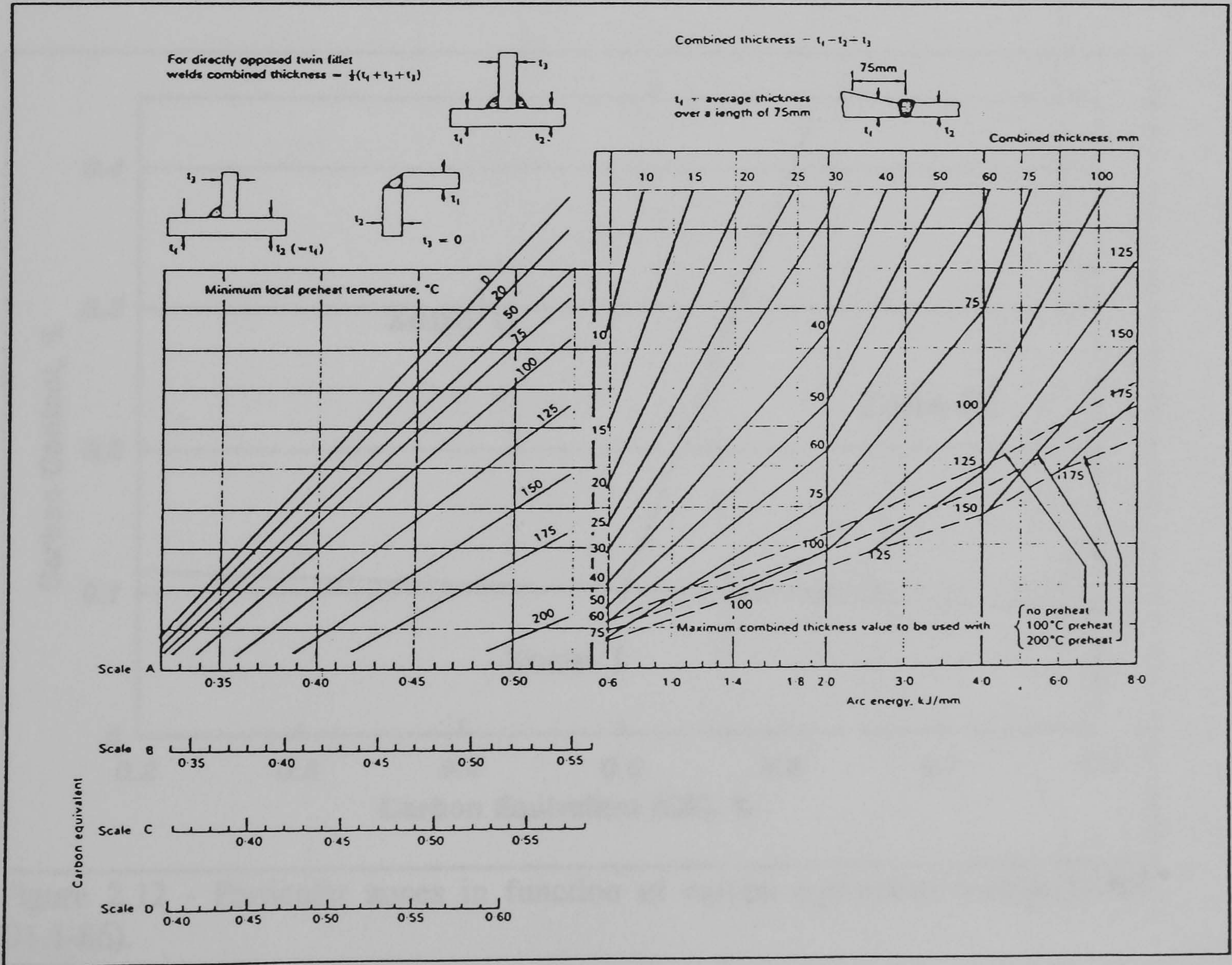


Figure 2.10 - Nomogram to determine the preheat temperature using Hardness Control Approach (Coe, 1973).

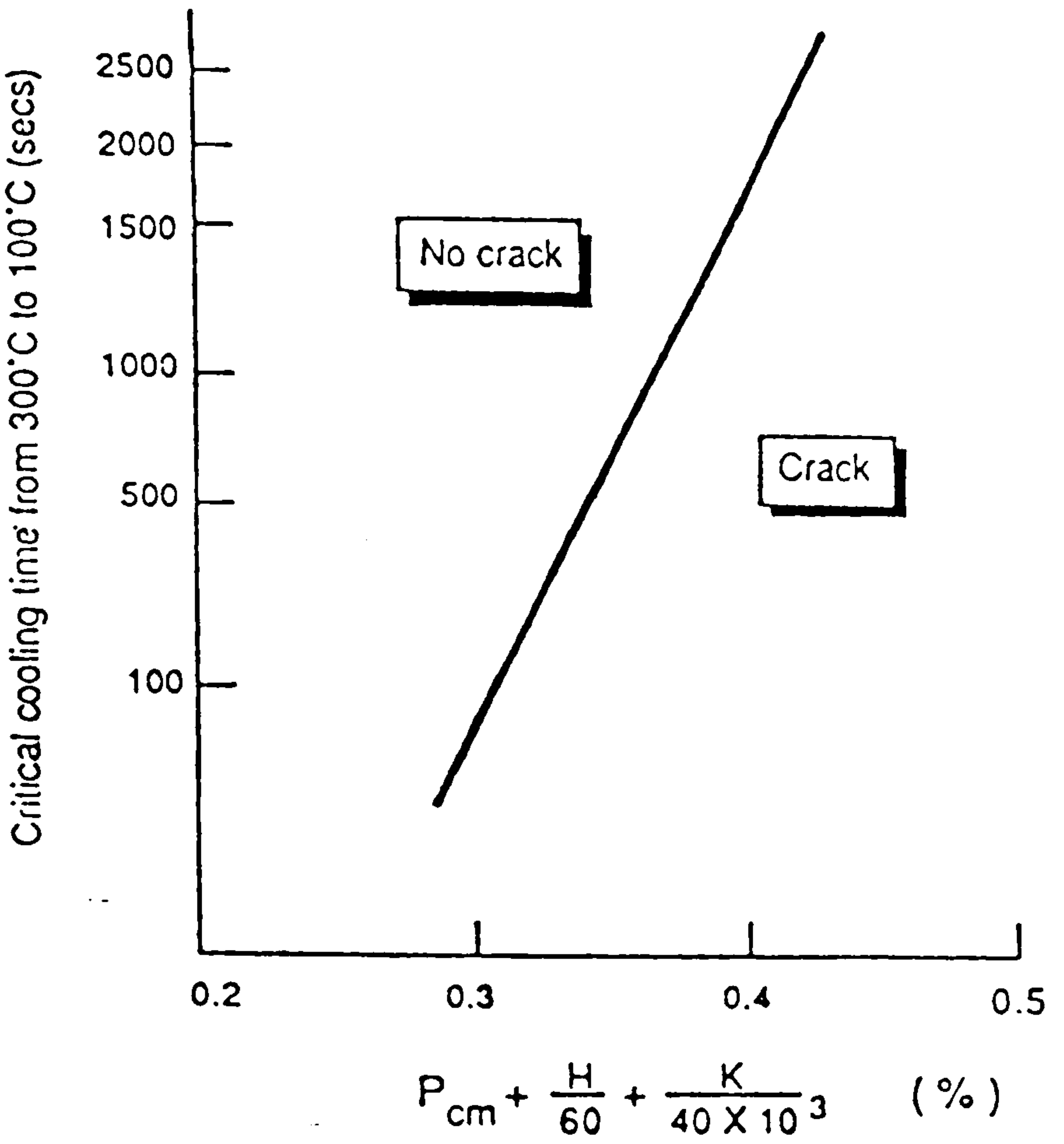


Figure 2.11 - Relation between cracking parameter Pw and critical cooling time.

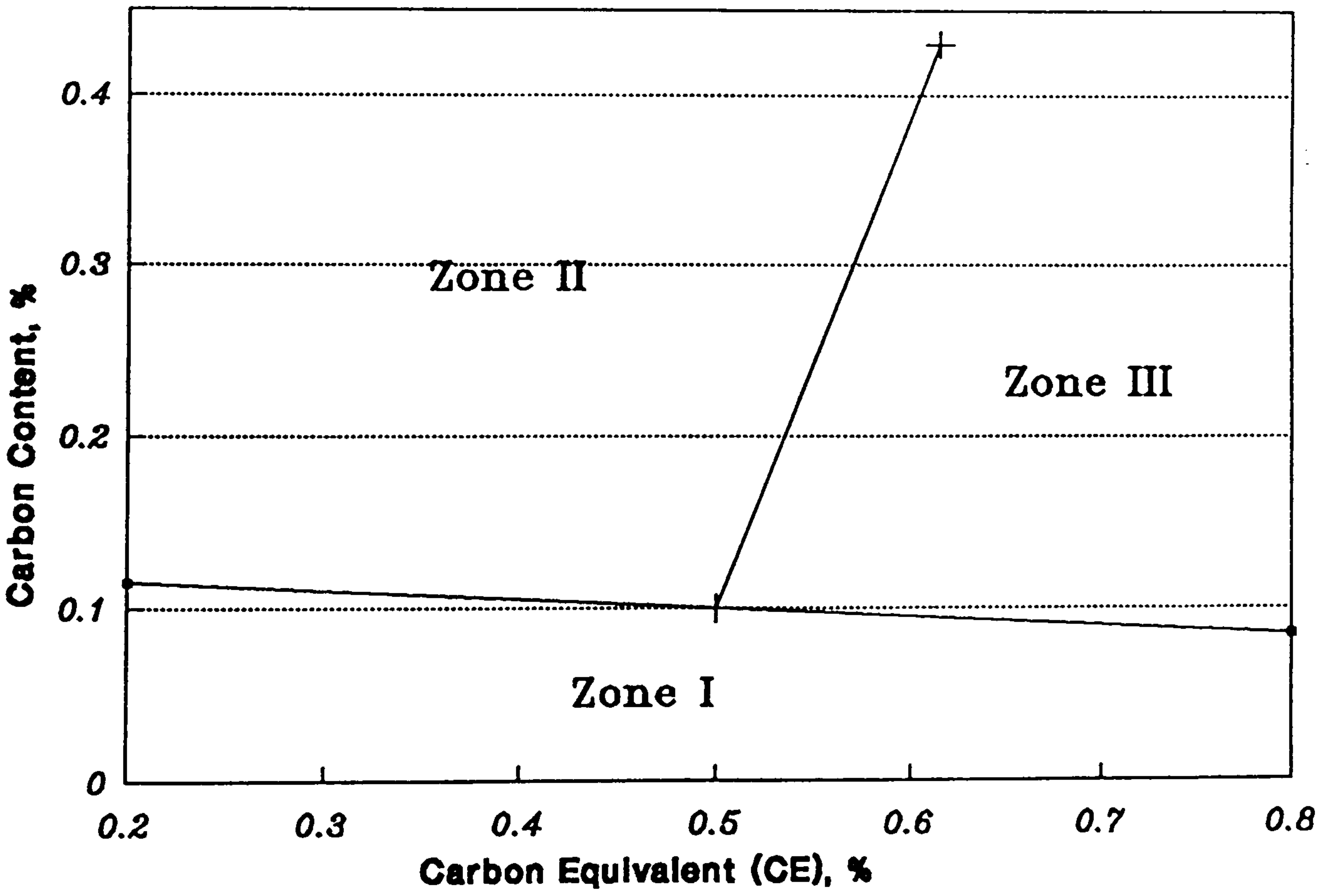


Figure 2.12 - Particular zones in function of carbon equivalent content (AWS D1.1-86).

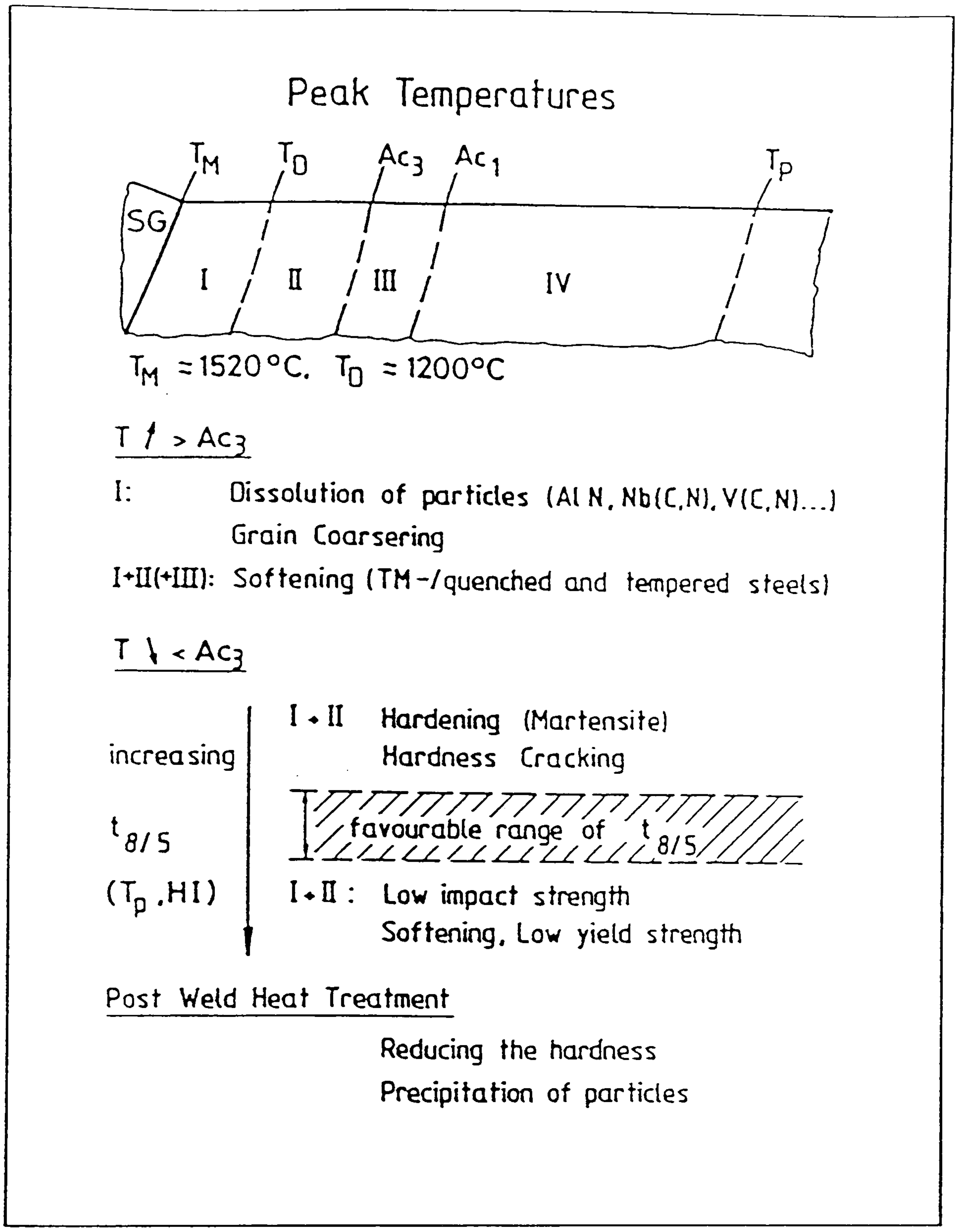


Figure 2.13 - Metallurgical process in the HAZ of low alloy steels (Thier, 1990).

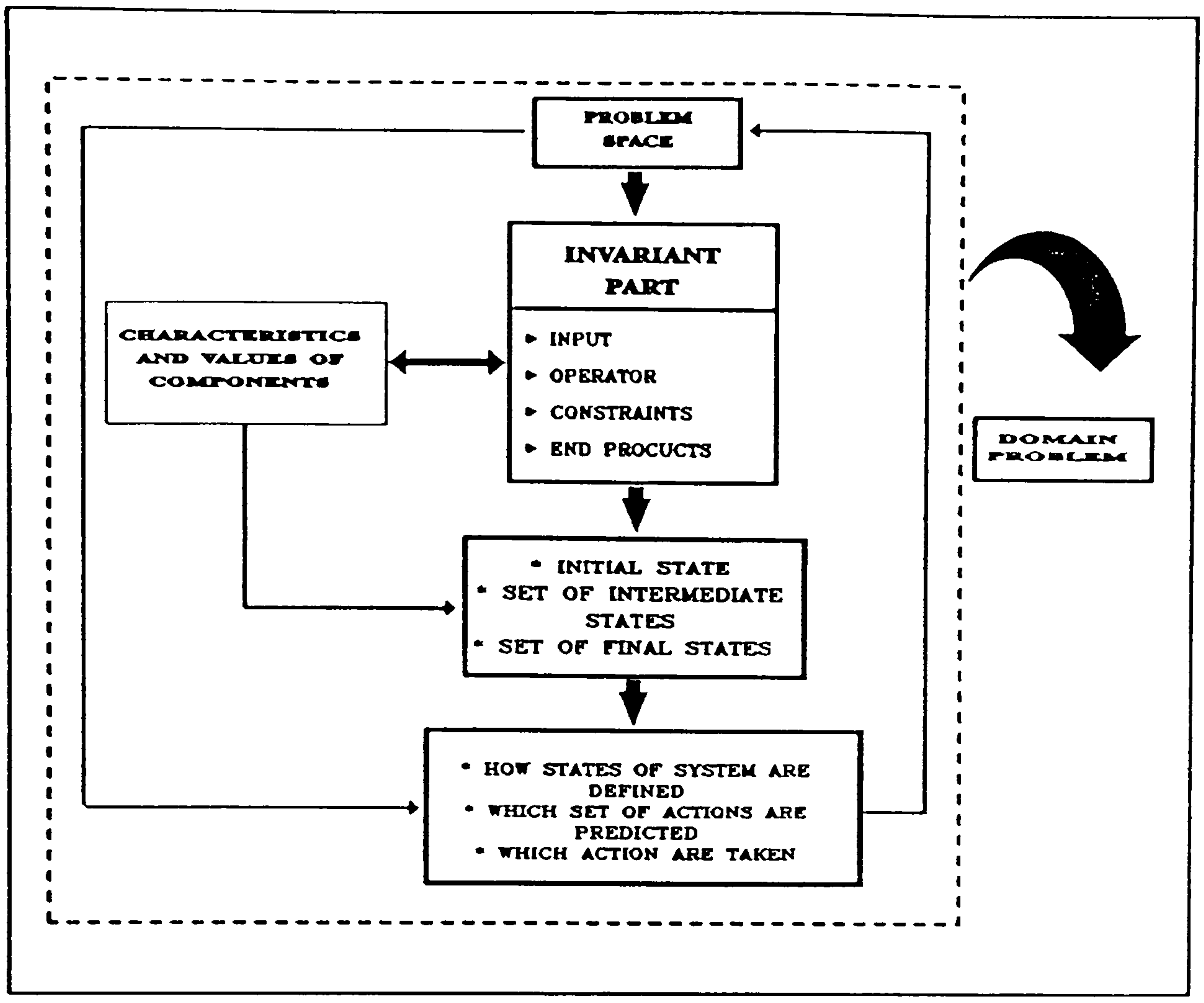


Figure 3.1 - Knowledge elicitation model.

