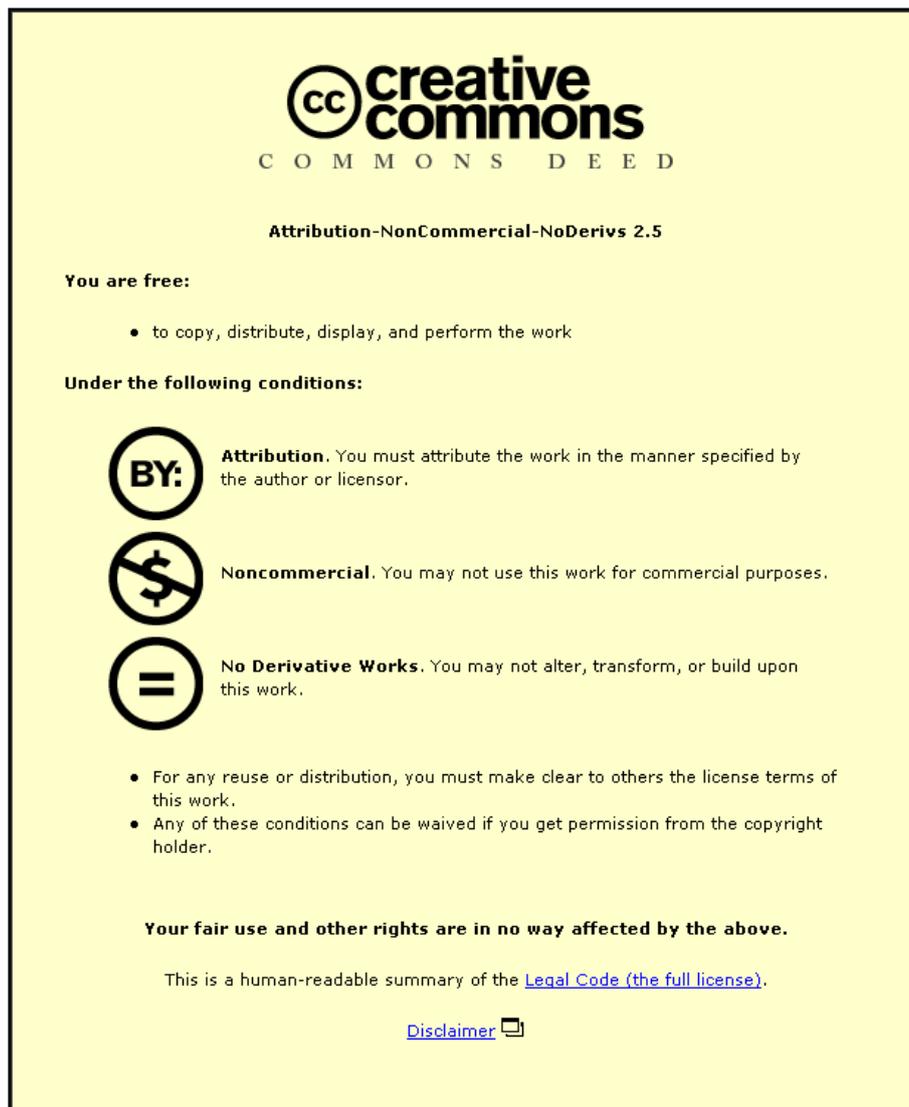


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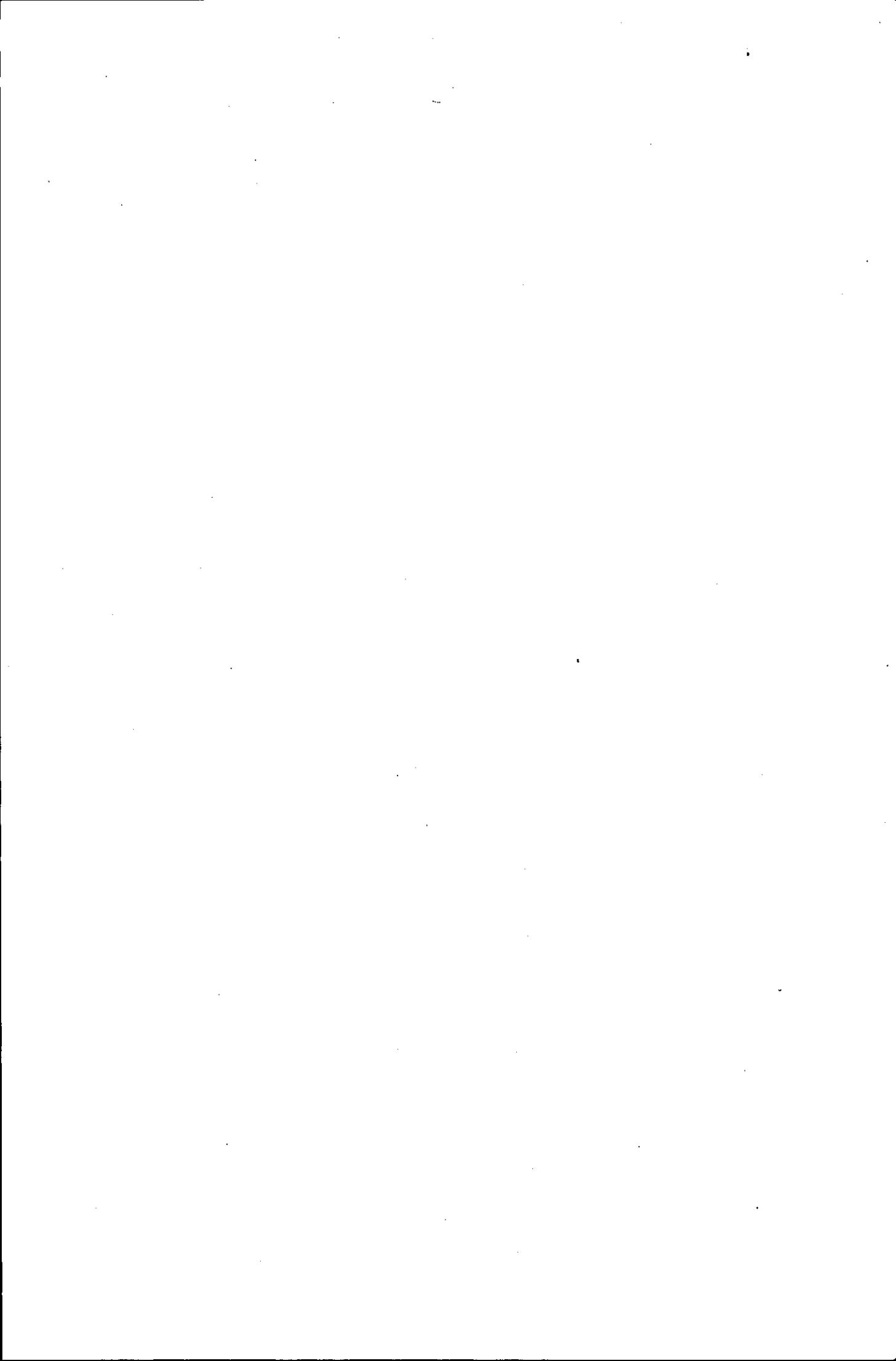
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P.I.K.B.E.S.
Expert System for Welding Process
Quality Control

by
Mehrdad Ghasemshahi
MSc.

A Doctoral Thesis
submitted in partial fulfilment of the requirements
for the award of
Degree of Doctor of Philosophy
of the Loughborough University of Technology
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ABSTRACT

The present research has arisen from a continuation of the WRAPS (Welding Robotic Adaptive Programming and Simulation) project at Loughborough University and its development as the supervisory controller of a flexible welding system. A knowledge based expert system (PIKBES) has been developed for on-line expert modification of pre-programmed welding procedures during fabrication of batches in a flexible adaptive robotic welding environment. A pre-weld joint inspection station comprising a 4-axis manipulator and a laser range finding sensor has been designed, calibrated and implemented on a flexible welding system. The control sub-systems and the triangulation laser sensor are used to measure and collect geometrical data of the joint parameters (such as joint type, plate thickness, gap or root gap, root face thickness, etc). This information is then communicated to the Pre-weld Inspection Knowledge Based Expert System (PIKBES) where it is compared with the nominal joint parameters and the welding procedure modified as necessary to assure quality welding. The modified procedure is then transferred to WRAPS overall supervisory system via a ring communication network (LAN) where it replaces the pre-programmed procedure. The communication between WRAPS supervisory system and the robot welding system to set welding parameters is then performed via 32 I/O channels. The pre-inspection station software has been written in PASCAL-2 and MACRO languages and has been developed on PDP11/23 minicomputer under RT11 operating system.

The PIKBES rules and heuristics have been formulated and implemented to provide optimised welding procedures based on joint data parameters obtained from the pre-inspection station, the WRAPS overall supervisory controller, and WELDSPEC procedure data-base. The optimum procedures are then transferred to the robot controller via the WRAPS supervisory system for welding operation.