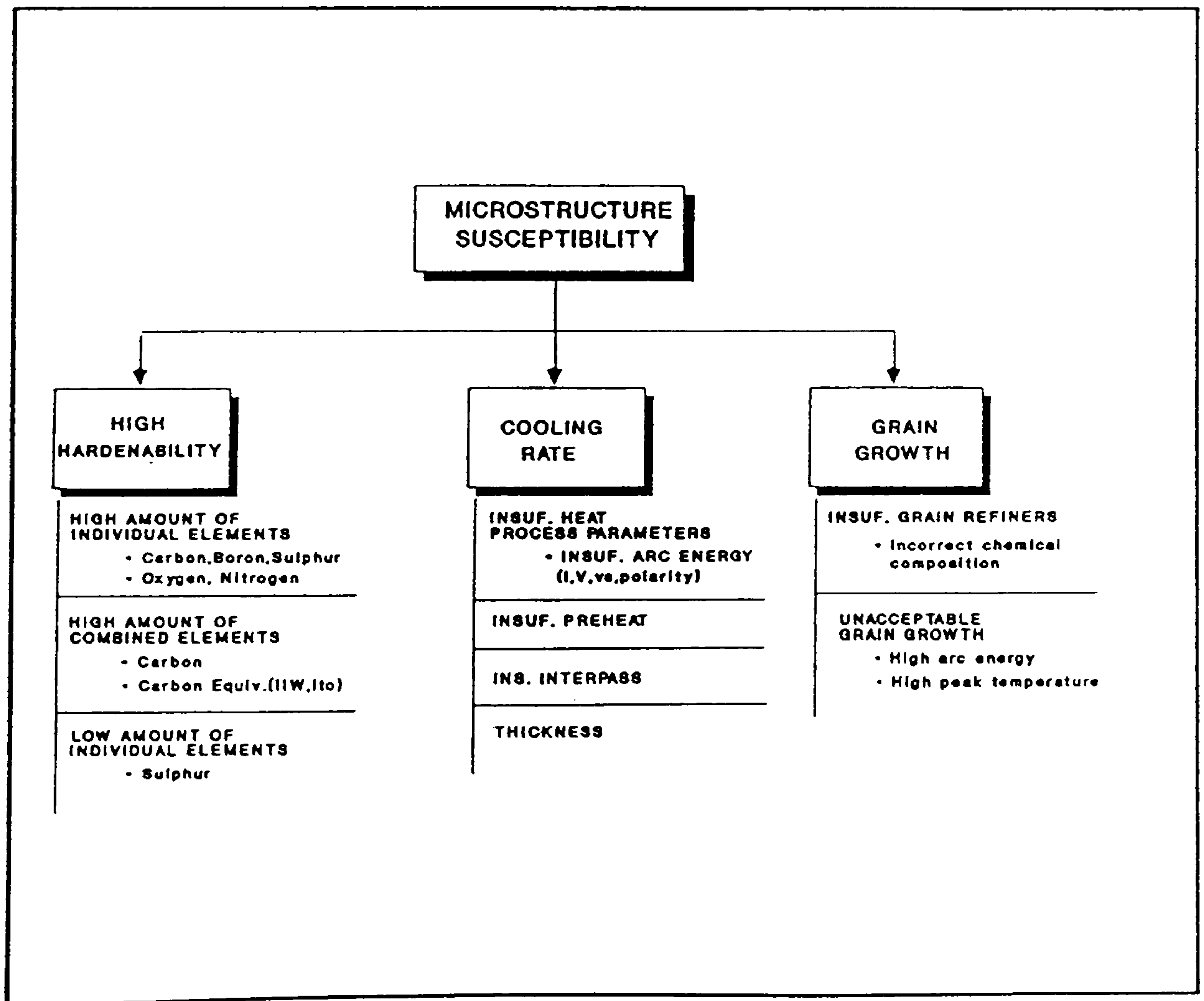


Figure 3.2 - Microstructure influencing factors.

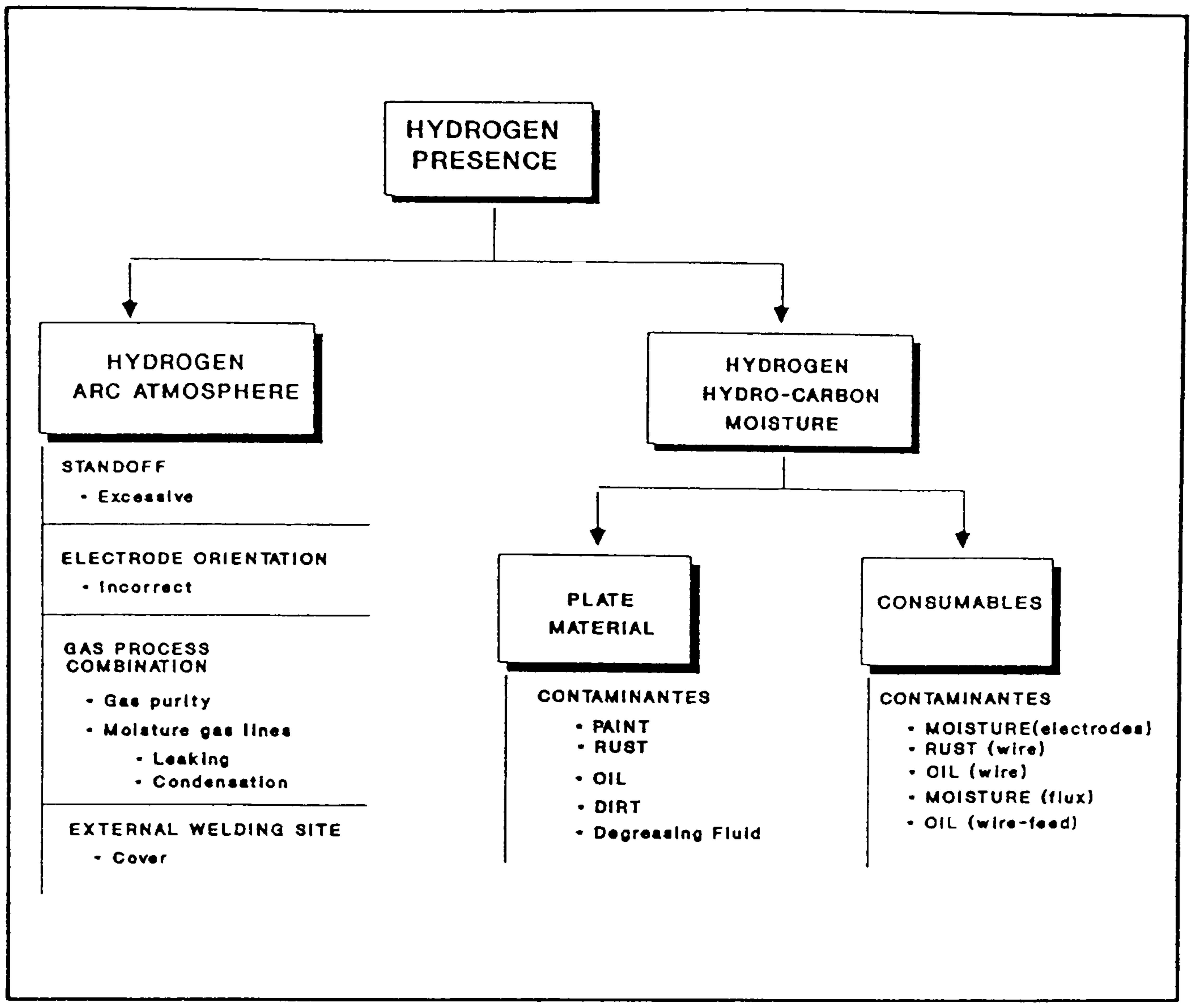


Figure 3.3 - Hydrogen influencing factors.

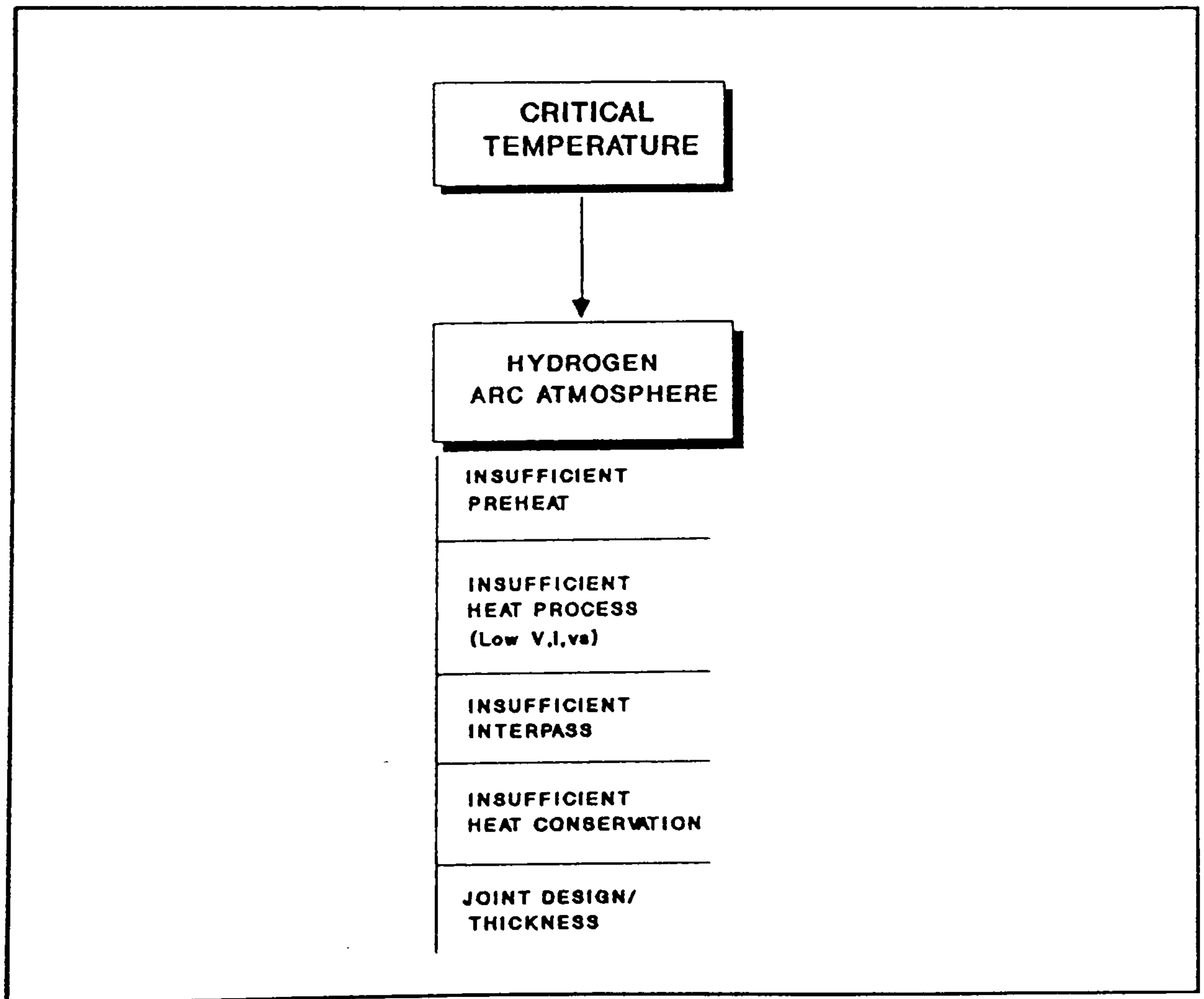


Figure 3.4 - Factors influencing critical temperature.

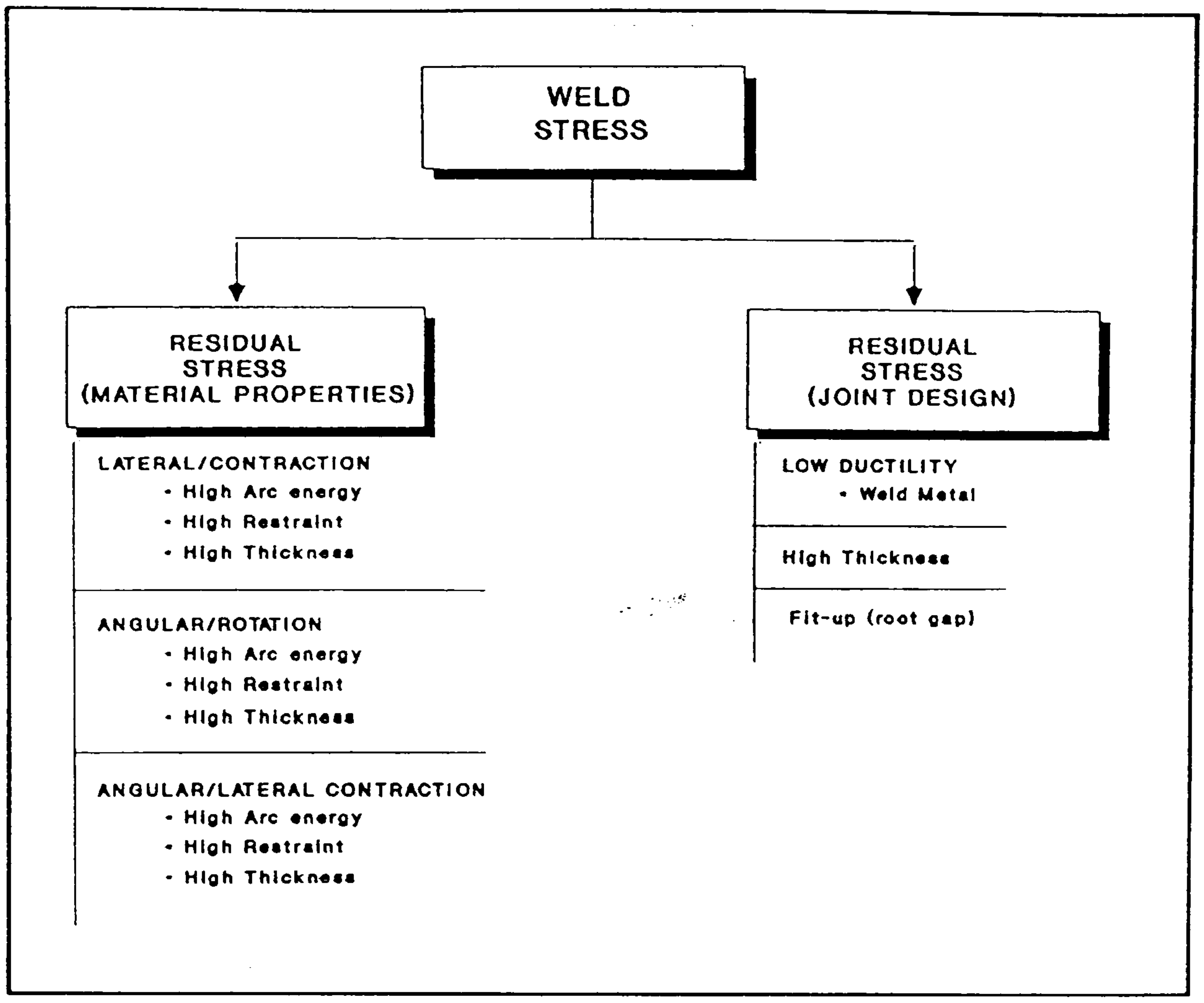


Figure 3.5 - Weld stress influencing factors.

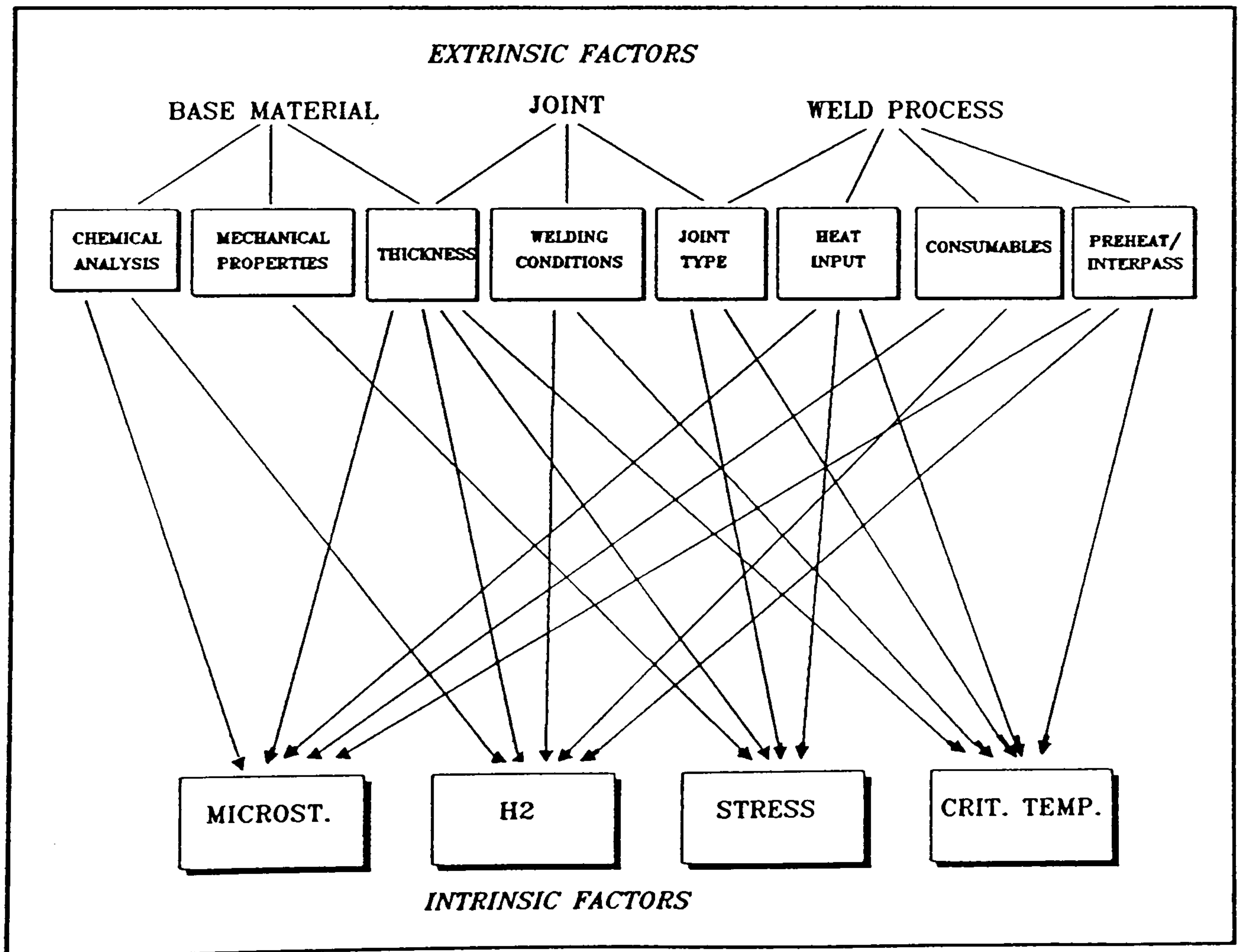


Figure 3.6 - Relation between factors influencing HICC (Bragard, 1984).

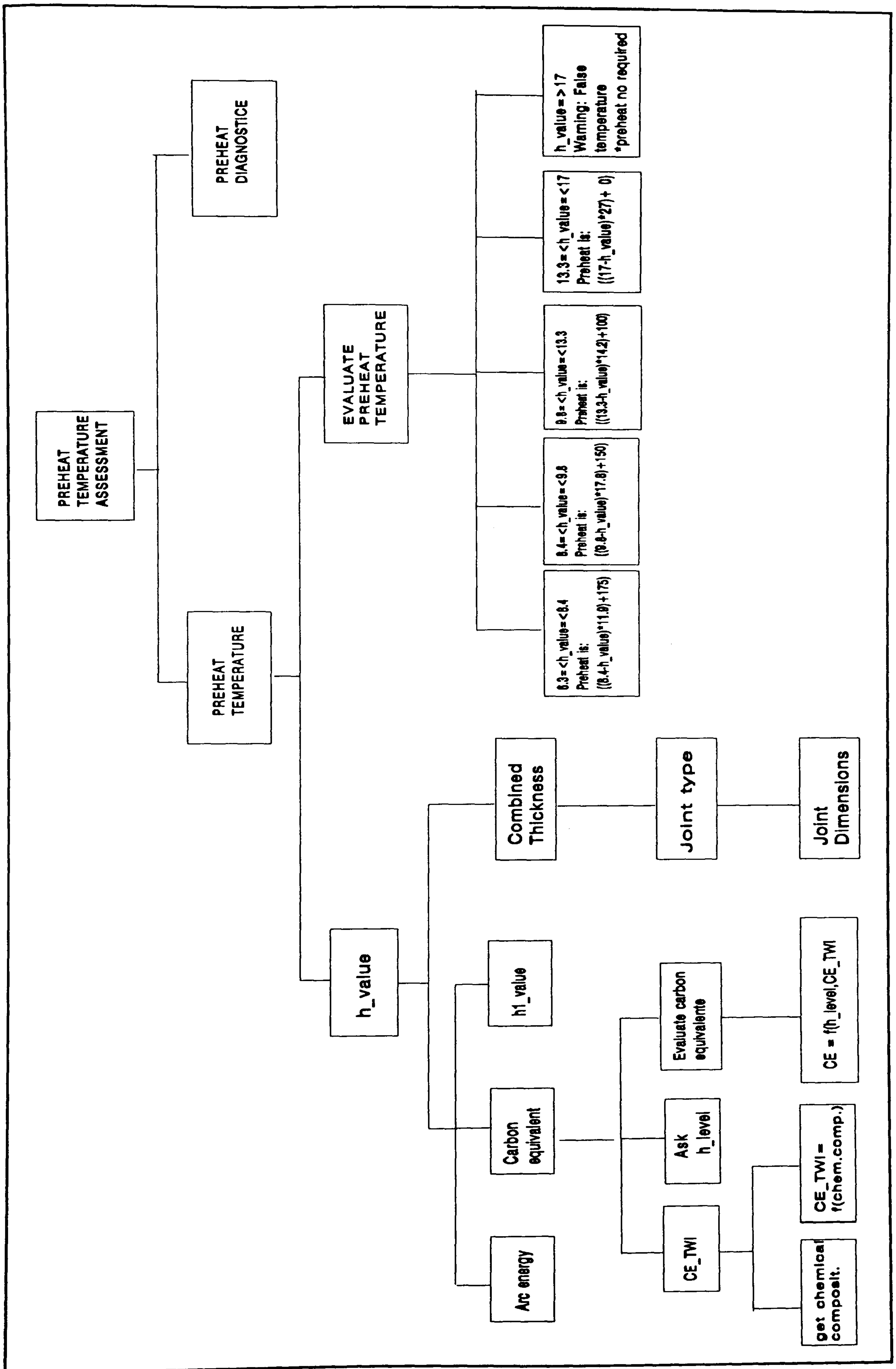
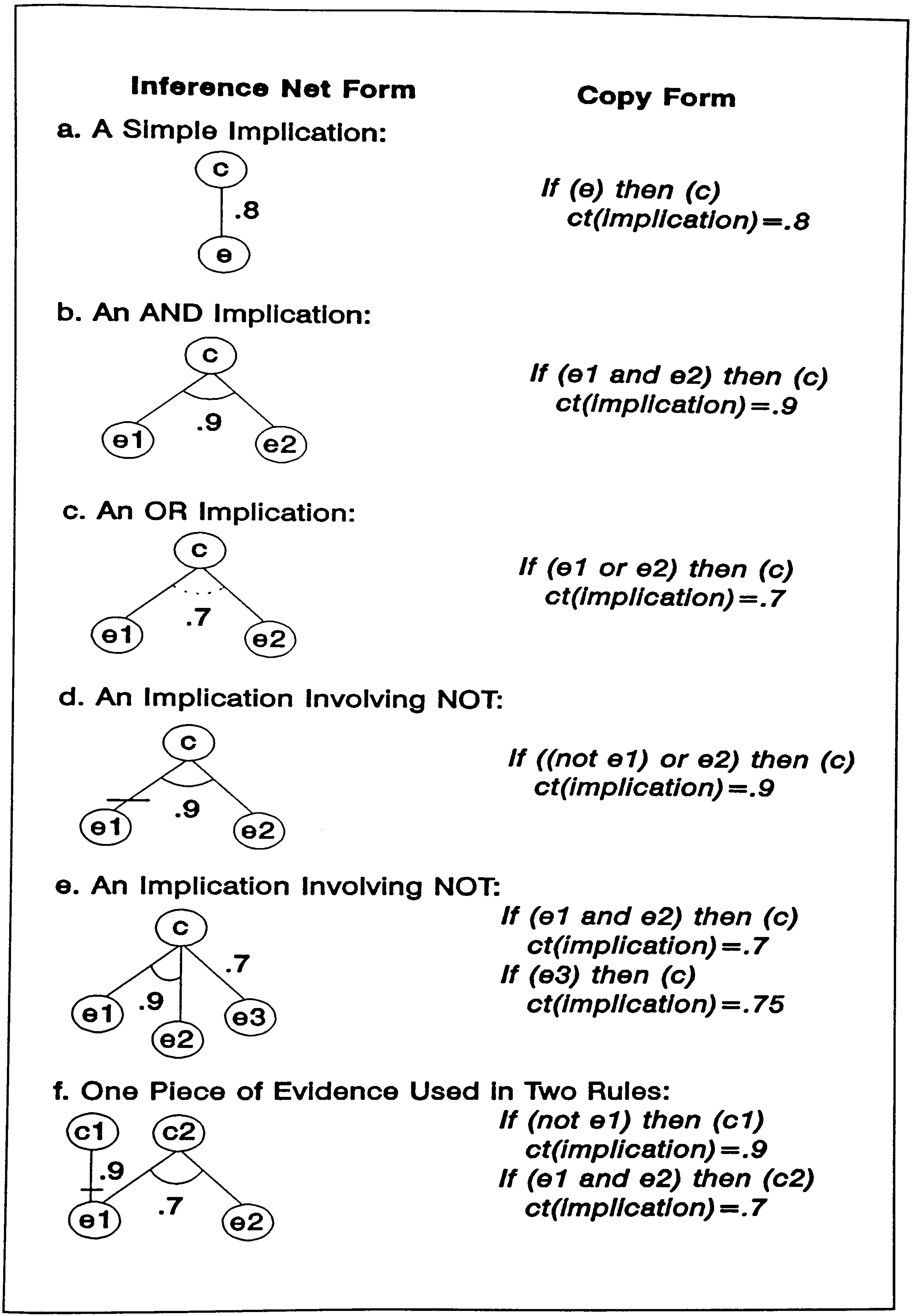


Figure 3.7 - Preheat temperature assessment.



If (e) then (c)
ct(implication)=.8

If (e1 and e2) then (c)
ct(implication)=.9

If (e1 or e2) then (c)
ct(implication)=.7

If ((not e1) or e2) then (c)
ct(implication)=.9

If (e1 and e2) then (c)
ct(implication)=.7
If (e3) then (c)
ct(implication)=.75

If (not e1) then (c1)
ct(implication)=.9
If (e1 and e2) then (c2)
ct(implication)=.7

Figure 3.8 - Equivalence between inference net notation and rule notation.

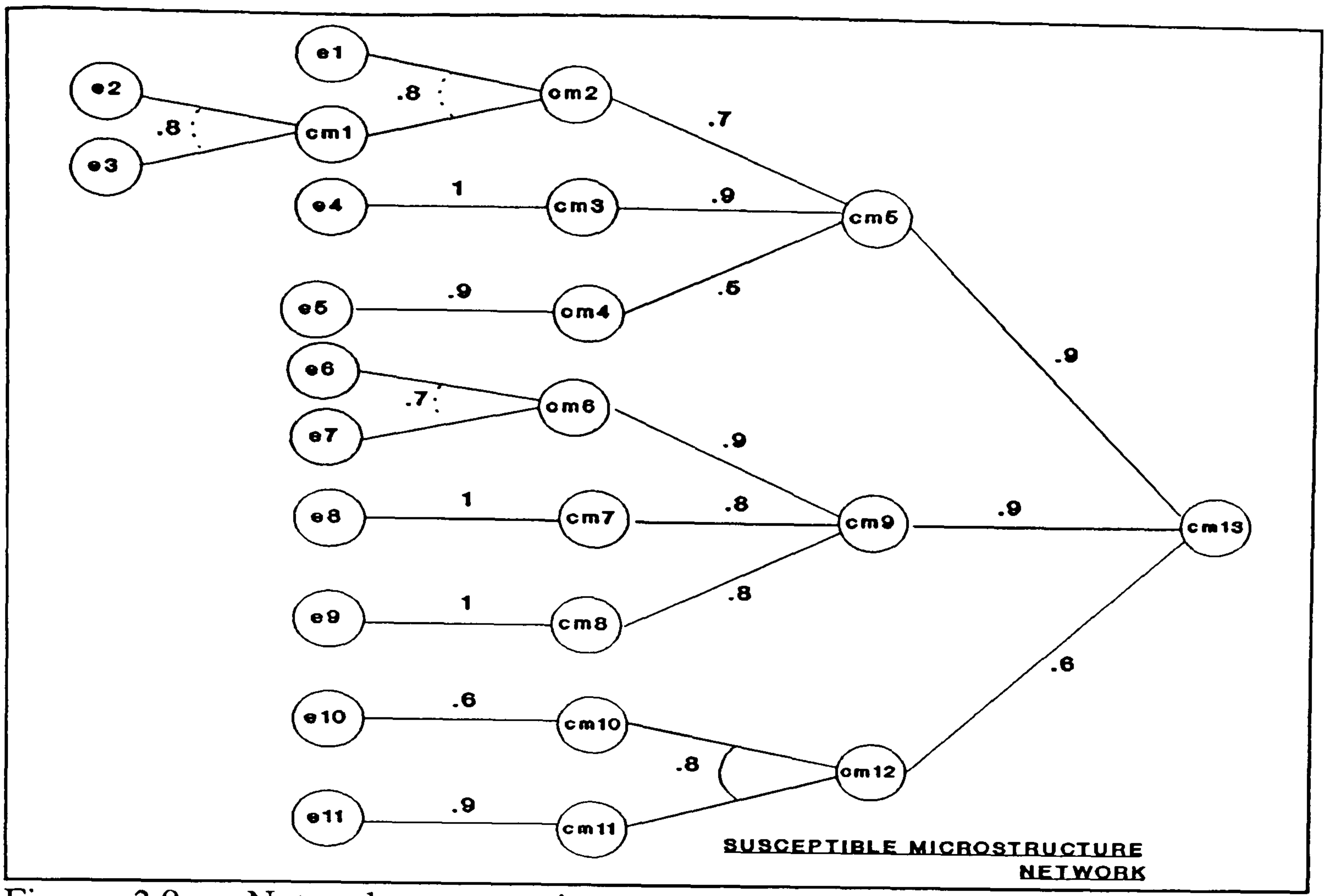


Figure 3.9 - Network propagation representing the factors influencing the microstructure stability.

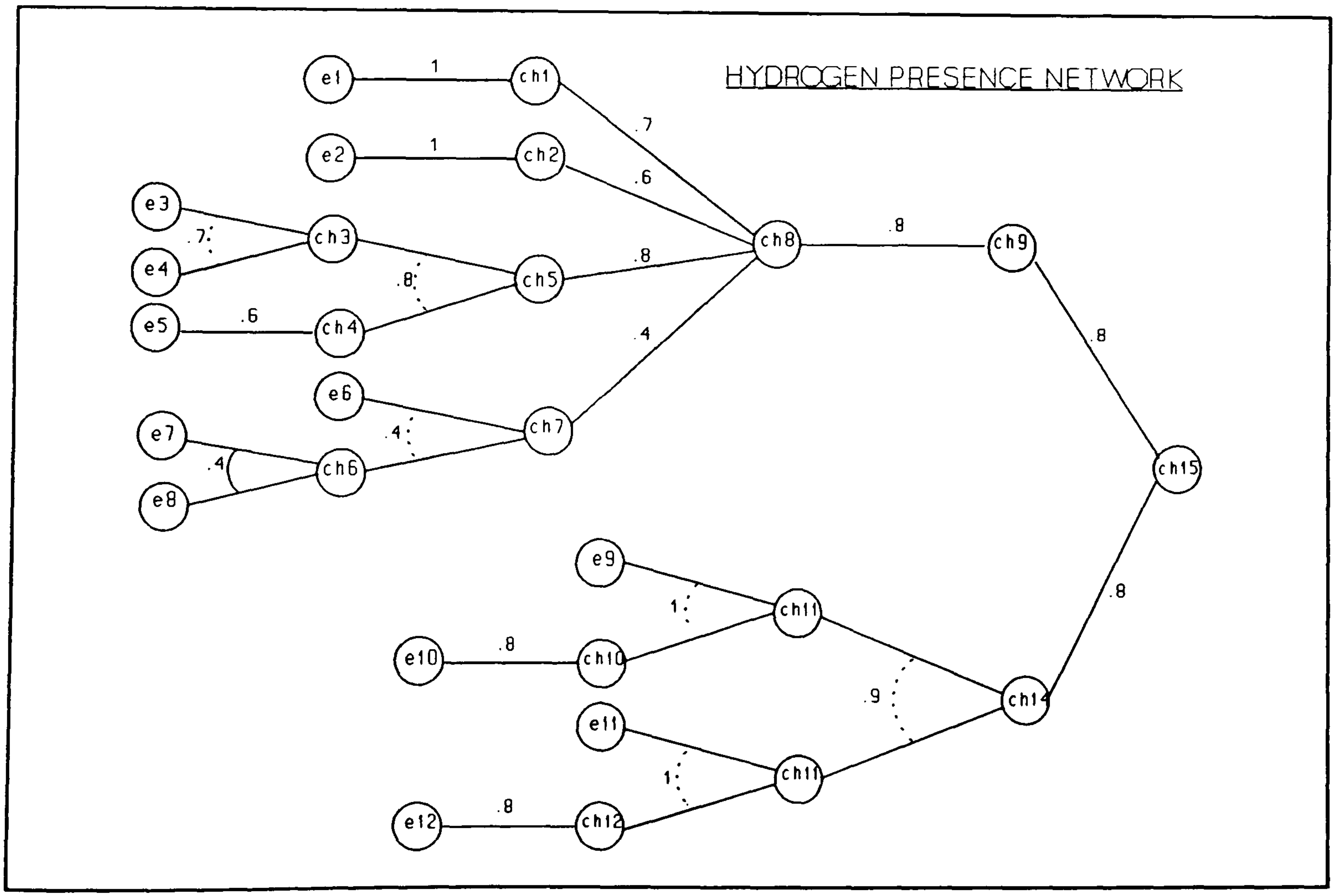


Figure 3.10 - Network propagation representing the factors influencing the hydrogen presence in GMAW process.

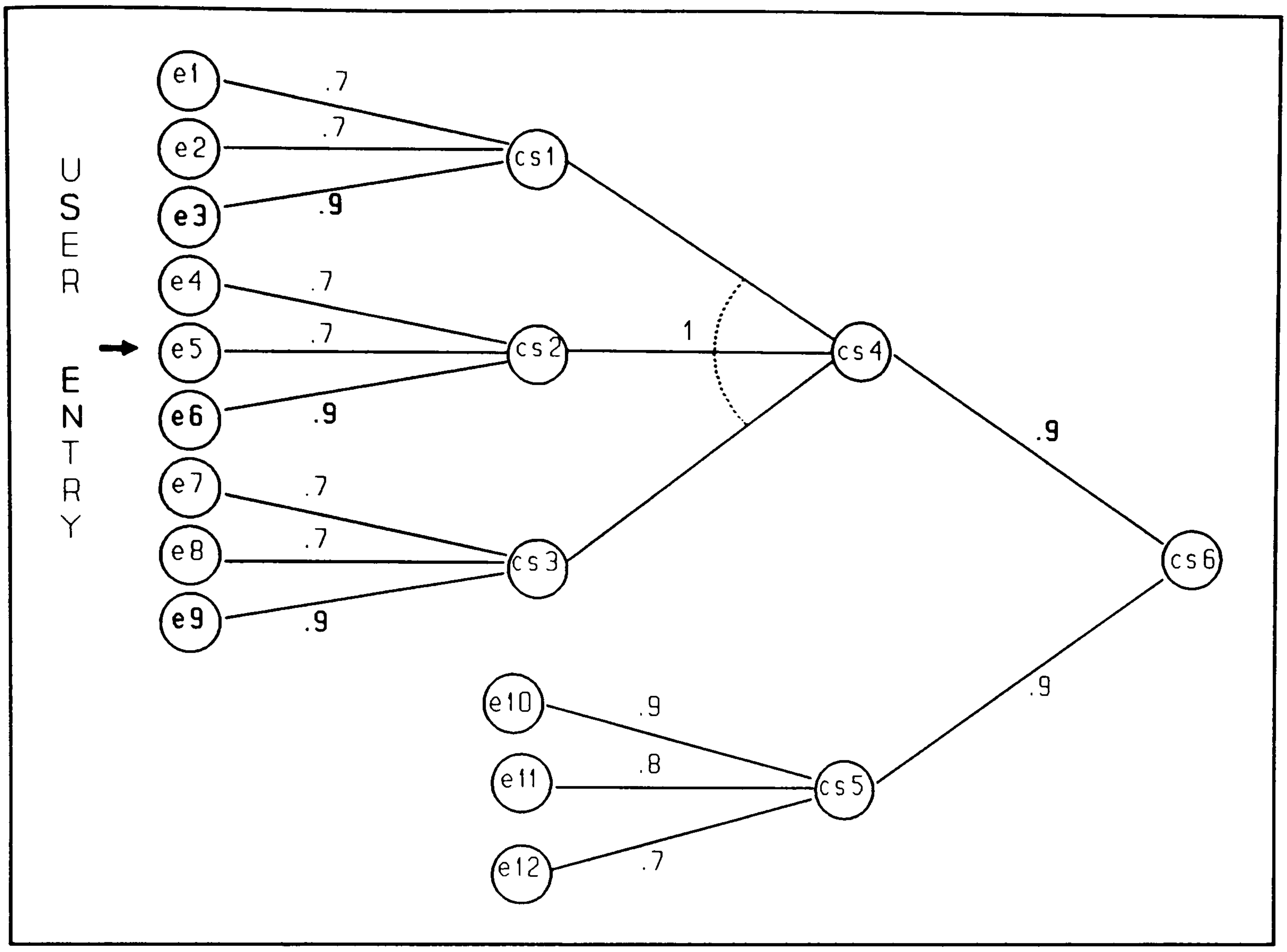


Figure 3.11 - Network propagation representing the factors influencing the weld stress.