The PIKBES rules have been applied to the mechanised MIG/MAG welding process for flat position square-butt and one sided V-butt joints for Carbon and Carbon-Manganese Steels of up to 12mm thickness and produced to British Standards BS5135. PIKBES has been developed on an expert system shell called Knowledge Engineering System (KES) on DELL 200 microcomputer with 1 Megabytes RAM memory under MS/DOS 3.5 operating system. The embedding technique has been used to tailor the interaction between data management software, written in the 'C' language, and the knowledge base of the expert system.

The PIKBES rules have been validated and it has been shown that the application of non-mathematical models in expert systems can be used to provide adaptive control of the process and weld quality in robotic welding systems. Significant time and cost savings compared to mathematical modelling techniques are realised. The system is suited to applications where otherwise many mathematical models would be needed, as in small batch fabrication operations.

ACKNOWLEDGEMENTS

I would like to record my appreciation of the expertise and advice offered to me at stages of this work by my colleagues at Loughborough University of Technology and The Welding Institute. In particular, to J. E. Middle, who as a supervisor, has provided his thoughtful criticisms and suggestions which have greatly added to the value of the thesis. His immense expertise in welding and experience in the batch fabrication industry have enabled the author to comprehend quickly the multitude of problems associated with robotic welding application.

Special thanks to J. Weston and N.T. Gutteridge of The Welding Institute for their valuable welding expertise during the development of the expert system, and The Welding Institute which provided this research with valuable welding software packages. Special thanks is also to helpful colleagues and friends, D. Hardwick for his help during development of the inspection station, T.W. Smith for helping to prepare the photographic work in this thesis, D. Walters, G.P. Charles, N.D. Carpenter for their computer and equipment support. The author has also found continuous support and encouragement from all the other technician in the department of manufacturing engineering specially R. Temple and J. Singh. The research was funded by the ACME Directorate of the U.K., Science and Engineering Research Council (SERC).

DEDICATION

This thesis is dedicated to my family who have been supporting me and my wife who has been my main sources of inspirations and loving support.

ABBREVIATIONS

AI	Artificial intelligence.
ASCII	American Standard Code for Information Interchange.
Bit	Binary digit.
BS	British Standards.
BV	Bevel Angle - the angle formed between the prepared edge of a plate and a plane perpendicular to the surface of the member (see fig 7.1).
CAD/CAM	Computer Aided Design/Computer Aided Manufacturing.
CAPP	Computer Aided Process Planning.
CCD	Charge Coupled Device.
CIM	Computer Integrated Manufacturing.
C-Mn	Carbon and Carbon Manganese Steel.
CPU	Central Processing Unit.
FMS	Flexible Welding System.
GMAW/MIG	Gas Metal Arc Welding (or Metal Inert Gas).
GSX	Graphical Kernel System, an emerging graphics,
KES	Knowledge Engineering System, an expert system shell of software & Engineering Co., USA.
LAN	Local Area Network.
MAP	Manufacturing Automation Protocol, an emerging communication standard.
MR	Measurement Range.
MS_DOS	Microsoft Disk Operating System.
PIKBES	Pre-weld Inspection Knowledge Base Expert System.
Pixel	Picture element.
PLC	Programmable Logic Controller.
POKBES	POst-weld inspection Knowledge Base Expert System.
PPU	Probe Processing Unit.
PS	KES expert system shell Production Rules.
RAM	Random Access Memory.
RFT	Root Face Thickness, The thickness of the prepared plates edge, measured normal to its back face (see fig 7.1).
RG/G	Root Gap (or Gap) - the distance between the prepared plate edges (see fig 7.1).
RS232-C	An EIA Recommended Standard (RS) for Connecting data processing devices.

SERC	Science and Engineering Research Council.
SO	Stand-Off Distance - here is referred to the distance from the contact tip to the workpiece surface measured along the axis of wire extension (see fig 7.1).
TA	Torch Angle (or Travel Angle) - the angle that the electrode makes in advance of a line perpendicular to the weld axis at the point of welding, taken in a longitudinal plane (see fig 7.19 (a) and (b)).
TCP	Tool Centre Point.
TOP	Technical and Office Protocol, an emerging communication standard.
TIG/GTAW	Tungsten Inert Gas welding (or Gas Tungsten Arc Welding).
TS	Torch Speed (or Travel Speed) - the speed at which the electrode traverses the seam measured along the length of the seam (see fig 7.1).
TTL	Transistor Transistor Logic.
V	welding Voltage - the potential difference measured between the contact tip and the workpiece surface.
WA	Weave Amplitude.
WF	Weave Frequency.
WFS	Wire Feed Speed - the speed at which the wire is fed, measured along the axis of the electrode (see fig 7.1).
WP	Weave Pattern Number.
WRAPS	Welding Robot Adaptive Programming and Simulation.
ABSLL - ABSUL	Limits outside of which automated welding is not possible.
LOLIM - UPLIM	Modified BS 5135 limit within which welding with nominal procedures is possible.
X	Area Ratio of joints (nominal area + actual area).