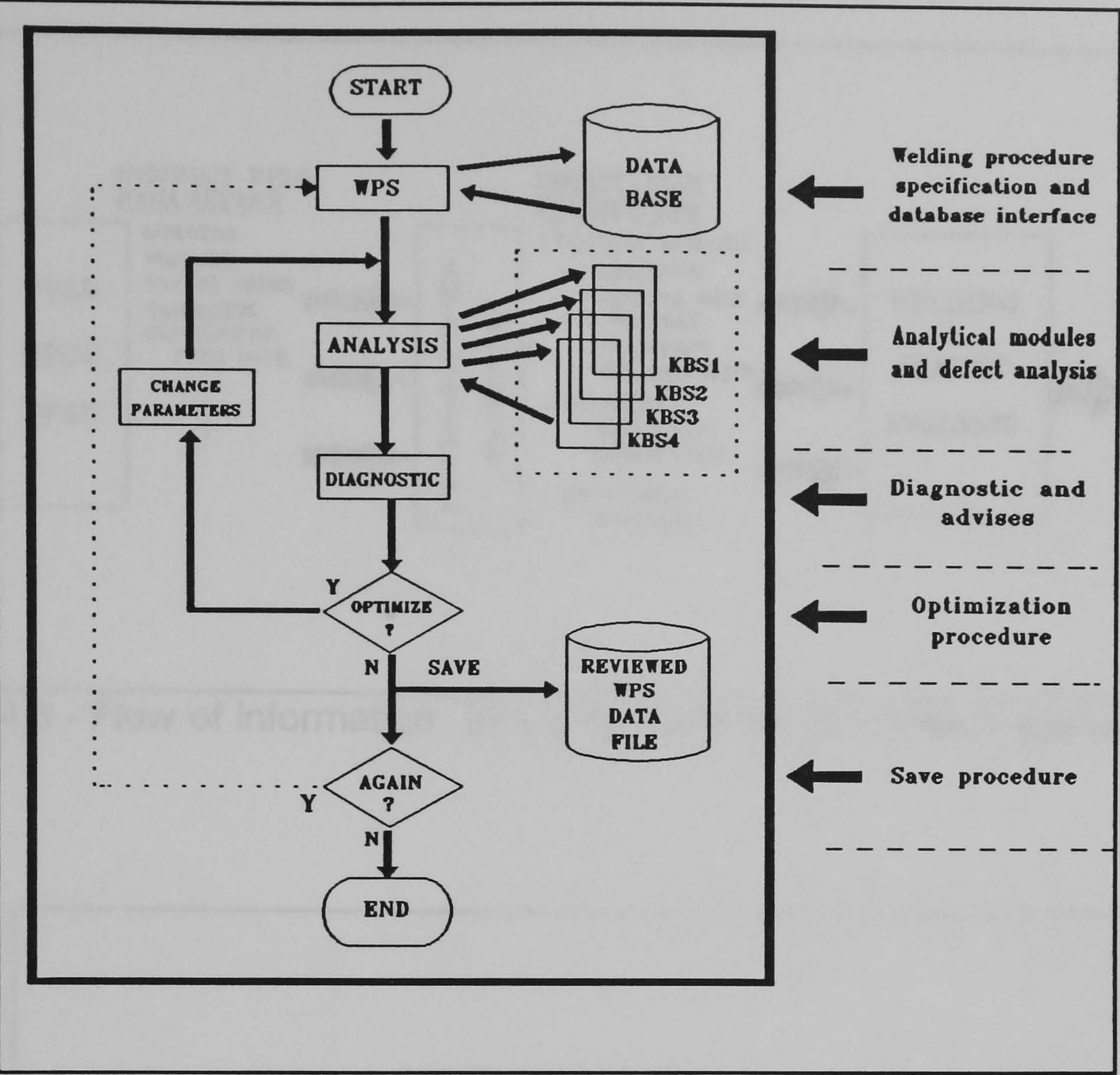
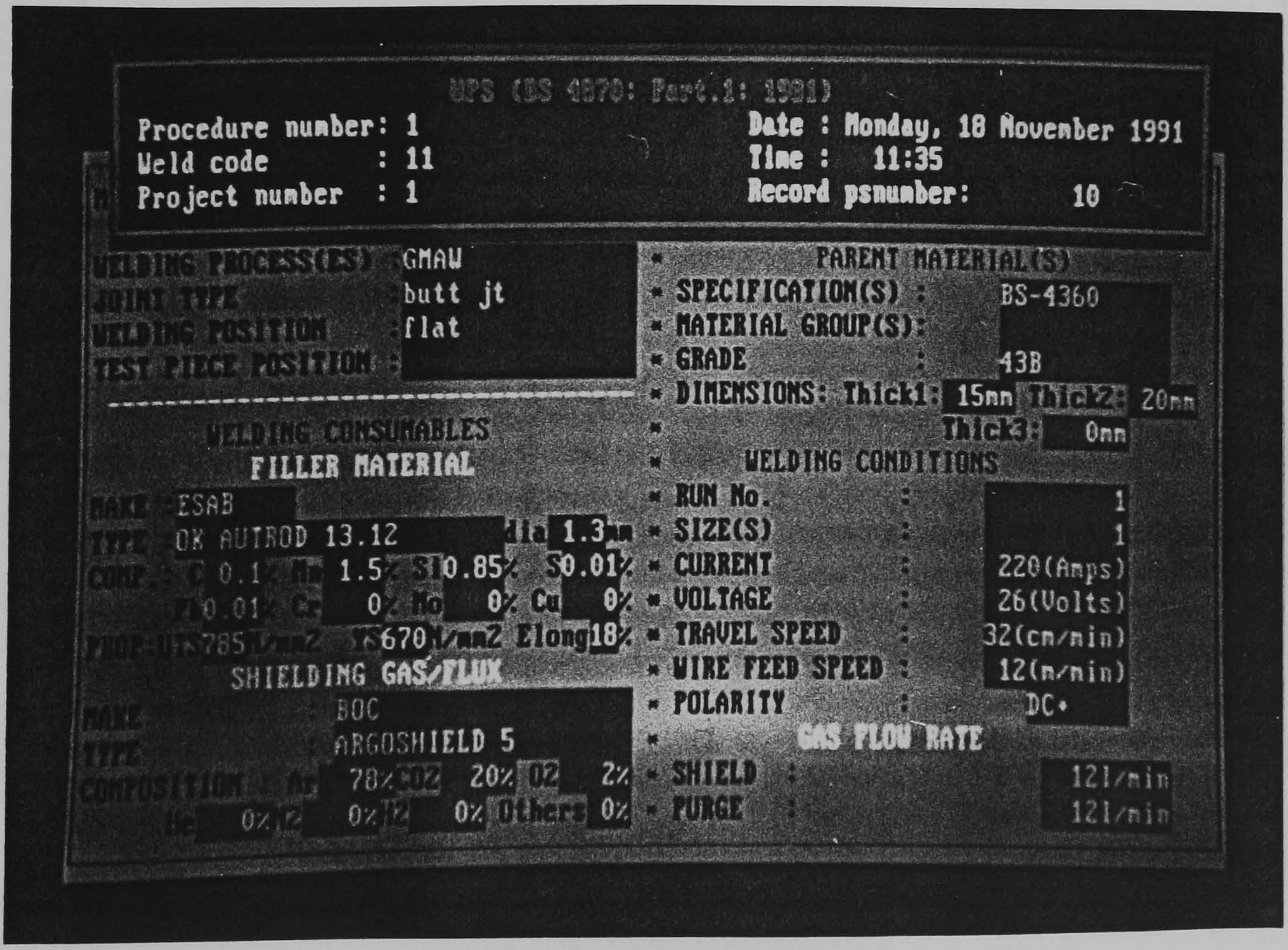


Figure 4.1 - Computer structure - main phases.



```
                     WPS (BS 4870: Part.1: 1981)
 Procedure number: 1                 Date : Monday, 18 November 1991
 Weld code        : 11               Time :    11:35
 Project number   : 1                Record psnumber:        10

WELDING PROCESS(ES) :GMAW            *        PARENT MATERIAL(S)
JOINT TYPE          :butt jt         * SPECIFICATION(S) :    BS-4360
WELDING POSITION    :flat            * MATERIAL GROUP(S):
TEST PIECE POSITION :                * GRADE            :    43B
-------------------------------------* DIMENSIONS: Thick1: 15mm Thick2: 20mm
       WELDING CONSUMABLES           *                    Thick3:   0mm
         FILLER MATERIAL             *      WELDING CONDITIONS
MAKE :ESAB                           * RUN No.          :           1
TYPE :OK AUTROD 13.12        dia 1.3mm * SIZE(S)        :           1
COMP.: C 0.1% Mn 1.5% Si 0.85% S0.01% * CURRENT         :   220(Amps)
       P 0.01% Cr   0% Mo   0% Cu  0% * VOLTAGE         :   26(Volts)
PROP: UTS785 N/mm2 YS670 N/mm2 Elong18% * TRAVEL SPEED  :  32(cm/min)
       SHIELDING GAS/FLUX            * WIRE FEED SPEED :   12(m/min)
MAKE                 : BOC           * POLARITY        :     DC+
TYPE                 : ARGOSHIELD 5  *        GAS FLOW RATE
COMPOSITION : Ar  78% CO2  20% O2  2% * SHIELD :              12l/min
      He    0% H2    0% N2   0% Others 0% * PURGE :           12l/min
```

Figure 4.2 - Welding procedure specification (BS4870: Part 1:1981).

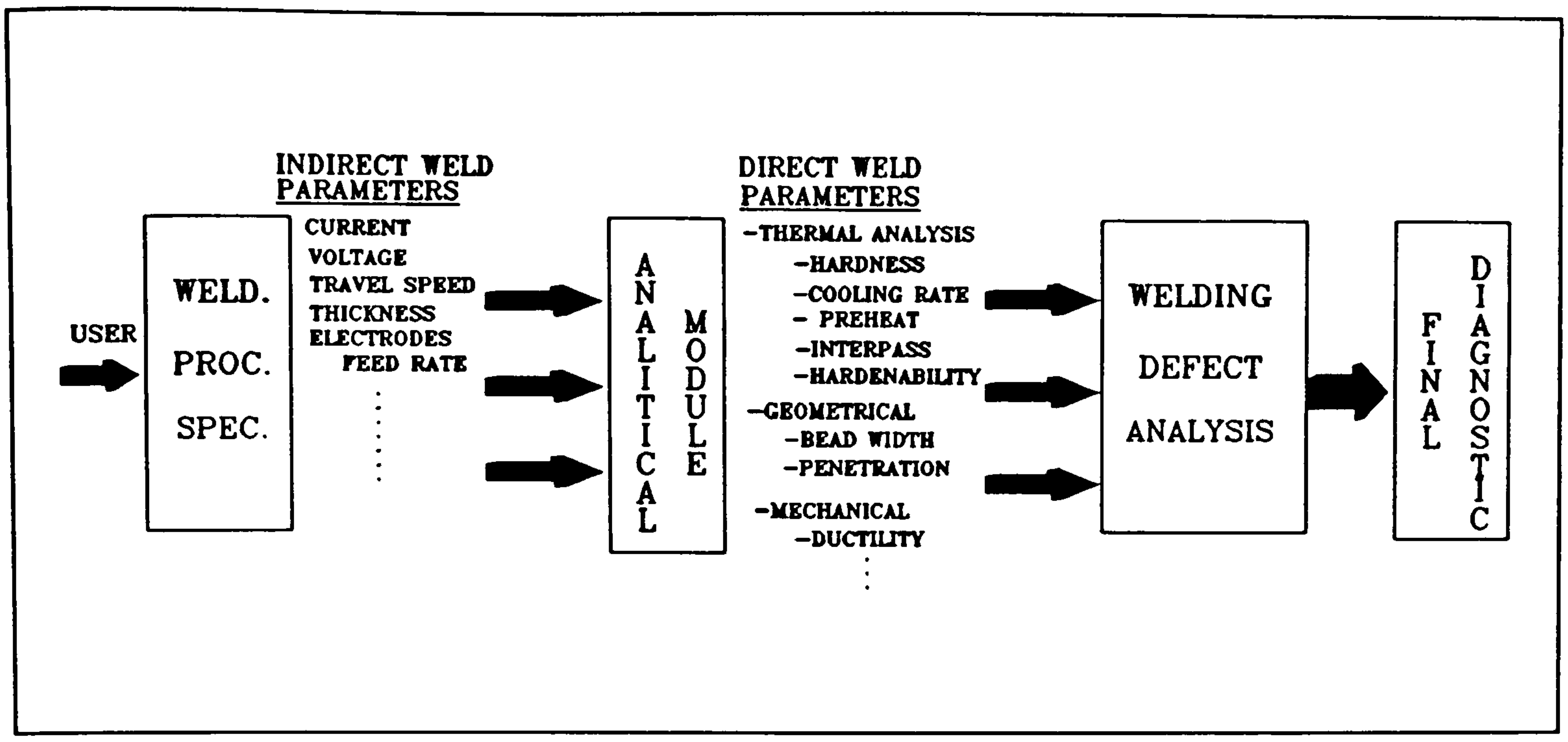


Figure 4.3 - Flow of information in a procedure for weld defect analysis.

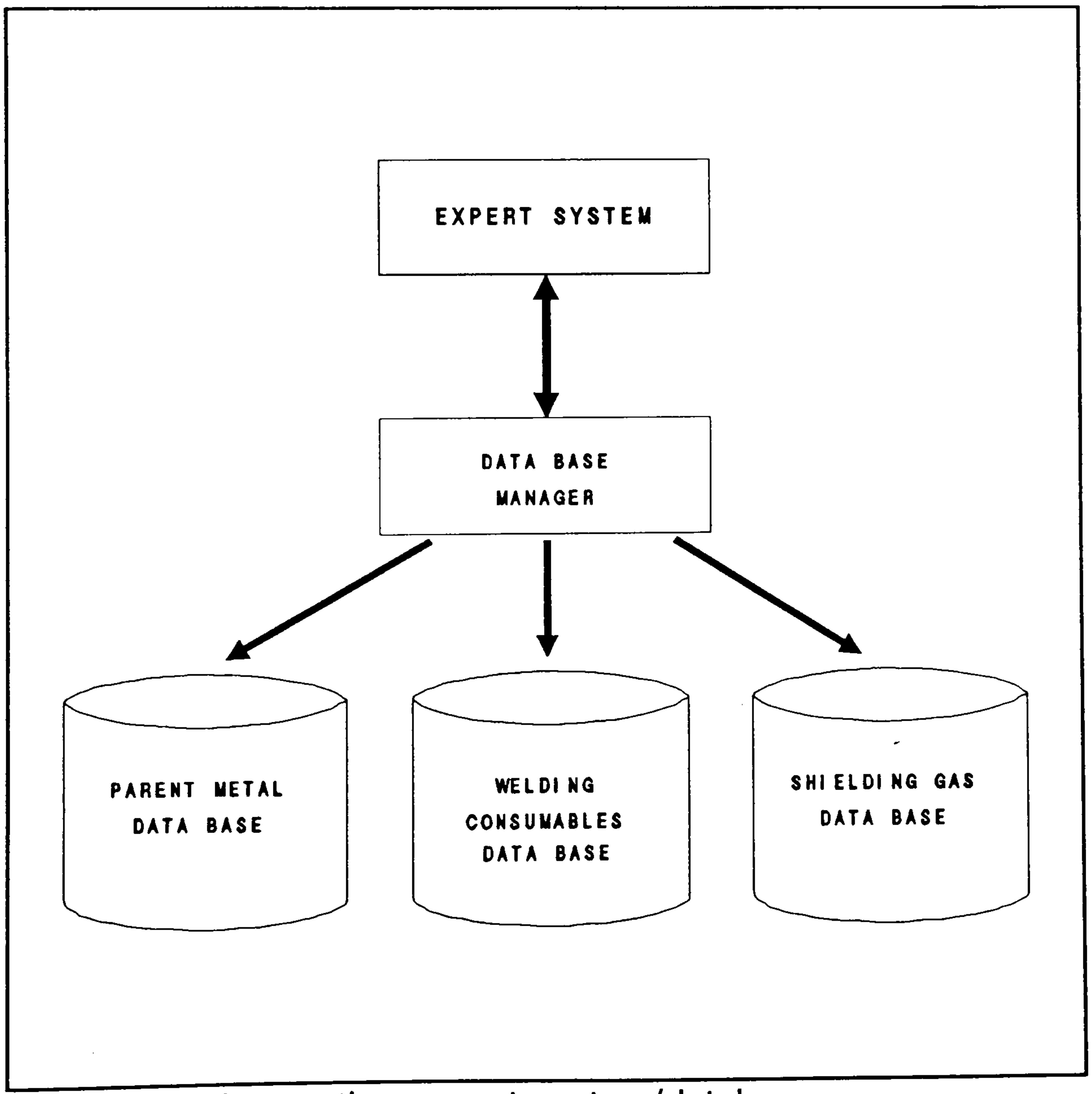


Figure 4.4 - Interaction expert system/database.

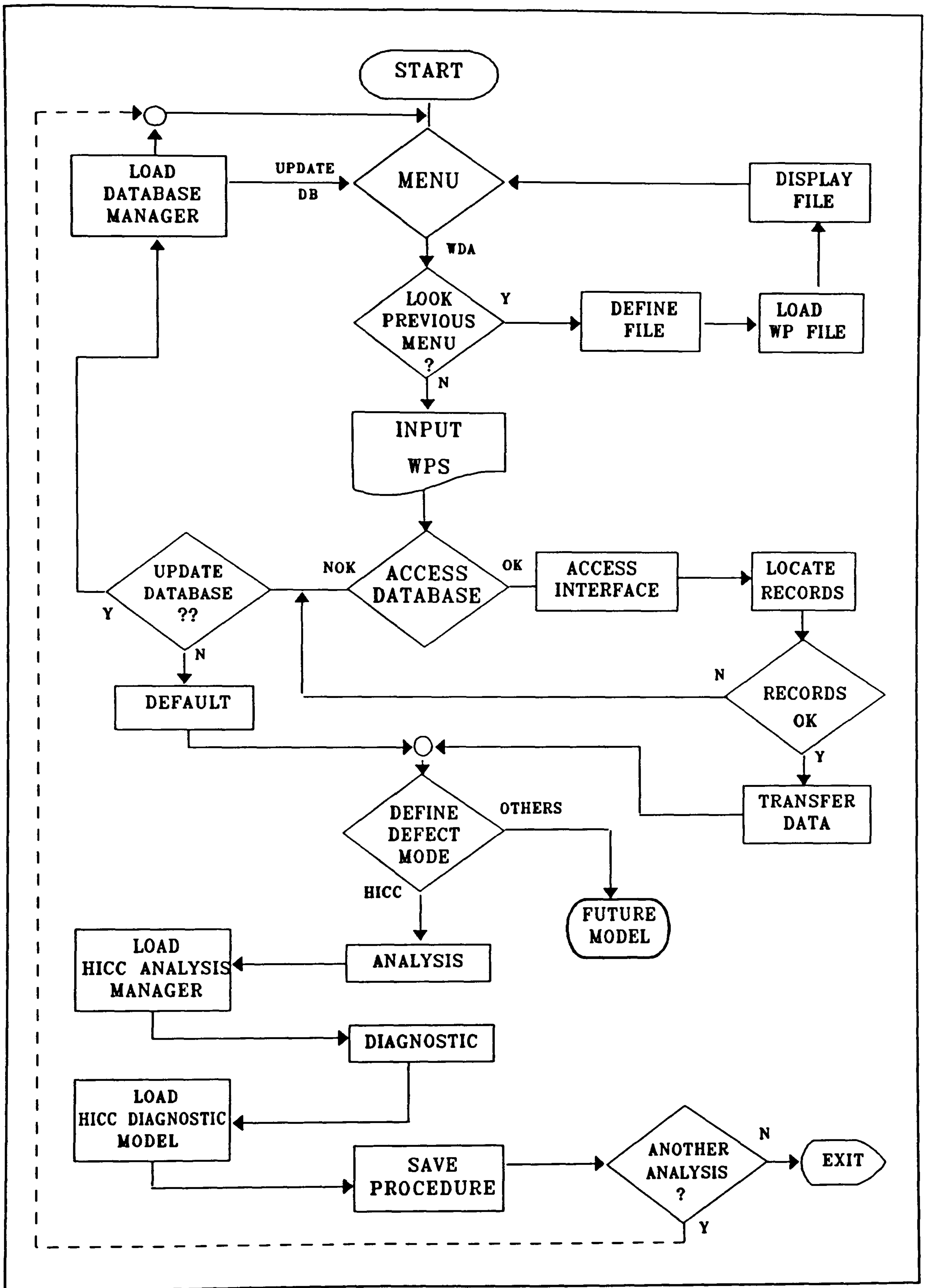


Figure 4.5 - Block diagram showing the main steps in the system designed.

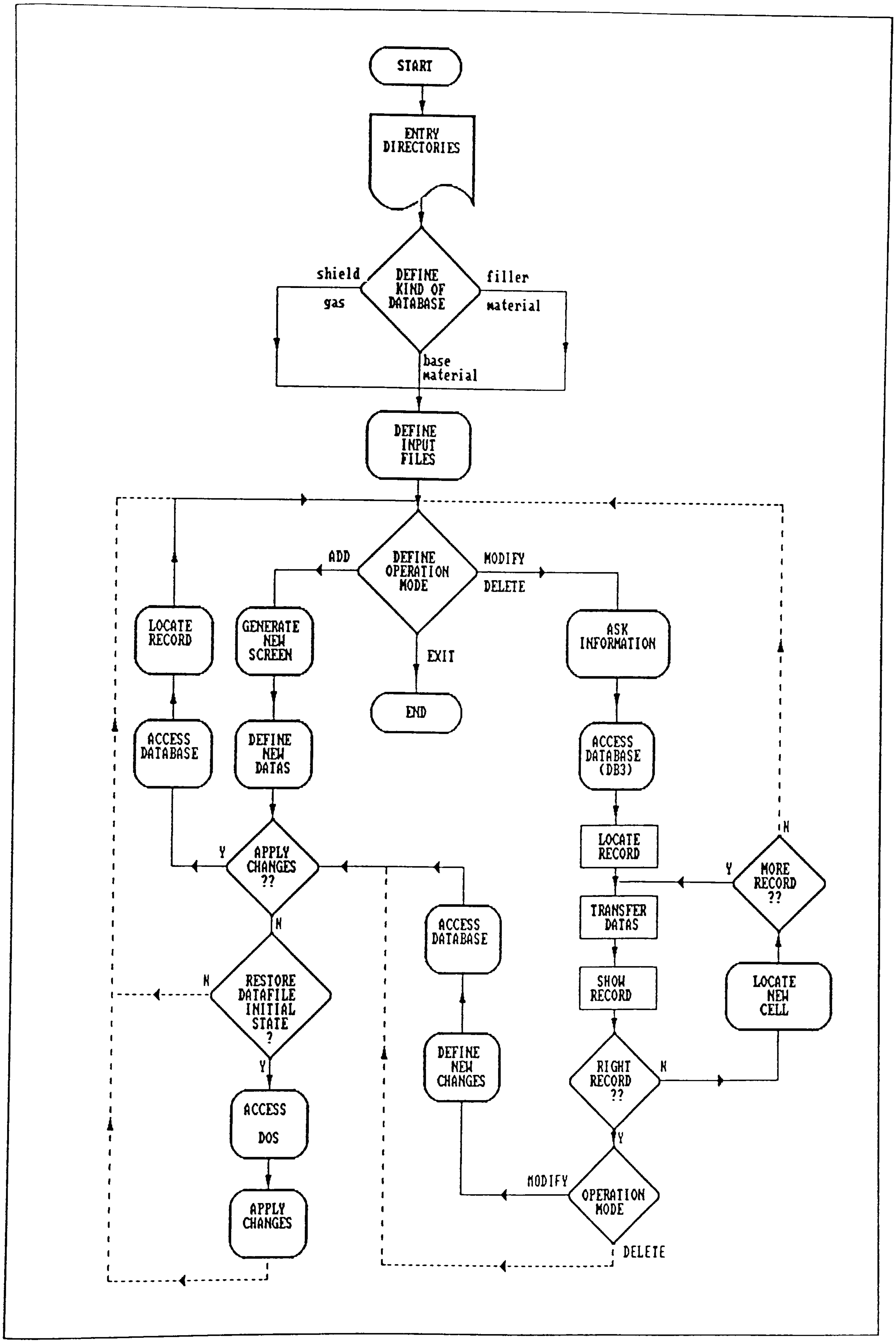


Figure 4.6 - Database management system block diagram.

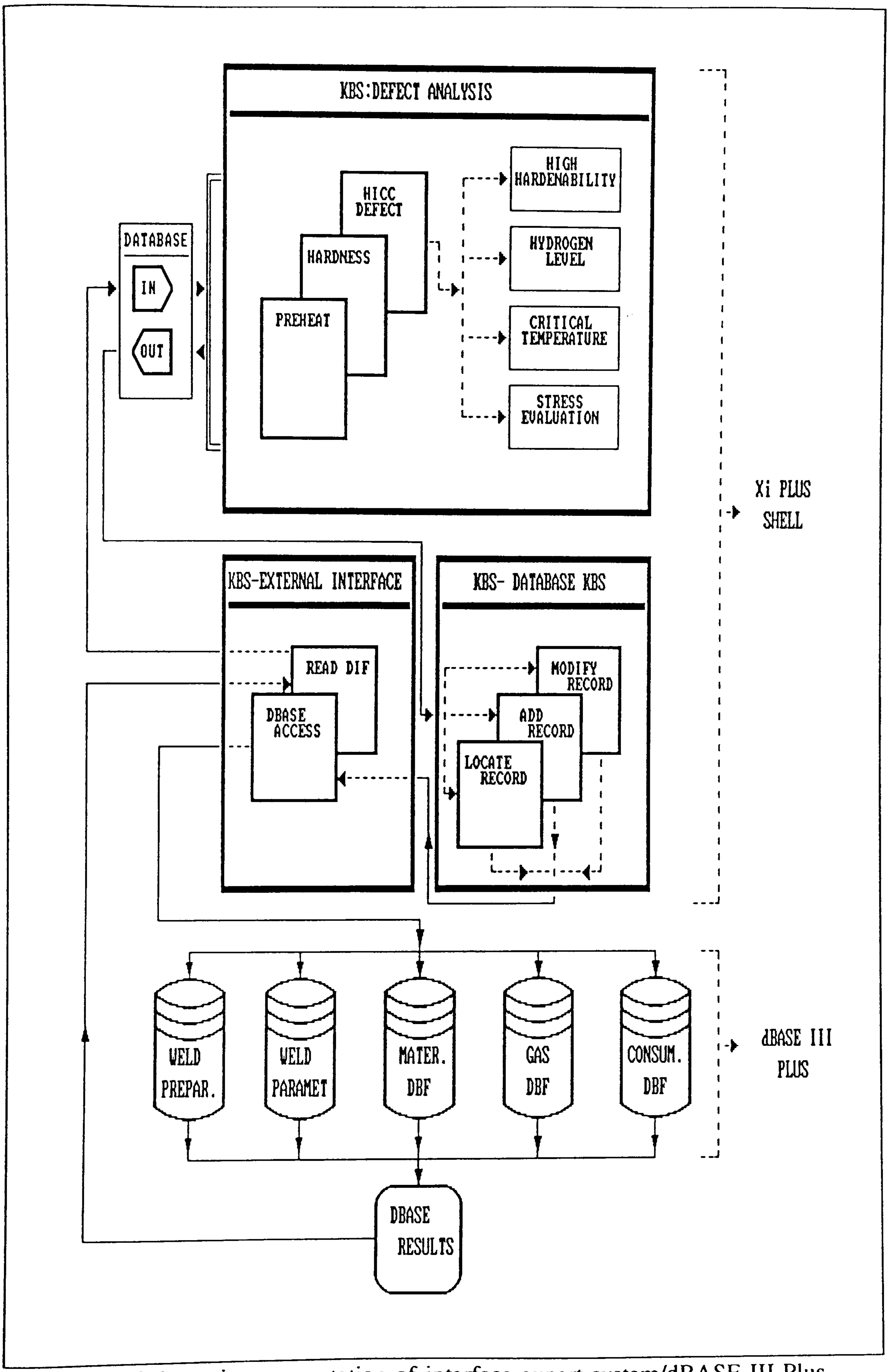


Figure 4.7 - Schematic representation of interface expert system/dBASE III Plus.

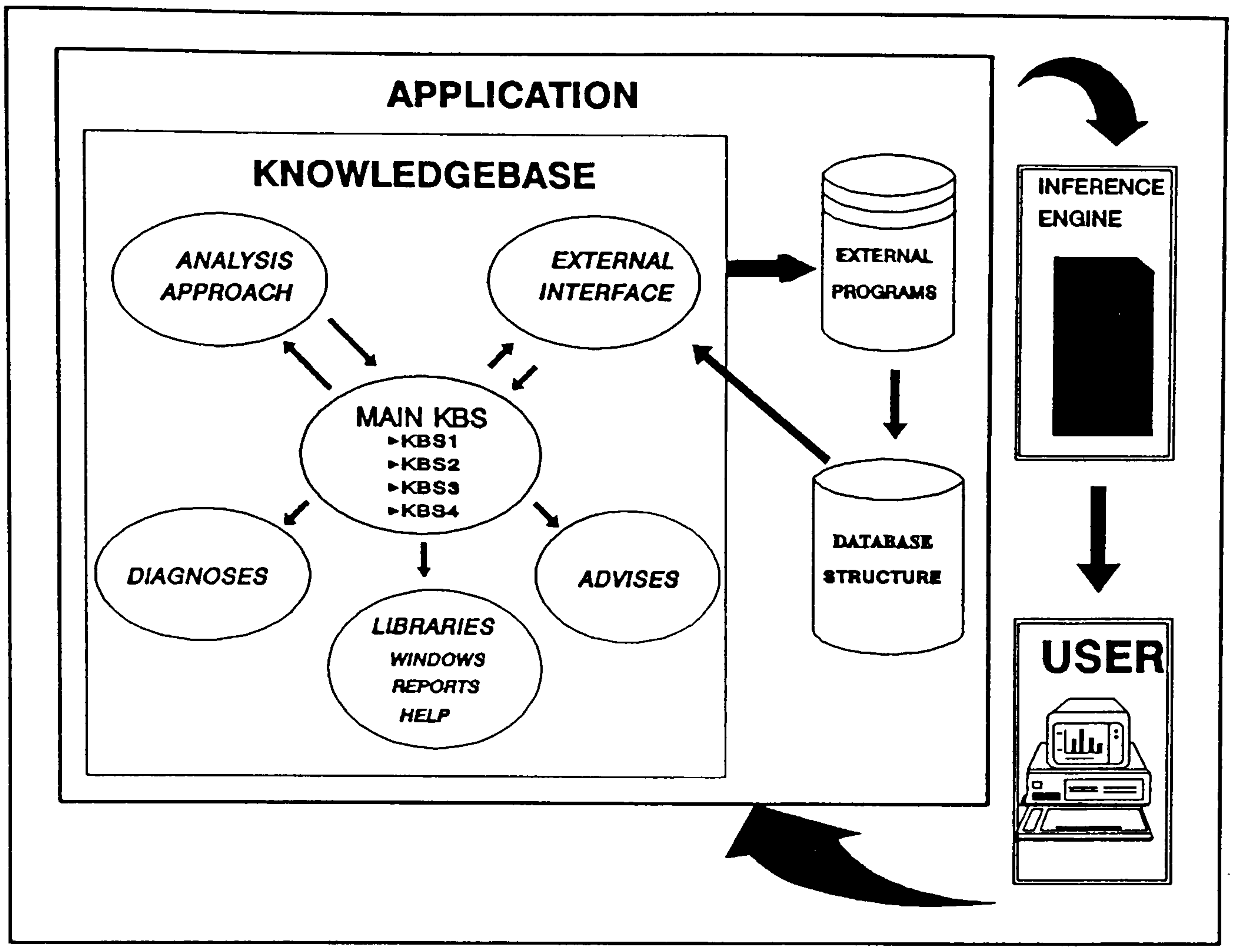


Figure 4.8 - The main program structure.

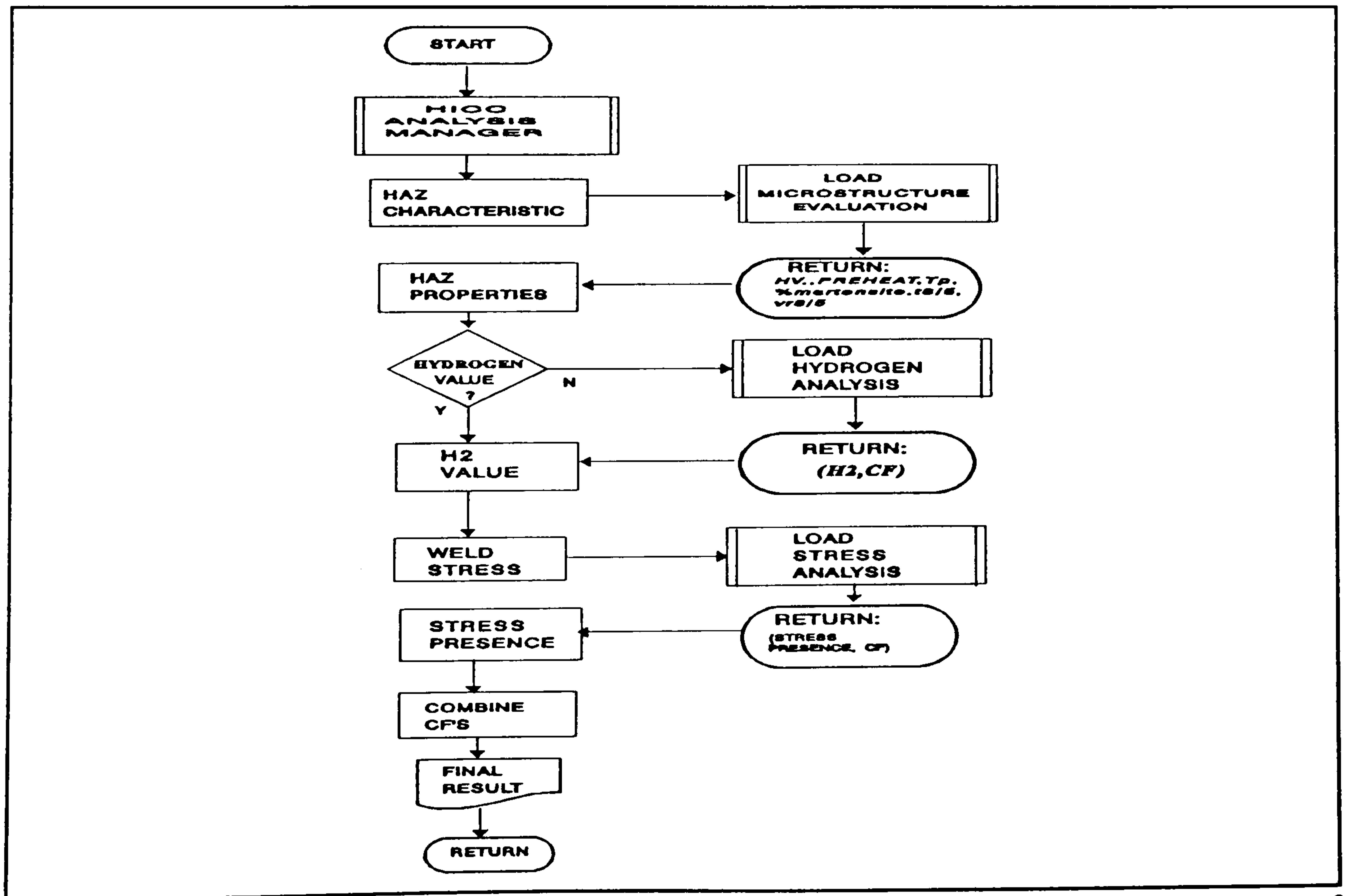


Figure 4.9 - Algorithm representing the main steps in the development of welding defect analysis.

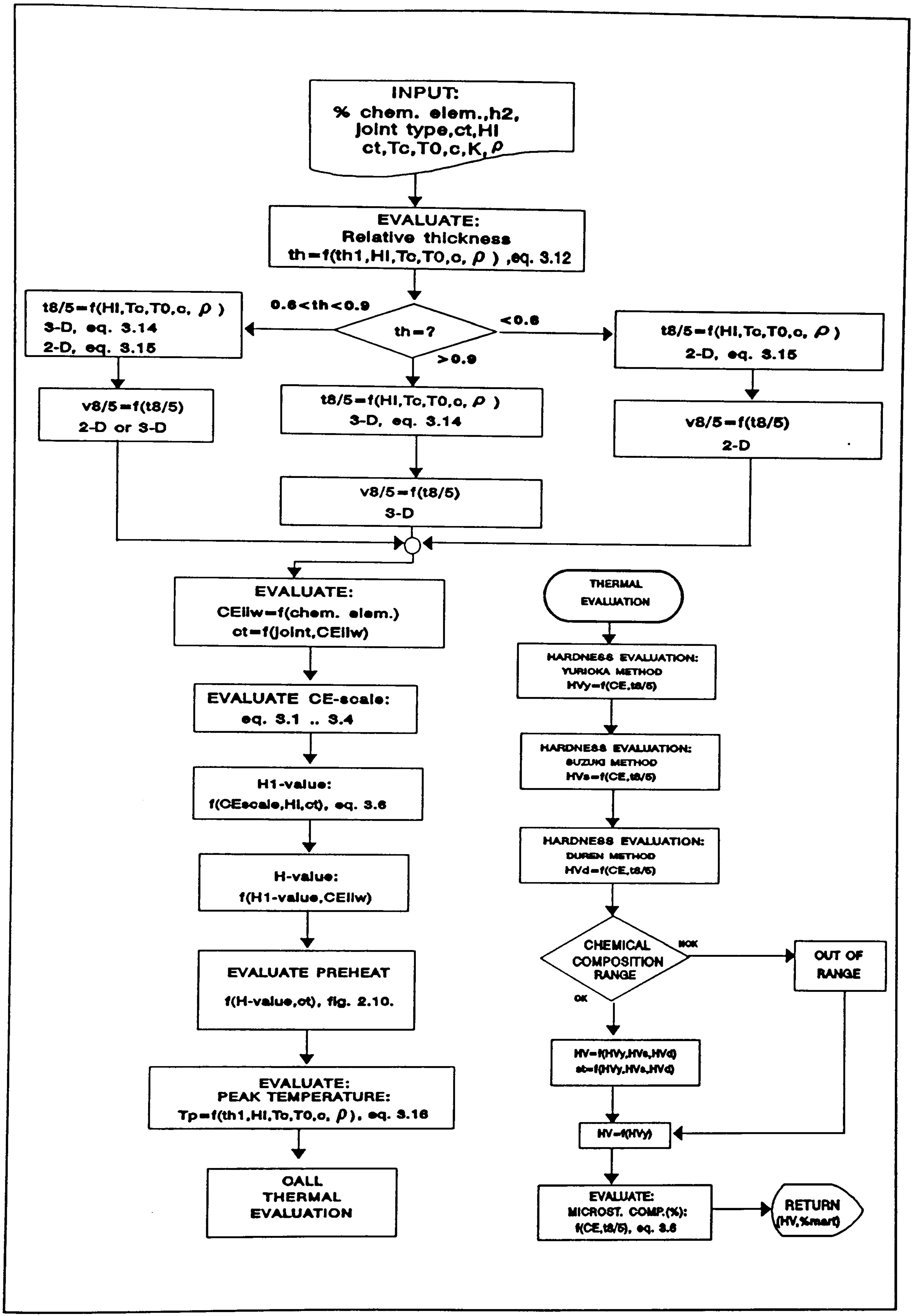


Figure 4.10 - Flow chart representing the main steps in thermal analysis.

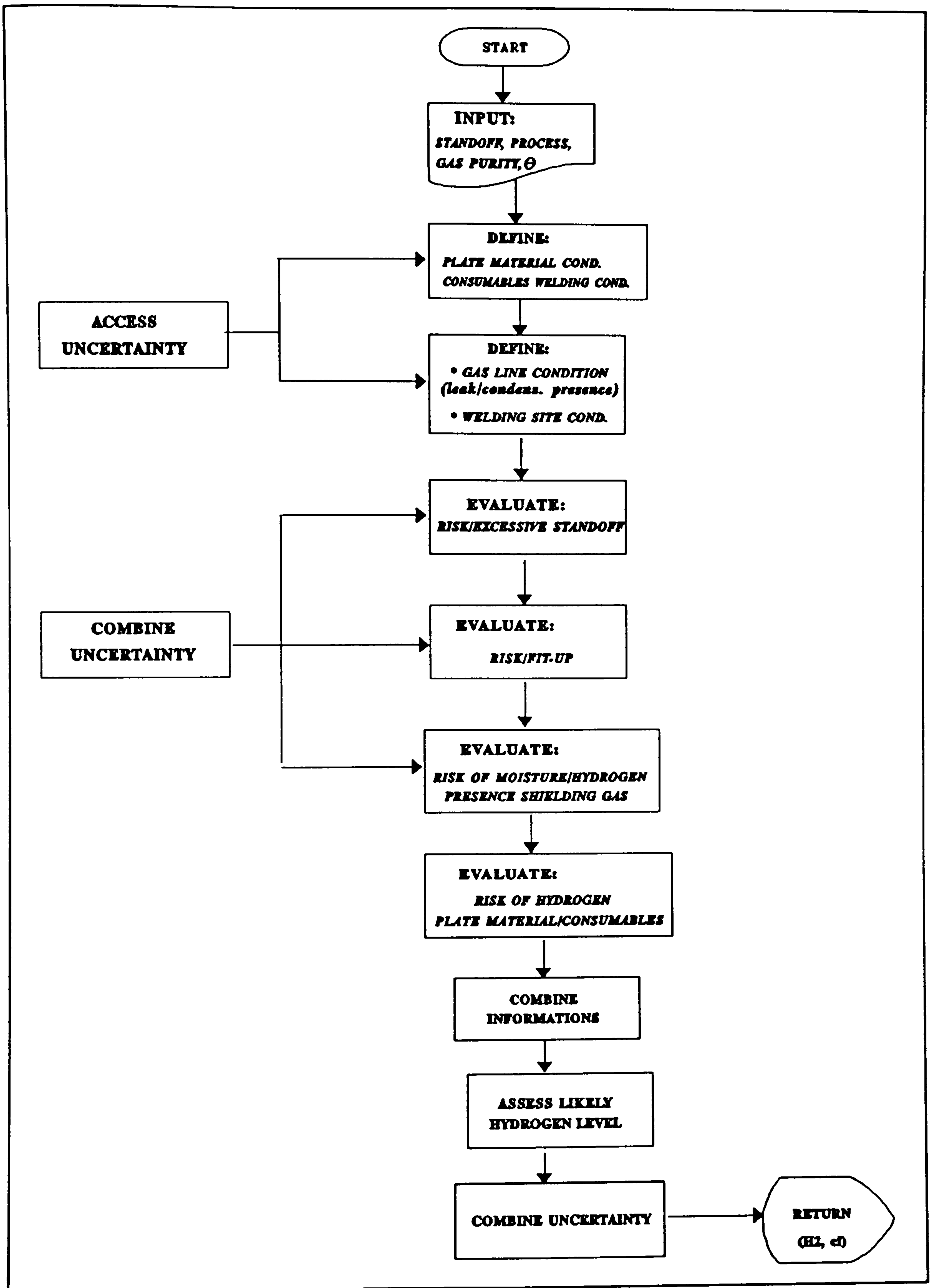


Figure 4.11 - Flow chart representing the main steps in hydrogen analysis.