CONTENTS

	Pages
Title	i
Declaration	ii
Abstract	iii
Acknowledgements	v
Dedication	vi
Abbreviations	vii
Contents	ix

Chapter 1 Introduction

1.1	Introduction	1
1.2	Background of Research	1
1.3	Extension of WRAPS	2
1.4	Objectives of PIKBES	3
1.5	Structure of thesis	3

Chapter 2 Quality Control of Welding

2.1	Introduction	5
2.2	Background	5
2.3	Close Loop Feedback Control of Manual Welding	6
2.3.1	Welder Approval	8
2.4	Open Loop Control of Automated Robotic Welding System	8
2.4.1	Components Tolerance	9
2.4.2	Components Design	9
2.4.2.1	Process Tolerance	10
2.4.2.2	Closer Dimensional Specification	10
2.4.3	Jigs and Fixtures	10
2.5	Close Loop Feedback/Feedforward Control of Automated Robotic Welding System	11
2.5.1	Design to Assist Sensors	13
2.5.2	Expert Systems in Welding Quality Control	13

Chapter 3 Literature Survey :**Flexible Robotic Welding Systems**

3.1	Introduction	15
3.2	Background	15
3.3	Flexible Welding Systems (FWS)	16
3.3.1	Graphical Simulation and Off-line Programming of Systems	24
3.3.2	The Loughborough FWS	28
3.4	Sensing Systems for Robotic Arc Welding	34
3.4.1	Tactile Sensing	35
3.4.2	Through-The-Arc Sensing	38
3.4.3	Inductive Sensing	43
3.4.4	Visual Sensing	45
3.5	The Suitability of Commercially Available Sensing Systems for The Pre-Weld Inspection Station	56
3.6	Robotic Welding Systems With Adaptive Process Control	58
3.6.1	Approaches in Development of Mathematical Models	59
3.6.2	Mathematical Models for Selecting Welding Procedure	62
3.7	Limitation of Current Adaptive Process Control Systems	66

Chapter 4 Literature Survey :**Expert Systems for Automated Welding**

4.1	Introduction	68
4.2	Background	68
4.3	General Issues in Expert Systems	69
4.3.1	Features of Expert Systems	69
4.3.2	Components of Expert Systems	71
4.3.2.1	The Knowledge Acquisition	71
4.3.2.2	The Knowledge Base	74
4.3.2.3	The Inference Engine	76
4.3.2.4	The User Interface	76
4.3.3	Motivation Behind Expert Systems Development	77
4.3.4	Problems Associated With Expert Systems	78
4.3.5	Comparison of Conventional Computer Programs and Expert Systems	79
4.3.6	Languages and Shells	81

4.3.7	Application of Expert Systems	83
4.4	Selection of KES Expert System Shell for PIKBES	86
4.5	Welding Software Packages	89
4.6	Expert Systems in Welding Applications	92
4.6.1	Expert Systems for Welding Procedure Generation	93
4.6.2	Expert Systems to Assist Welding Designers	95
4.6.3	Expert Systems for Welding Process Selection	96
4.6.4	Expert Systems for Process/Equipment Diagnostics	98
4.6.5	Expert Systems for Welding Process Control	101
4.6.6	Expert Systems in Weld Crack or Defect Analysis	102
4.7	Proposed Expert System - PIKBES	103