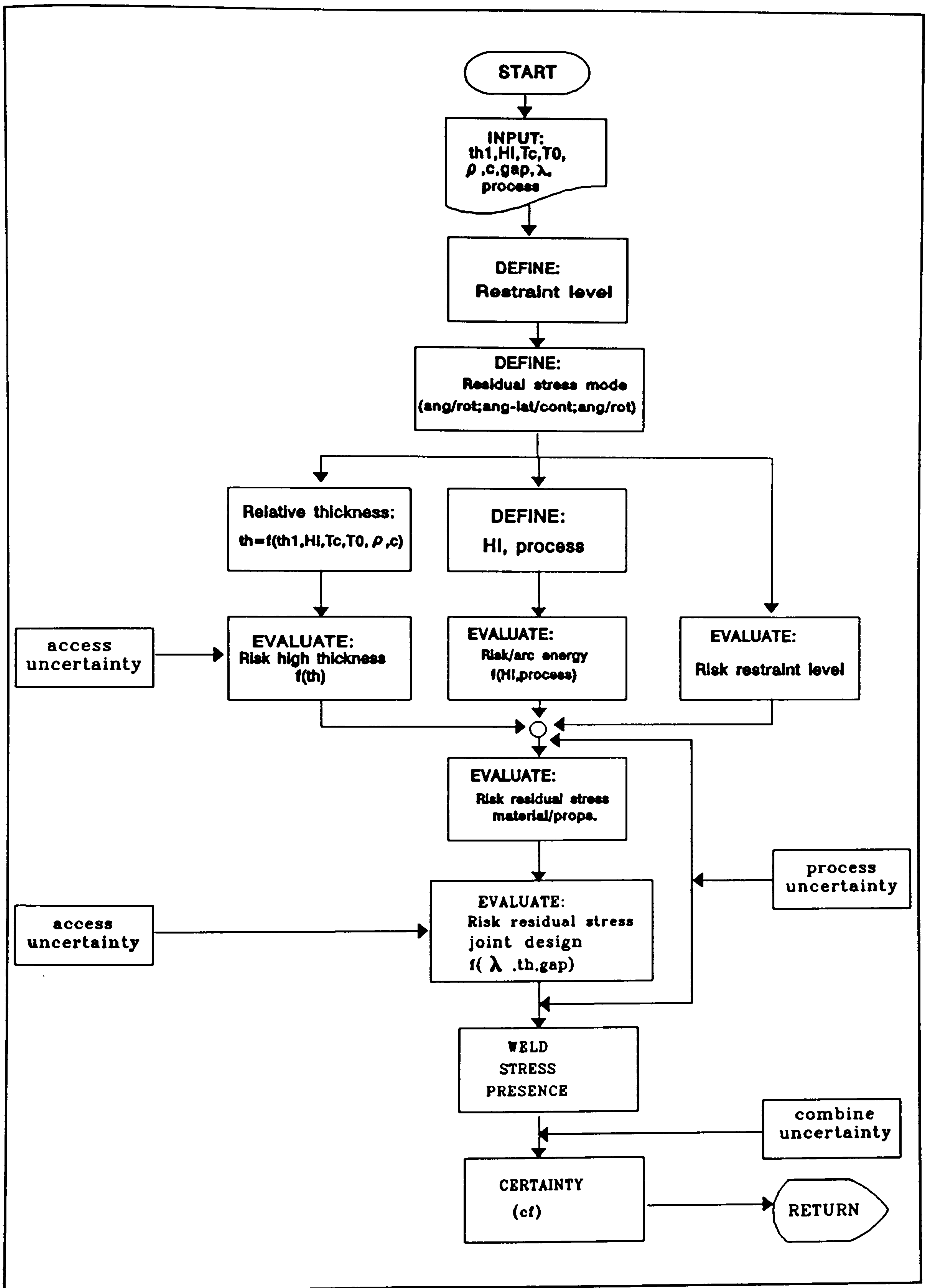


Figure 4.12 - Algorithm representing the main steps in weld stress analysis.

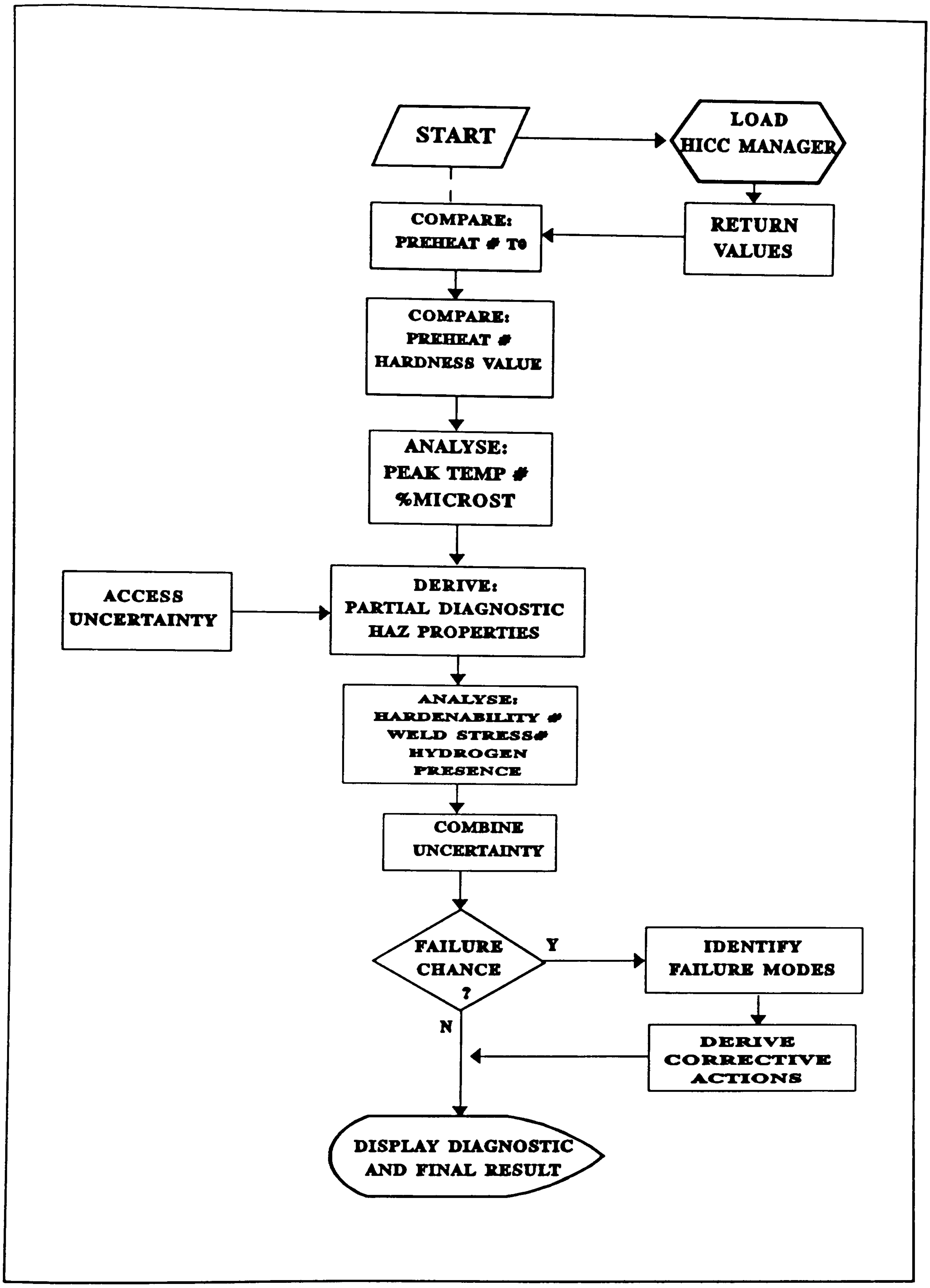


Figure 4.13 - Algorithm representing the main steps in a welding procedure diagnosis.

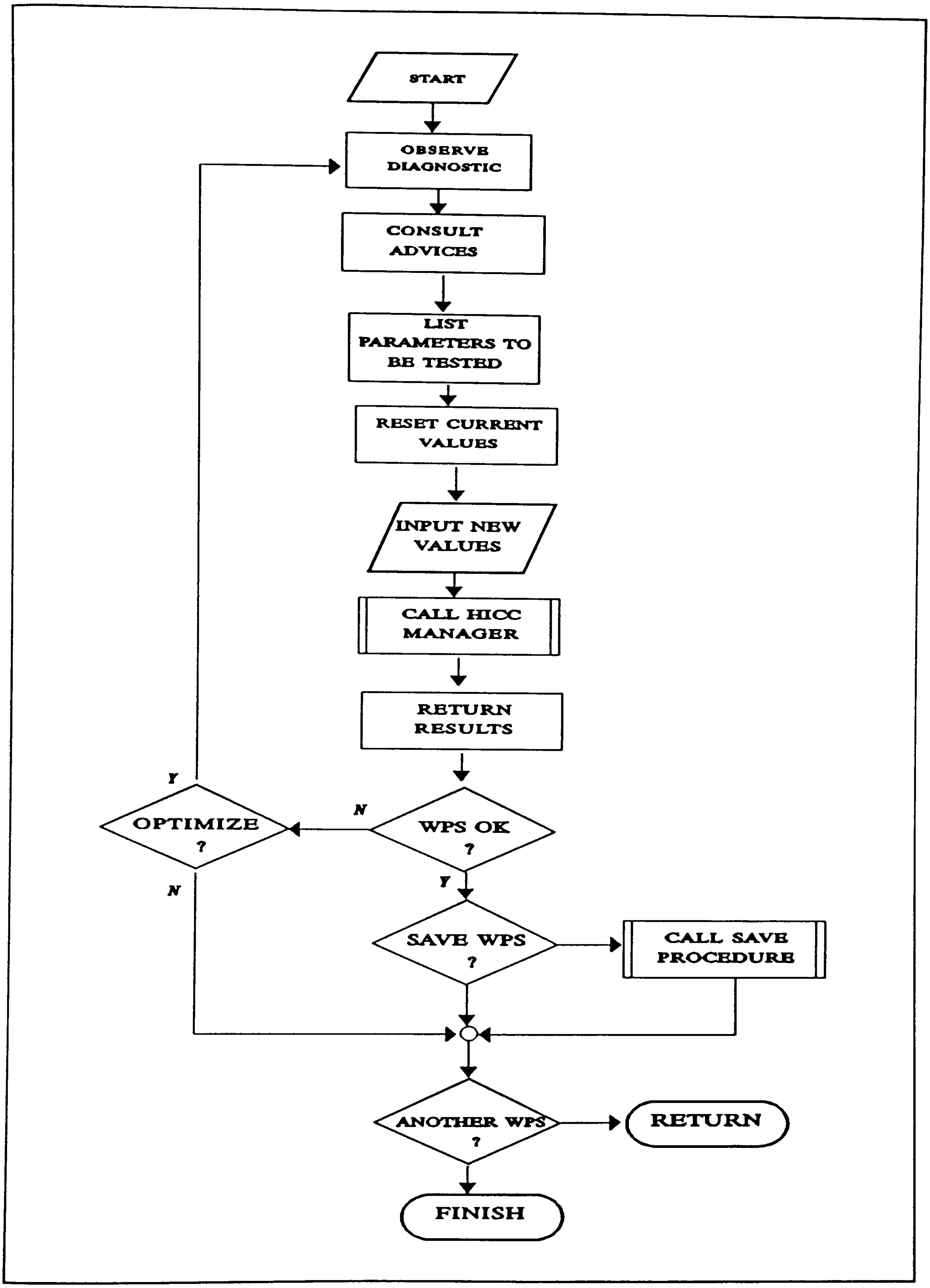


Figure 4.14 - Algorithm representing the main steps in the optimization procedure.

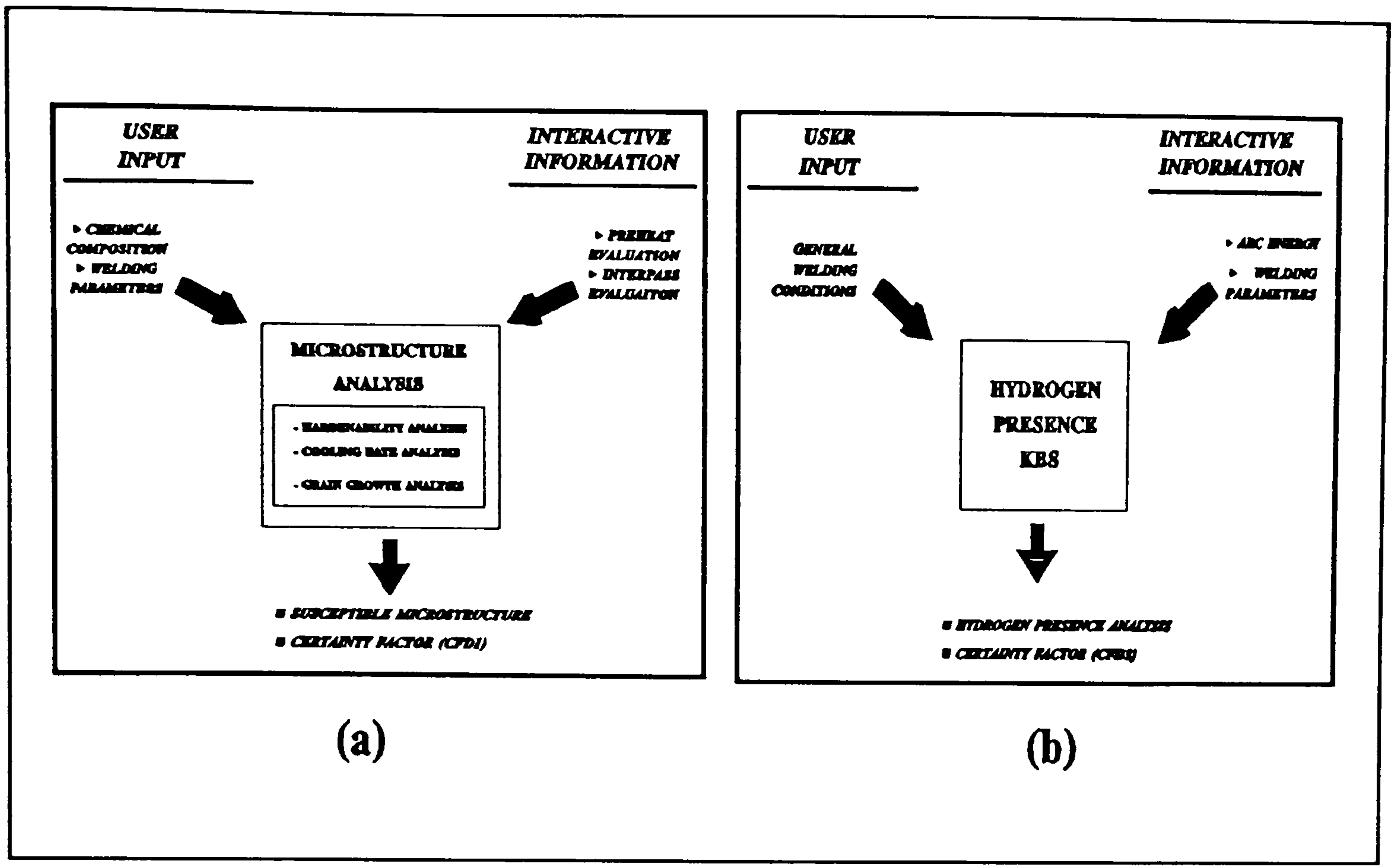


Figure 4.15 - Computer program structure - a) Microstructure analysis; (b) Hydrogen analysis.

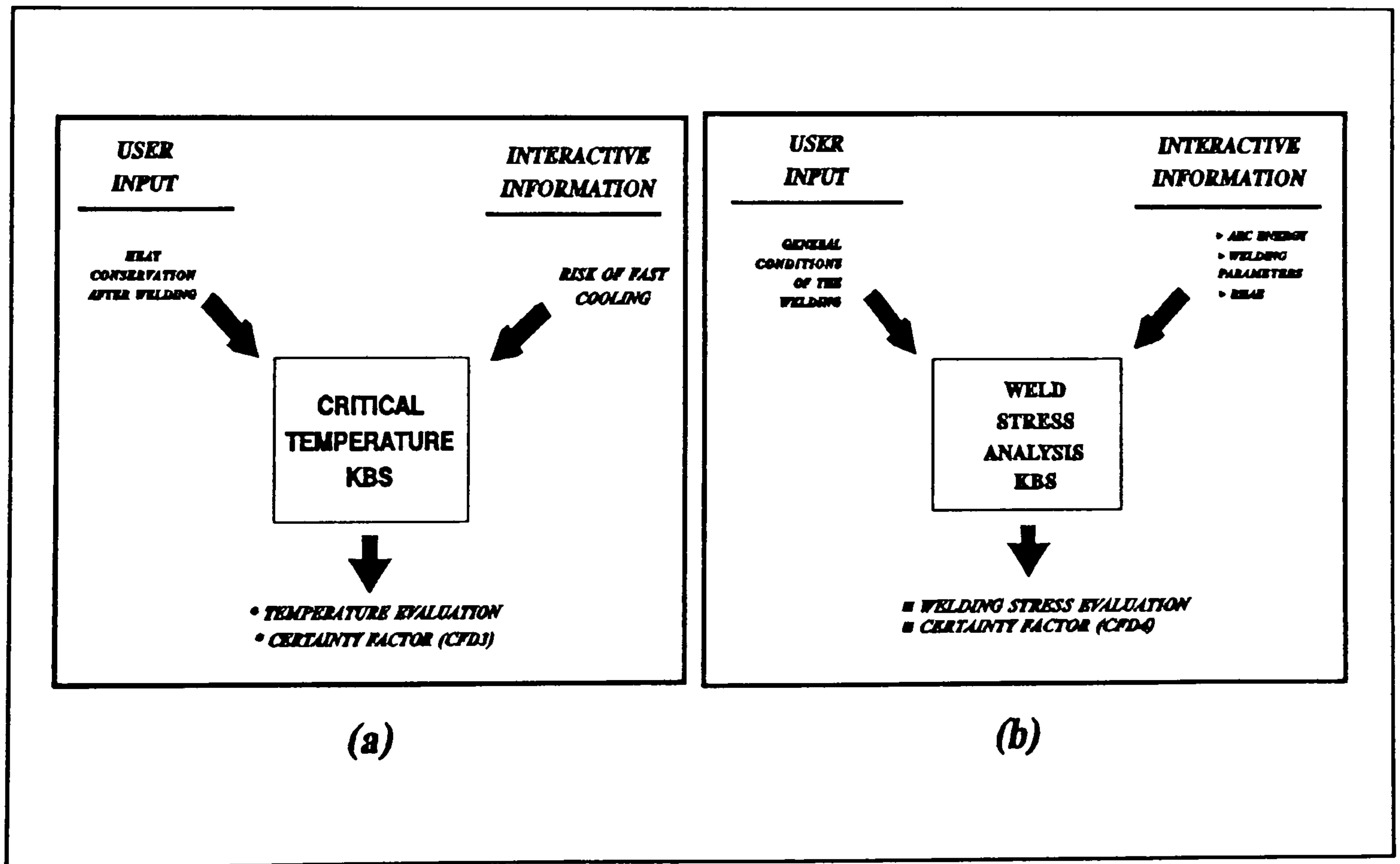


Figure 4.16 - Computer program structure - a) Critical temperature analysis; (b) Weld stress analysis.