Chapter 5 Data Acquisition and Processing in Pre-Weld Inspection Station

5.1	Introduction	104
5.2	The Pre-Weld inspection Control Strategy	104
5.3	Design Consideration of the Pre-weld inspection Station	106
5.4	Configuration of Pre-weld inspection Station	108
5.4.1	Ancillary Set Up and Equipment	109
5.4.2	The Optocator System	109
5.4.2.1	The Optocator Operating Principle	112
5.4.2.2	Probe Processing Unit (PPU)	113
5.4.2.3	Probe Central Processing Unit (CPU)	113
5.4.3	Tests for Conformance of the Optocator Output Specification	114
5.4.3.1	Output Voltage Test in Relation to Measurement Range (MR)	114
5.4.3.2	Optocator Thickness Measurement Calibration	116
5.4.3.3	Sources of Error in Optocator	116
5.5	Interfacing for the Pre-Weld Inspection Station	124
5.5.1	Integration of the Optocator With Motorised Axes	124
5.5.1.1	Use of DRV11-J Interface Card	124
5.5.1.2	Use of KVV11-A Interface Card	124
5.5.2	Integration of the Optocator CPU with DRV11-J	126
5.5.3	The Pre-weld Inspection Station Communication	126

5.6	Software Development for the Pre-Weld Inspection Station	127
5.6.1	Point-to-Point Inspection	130
5.6.2	Effect of Scanning Interval on Edge Detection	134
5.6.3	Feature Extraction and Joint Recognition In the Pre-Weld Inspection Station	134
5.6.3.1	Smoothing	134
5.6.3.2	Edge Detection	136
5.6.3.3	Joint Recognition	137
5.6.3.4	Calculation of Bevel Angles	140
5.6.3.5	Calculation of Joint Area	140
5.7	Data Format Required by PIKBES	141

Chapter 6 Knowledge Elicitation and Implementation for PIKBES

6.1	Introduction	143
6.2	Background	143
6.3	Fitting PIKBES into a Flexible Welding System	144
6.4	PIKBES Development Sequence	147
6.5	Analysis of PIKBES Requirements	150
6.5.1	Communication Capability of KES Shell in PIKBES	151
6.5.2	PIKBES Communications	157
6.5.3	Selection of WELDSPEC Database	159
6.5.3.1	WELDSPEC Database Search	163
6.5.4	Achieving High Performance, Compatibility, Portability	167
6.5.5	Expansion Capability	168
6.6	Knowledge Elicitation and Formulation for PIKBES	168
6.6.1	'Window' Technique	175
6.6.1.1	Adoption of Heat Input	179
6.6.1.2	Adoption of Metal Deposition Rate	182
6.6.2	Linear Relationship Technique	185
6.7	Knowledge Implementation for PIKBES	202
6.8	Knowledge Validation for PIKBES	202

Chapter 7 Validation of PIKBES

7.1	Introduction	204
7.2	Background	204
7.3	Experimental Design	205

7.3.1	Selection of Variables and Levels	205
7.3.2	Design of Factorial Experiments	210
7.4	Plate Edges Preparation	215
7.5	Preparation of Weld Tests	220
7.6	Quality Assessment Techniques	220
7.7	Welding Experiment Tests	221
7.7.1	Welding Experiments on 'Window' Technique	225
7.7.2	Welding Experiments on 'Linear Relationship' Technique	228
7.8	PIKBES/End-user Interaction Capability	232

Chapter 8 Future Work

8.1	Introduction	243
8.2	Future Research and Development Work	243
8.2.1	Pre-Weld Inspection Station	243
8.2.2	In-Process Inspection Station	245
8.2.3	Post_Weld Inspection Stations	245
8.2.3.1	Automatic Inspection	246
8.2.3.2	POKBES	248
8.2.3.3	Manual Inspection	249

Chapter 9 Discussions and Conclusions

9.1	Introduction	250
9.2	Discussions	250
9.3	Conclusions	251

References R-1

Appendices

A1	Additional features of KES PS	A1-1
A2	Illustrates an example of linear motorised and rotary system which has been considered for the pre-weld inspection station.	A2-1
A3	Information regarding shaft and ball bearing specification used for position holder in the pre-weld inspection station.	A3-1

A4	Technical specification of the Selcom Optocator probe.	A4-1
A5	I/O signal pin connection for DRV11-J interface card.	A5-1
A6	Calculation of 'window' size for nominal joint	A6-1
A7	Metallic area calculation for different joint geometry	A7-1
A8	Tables of treatment combinations (for factorial experiment test) for 6, 8, 10 and 12mm V-butt joints.	A8-1
A9	Typical 'help' facilities provided during PIKBES consultation session.	A9-1

CHAPTER 1:

Introduction

CHAPTER 1 : INTRODUCTION

1.1 Introduction

This chapter discusses the background to this research and its extension of the WRAPS project which provides the overall system core for a flexible welding system. It also describes the problems associated with statistical process modelling for drawing up optimum welding procedures during welding operations for fabrication in small batches, and features which make the application of knowledge based expert system to on-line quality control of welding desirable.