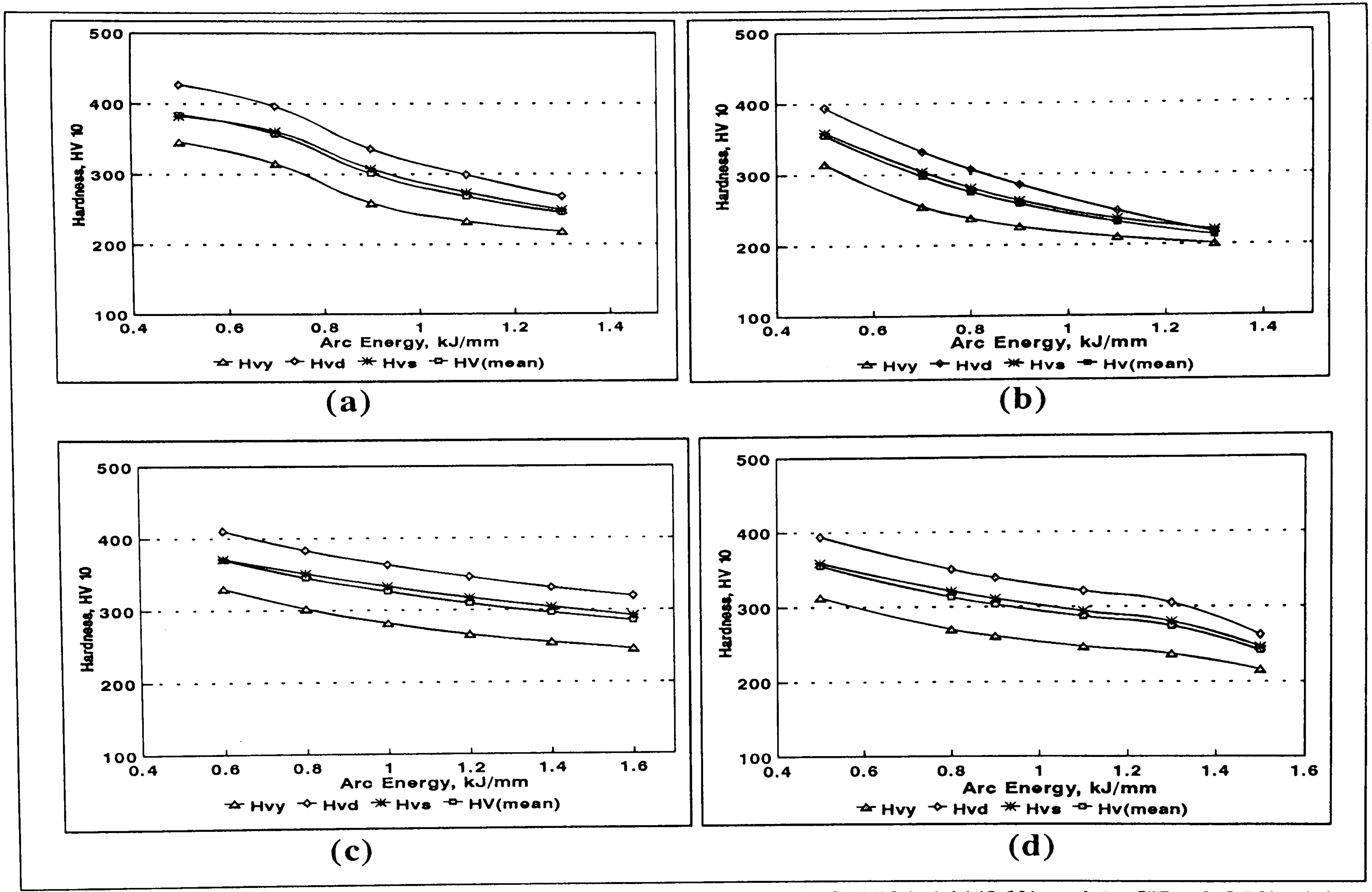


Figure 4-17 - Predicted HAZ hardness for C-Mn steel (BS 1501-141/360), with CE=0.35%. (a) th=15mm, T0=0°C; (b) th=15mm, T0=100°C; (c)th=25mm, T0=0°C; (d)th=25mm, T0=100°C.

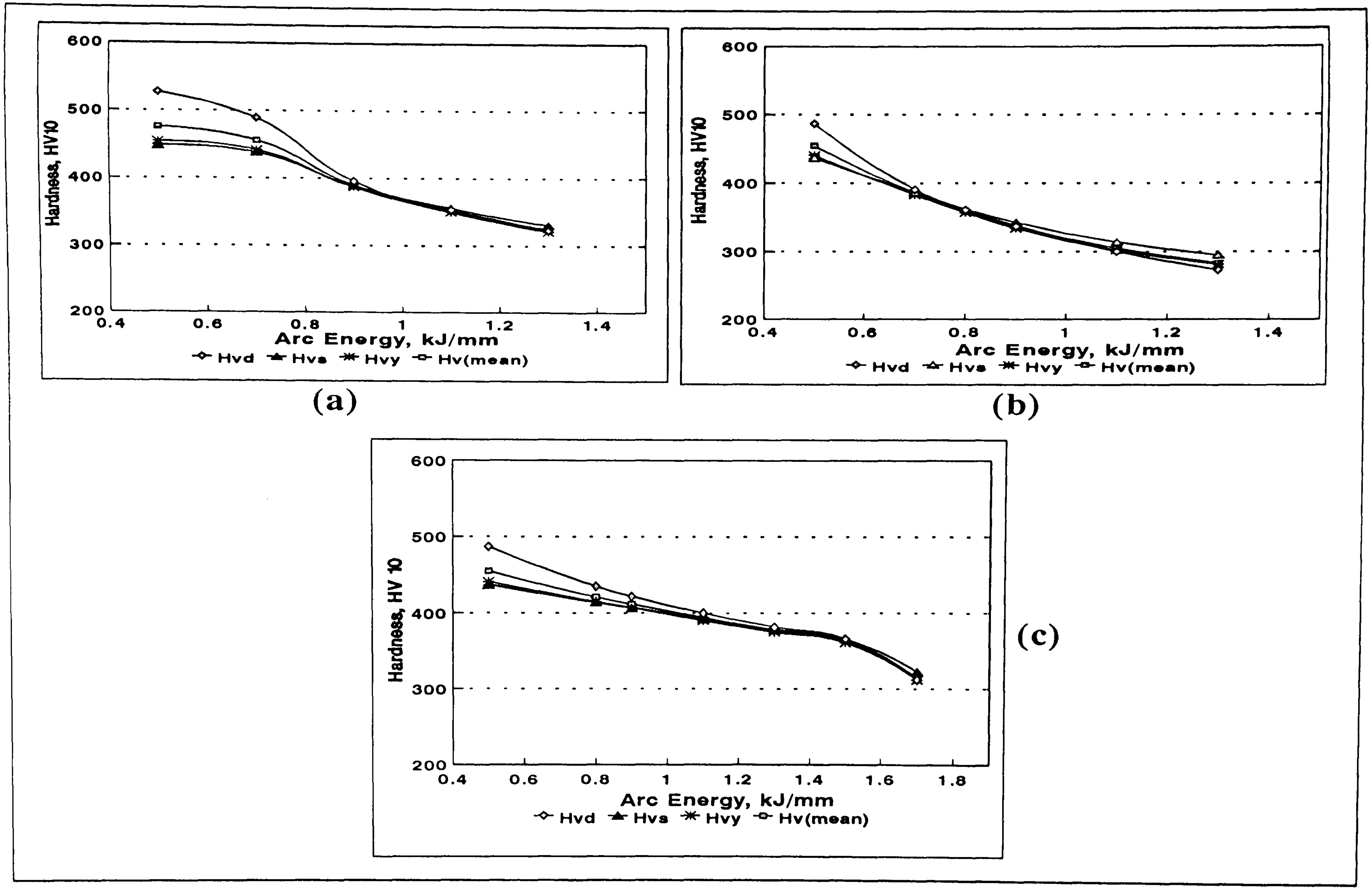


Figure 4-18 - Predicted HAZ hardness for C-Mn steel (BS 4360/40B), with CE=0.45%. (a) th=15mm, Tø=0°C; (b) th=15mm, Tø=100°C; (c) th=25mm, Tø=100°C.

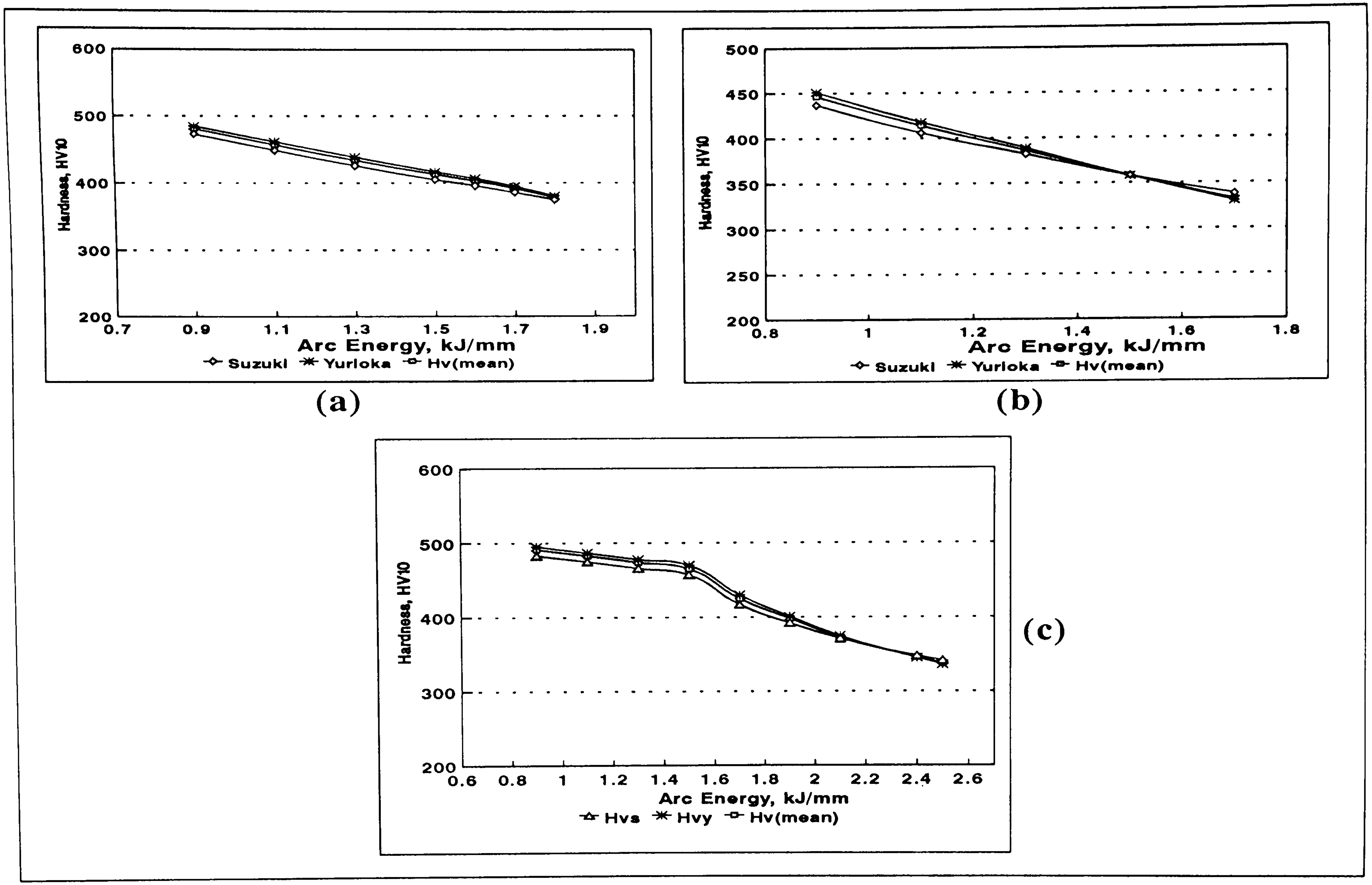


Figure 4-19 - Predicted HAZ hardness for C-Mn steel (BS 1501-151/430), with CE=0.56%. (a) th=15mm, T0=0°C; (b) th=15mm, T0=100°C; (c) th=25mm, T0=100°C.

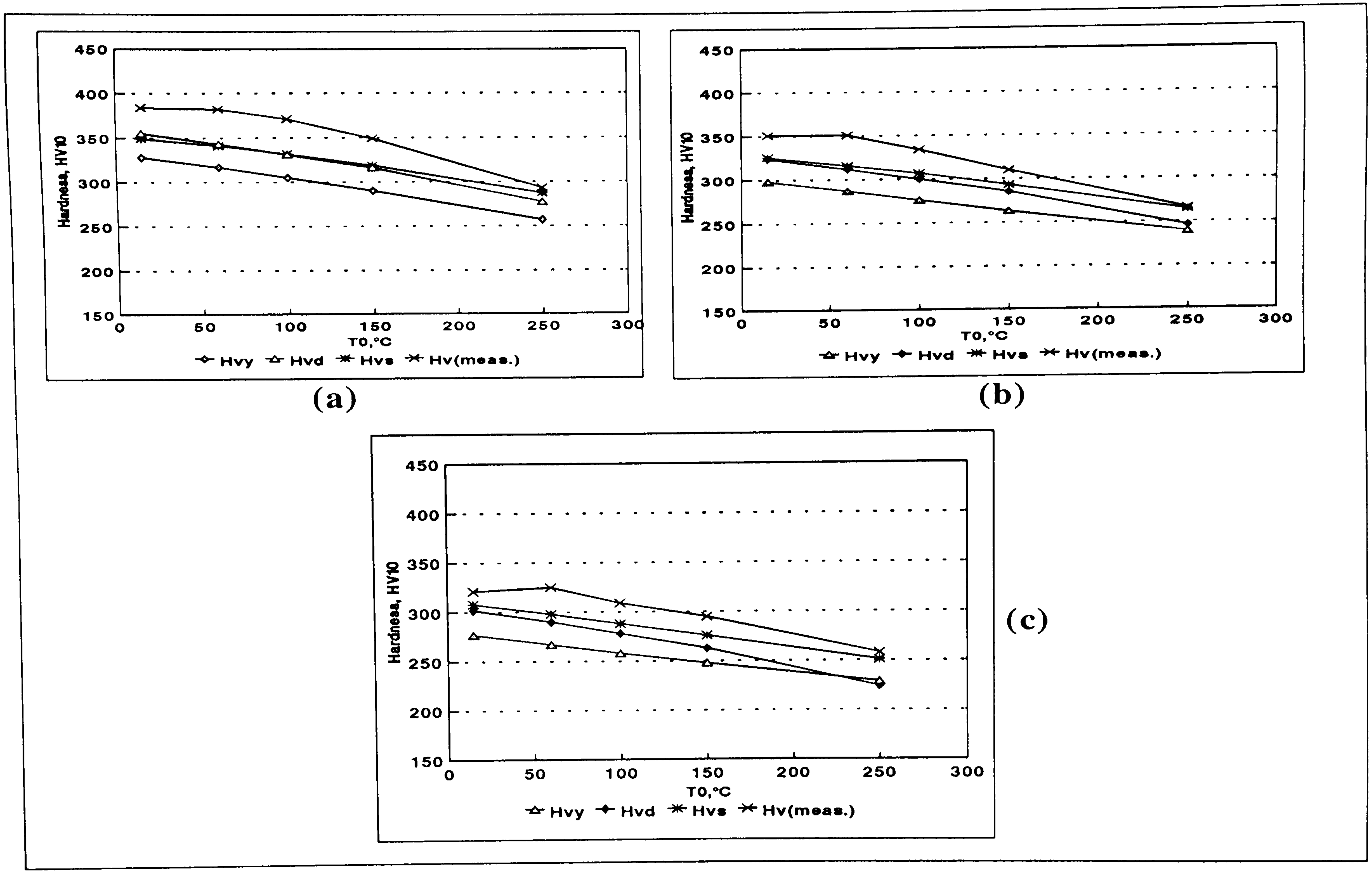


Figure 4-20 - Predicted and real HAZ hardness for material BS4360/55E, CE=0.386% - compared results using different equations.(a) th=40mm,HI=1.0kJ/mm; (b) th=40mm,HI=1.5kJ/mm; (c) th=40mm,HI= 2.0kJ/mm.

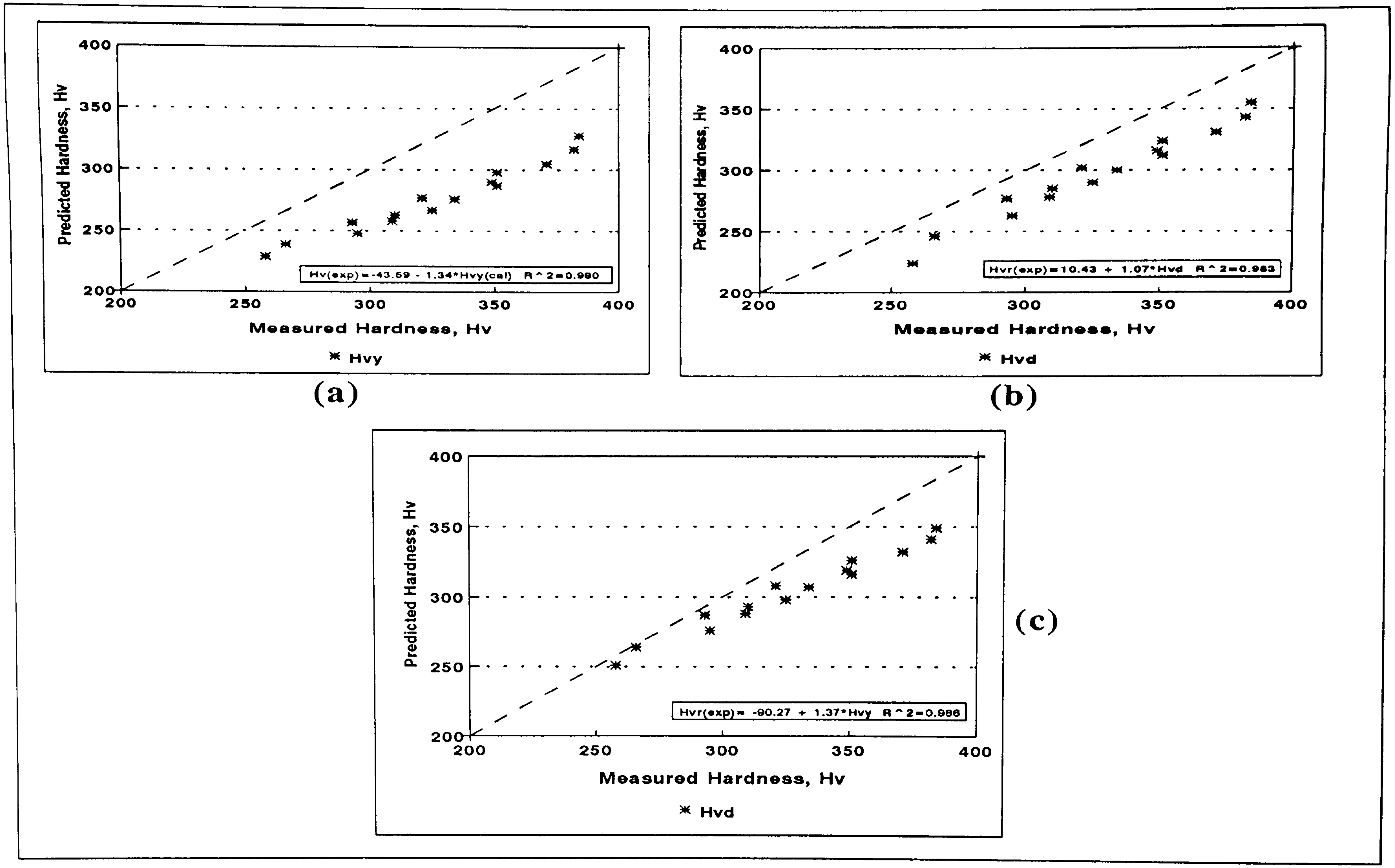
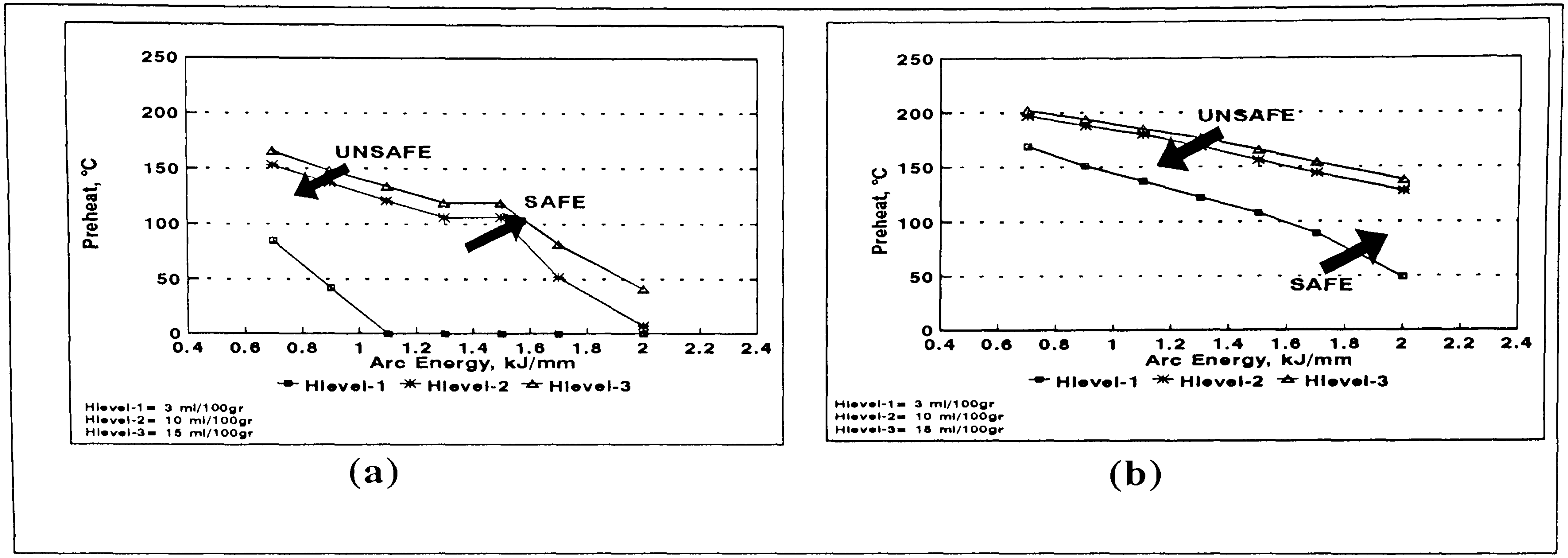


Figure 4-21 - Compared results between real and predicted HAZ hardness for material BS 4360/55E using different equations. (a)Yurioka equation; (b) Duren Equation; (c) Suzuki equation.



(a) (b)

Figure 4-22 - Influence of hydrogen concentration level on the predicted preheat temperature. (a) th=25mm, CE=0.45%; (b) th=25mm, CE=0.56%.

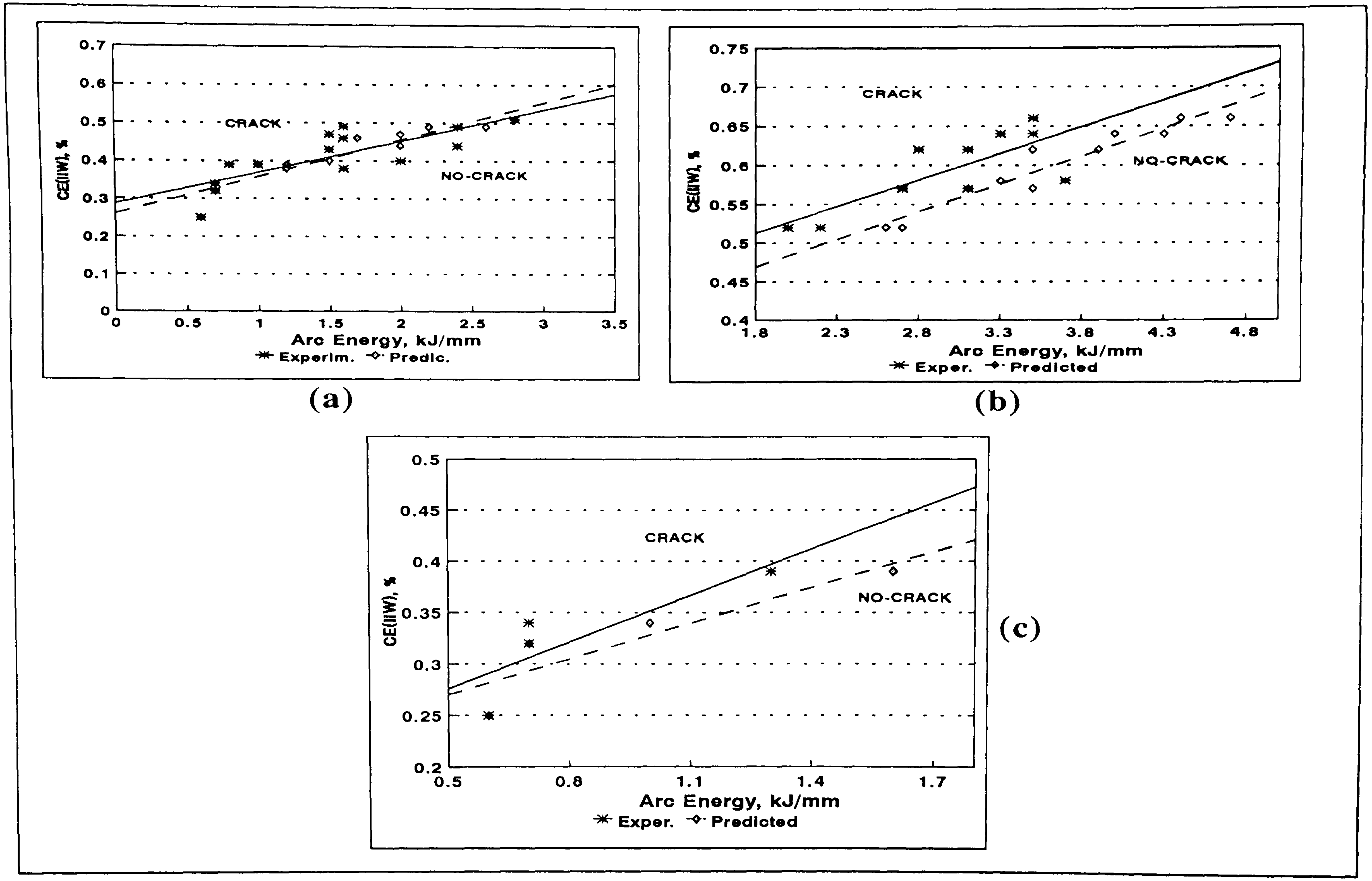


Figure 4-23 - Critical arc energy representing the boundary crack/no crack for different alloy steel (a)th=25mm,HI=0.6-3kJ/mm; (b)th=25mm,HI=2-5kJ/mm; (c)th=50mm,HI=0.6-1.7kJ/mm.

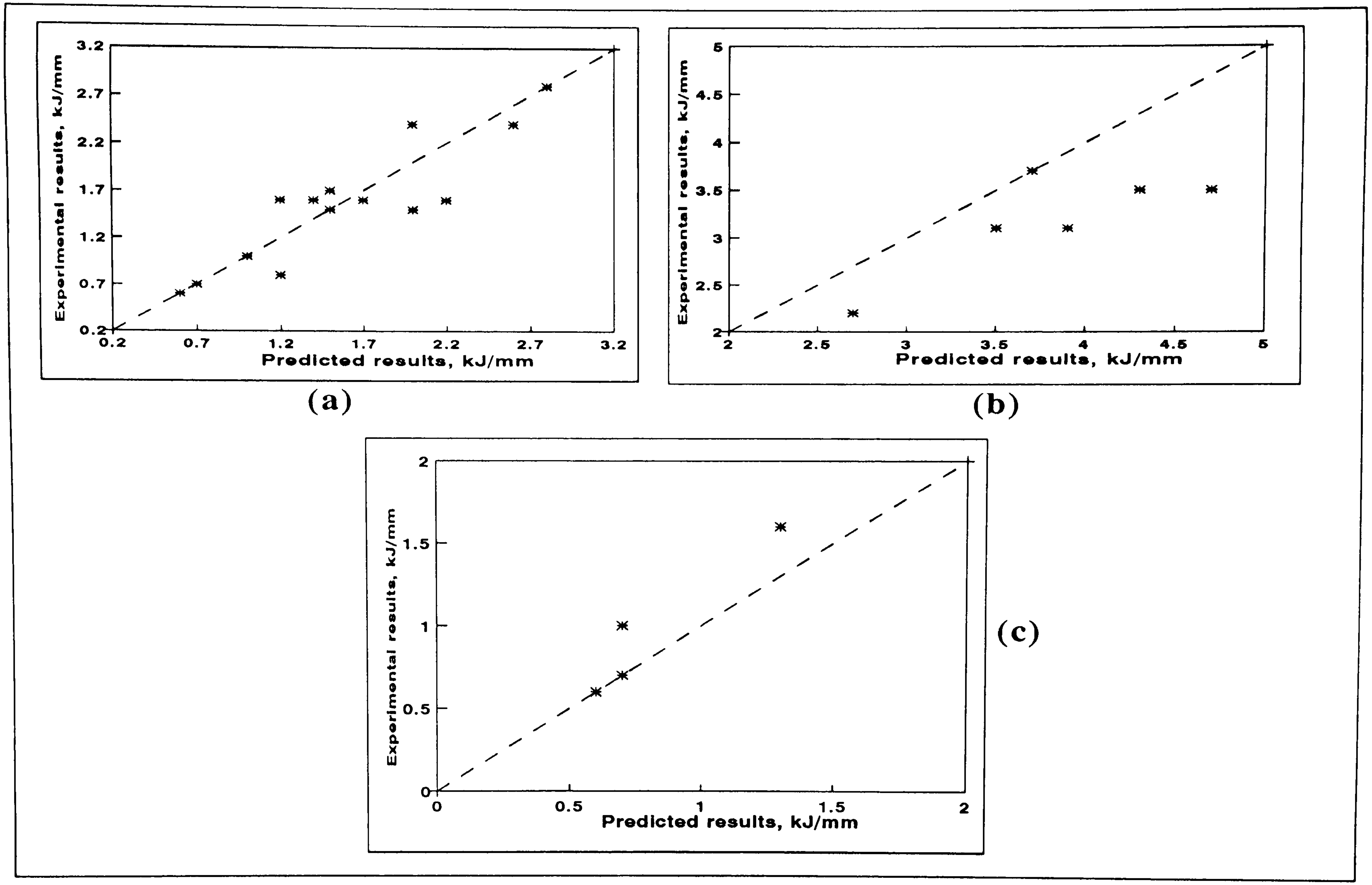


Figure 4-24 - Compared results between real and predicted critical arc energy for different alloy steels. (a)th=25mm, HI=0.6-3kJ/mm; (b) th=25mm,HI=2-5kJ/mm; (c)th=50mm,HI=6-3kJ/mm.

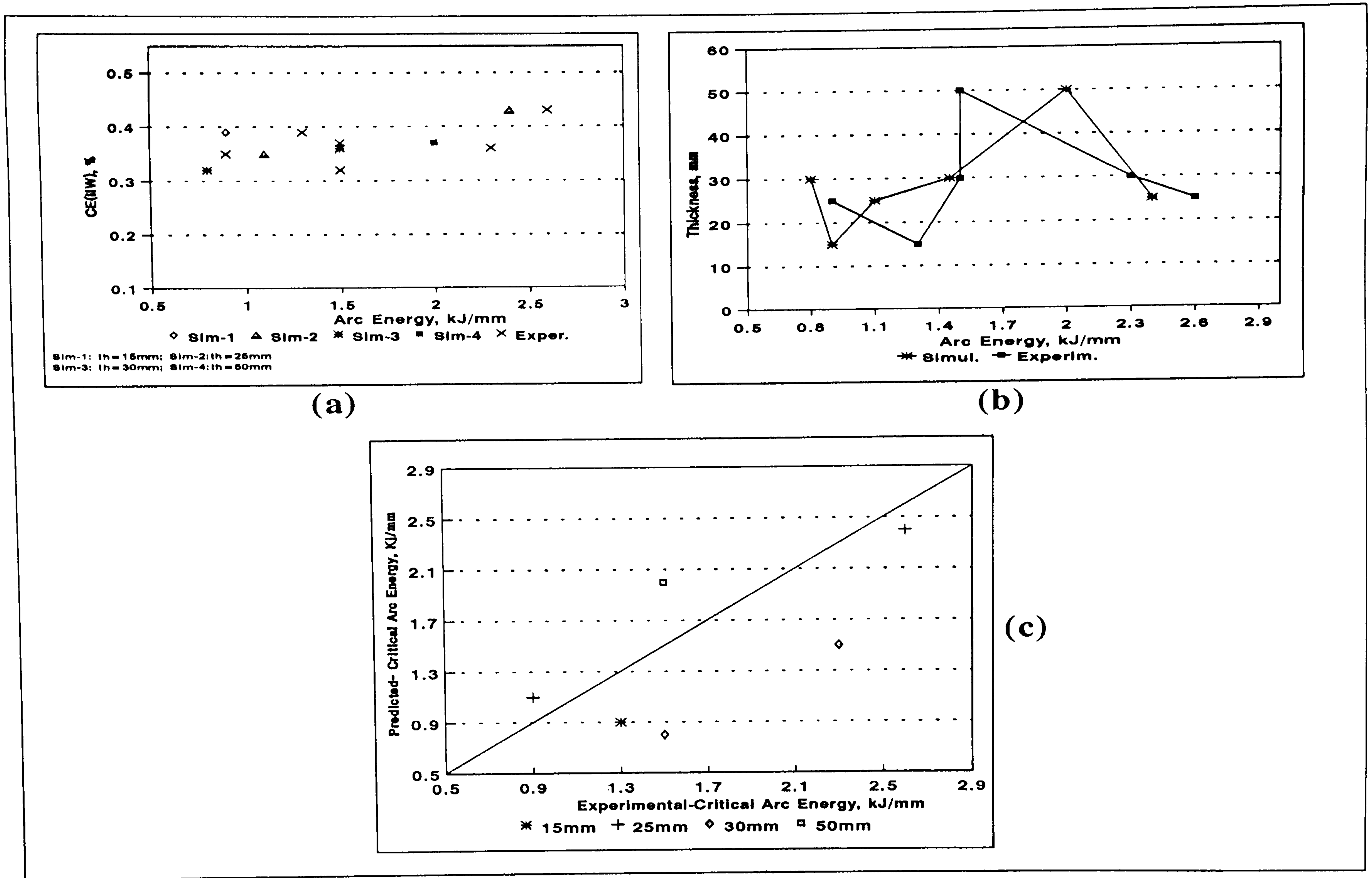


Figure 4-25 - Compared results between simulated and real measurements for different lean alloy steels.

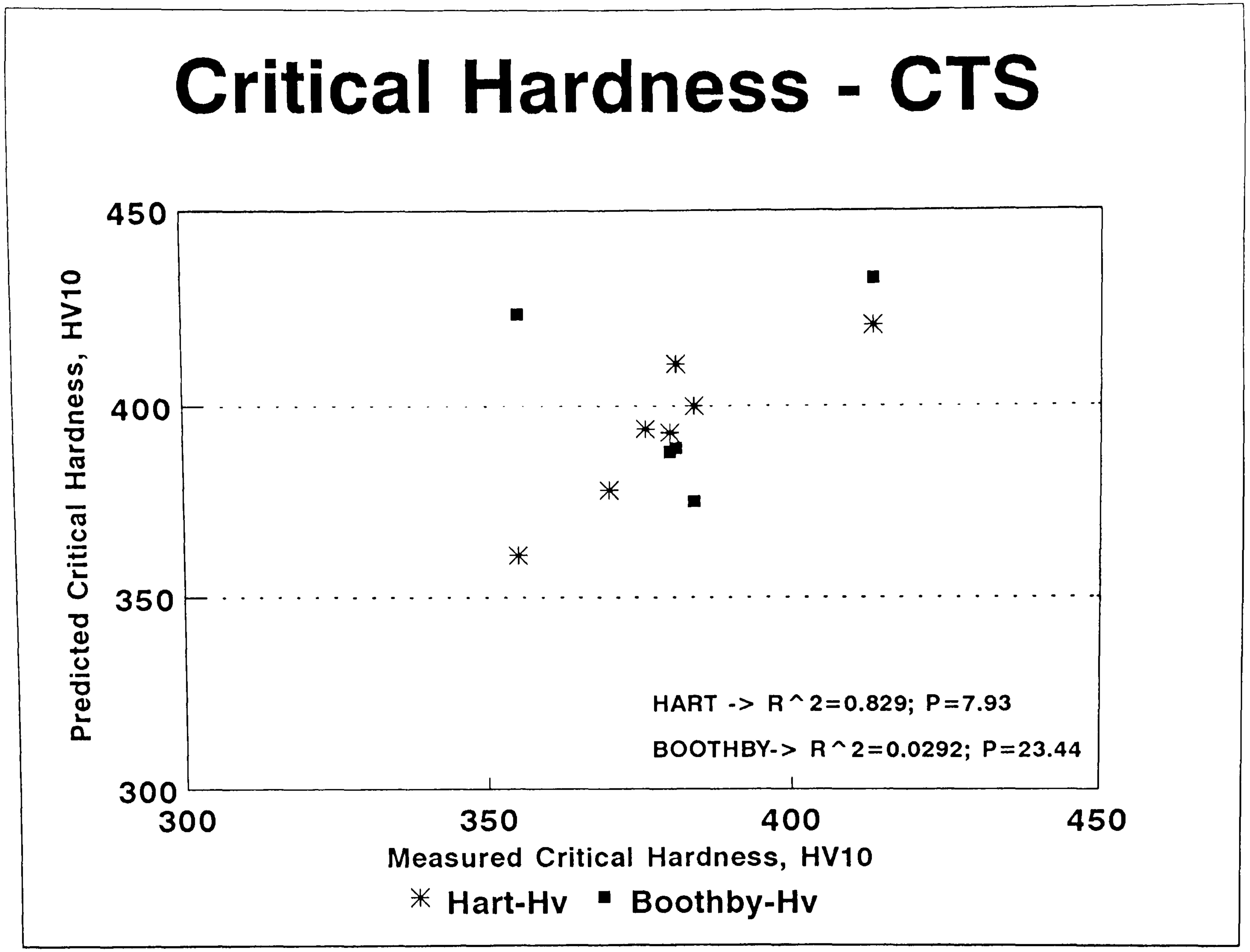


Figure 4-26 - Compared critical HAZ hardness for lean alloy steels by using different models (Hart; Boothby).

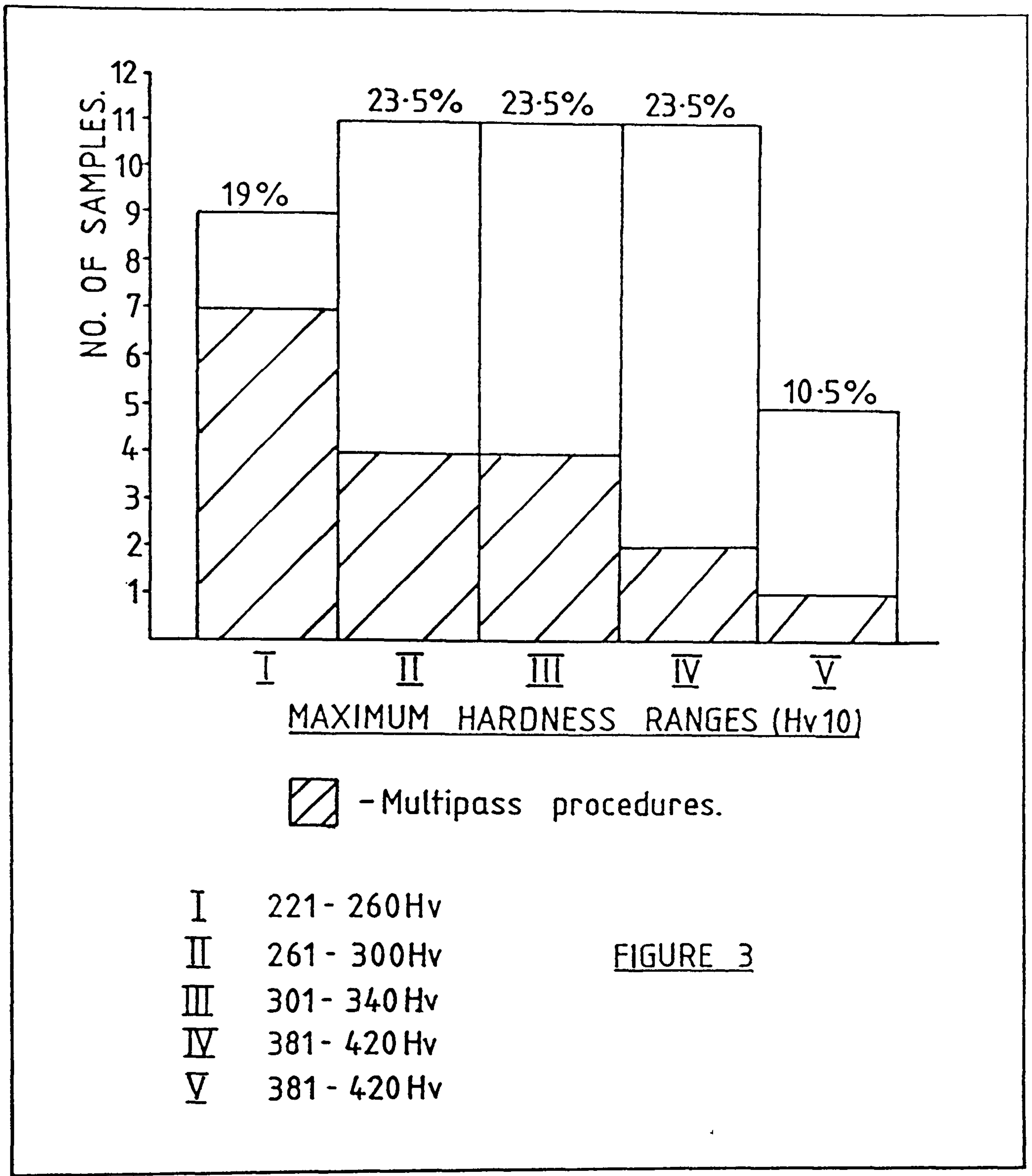


Figure 5.1 - Compared hardness measurement for single and multipass fillet welding (Swetnan, 1984).