1.2 Background of Research

This research was in collaboration with the Welding Institute and the CEGB (Marchwood Engineering Laboratories), and was supported by SERC grant (GR/C/83326 - June 1986). The primary objective was to develop a sub-module Pre-weld Inspection station together with its Knowledge Based Expert System (PIKBES) [2] rules and heuristics for on-line optimisation of welding procedures based on the WRAPS project [1]. WRAPS is an acronym for Welding Robot Adaptive Programming and Simulation which was developed as a low cost off-line robotic programming and simulation software tool and has the following built-in concepts:

- i) Off-line programming of robotic arc welding operations.
- ii) The basis of a flexible integrated robotic welding.
- iii) Expert selection of optimum welding procedures.
- iv) Process planning extension.
- v) Off-line simulation with process optimisation.
- vi) Possible flexible post-processing to enable output to different robot systems.
- vii) Import of data from CAD and other packages.
- viii) A generic tool to be used for programming in other processes.

Chapter 3 section 3.3.2 discusses these concepts in more details.

1.3 Extension of WRAPS

An extension of WRAPS project was to research and develop expert systems in the area of:

- a) Expert prediction of welding procedures where non-previously exist.
- b) Expert generation of adaptive control algorithms.
- c) On-line optimisation of welding procedures in process using non-mathematical expert system models.

(a) Is the subject of a parallel research study [32] and is not reported here in detail. It is intended that (b) will utilise data collected from the long term operation of system developed for (c). A sub-module extension of (c) was to design, calibrate, and implement a pre-weld inspection station in a flexible welding cell for on-line quality control of components prior to fabrication. Furthermore, to develop expert knowledge rules by means of direct knowledge elicitation from the welding domain and from published knowledge, and the formulation of such knowledge into rules in order to modify welding parameters (such as voltage, torch speed, wire feed speed, torch angle, etc.) based on any deviation detected in the nominal joint (e.g. root gap, root face thicknesses, bevel angles, etc.) such that acceptable weld bead geometry is produced. The system works at three 'levels'; joints within an established tolerance at which nominal welding parameters can apply, joint outside expertly established absolute limits which can be considered unweldable by automatic means, and finally the intermediate level requiring an expert system with appropriate rules to suitably modify the nominal welding procedures and thus enable satisfactory welding.

Currently, modification of such welding procedures during fabrication of components necessitate that data be represented in the form of equations or mathematical models but, as the detailed survey in chapter 3 (section 3.6 and 3.7) will show, the application of mathematical process modelling to adaptively controlled robotic welding systems is a significant time and cost consuming factor in the economic viability of application to small batch manufacturing operations. A vast amount of data relating to welding procedures needs to be empirically collected and employed and their performance in practice has to be tested. It is this costly and time consuming development of mathematical models together with their lack of generality which is the motivation for use of knowledge base expert system for welding

procedure control (PIKBES).

A further sub-module of (c) is to similarly produce a post welding inspection station to provide data input to a further knowledge base expert system which will provide feedback and if necessary further modification of the welding procedure which had been used and this is discussed further in section 8.2.3.

1.4 Objectives of PIKBES

The main objectives of PIKBES research are:

- a) To produce a cost effective means of providing an on-line quality control loop in a flexible computer integrated welding cell for small batch manufacturing operations.
- b) To design, calibrate and implement an inspection work station.
- c) To demonstrate the feasibility of the concept (a) by means of elicitation of expert knowledge and formulation of such knowledge into rules base form, and their implementation and validation on data collected from the automatic joint pre-weld inspection station incorporated within the welding cell.

1.5 Structure of Thesis

This thesis is divided into the following chapters below, each chapter has been separated from another by a pink coloured sheet :

- CHAPTER 1** : Introduction
- CHAPTER 2** : Quality Control of Welding.
- CHAPTER 3** : Literature Survey:
Flexible Robotic Welding Systems.
- CHAPTER 4** : Literature Survey:
Expert System for Automated Welding.
- CHAPTER 5** : Data Acquisition and Processing in the Pre-Weld Inspection Station.

- CHAPTER 6** : Knowledge Elicitation and Implementation for PIKBES.
CHAPTER 7 : Evaluation of PIKBES.
CHAPTER 8 : Further Work.
CHAPTER 9 : Discussions and Conclusions.

Chapter 1 discusses the background of this research as an extension of WRAPS project and the novelty in application of knowledge based expert system rules for adaptively control of welding procedures. **Chapter 2** deals with the methods by which the quality of welds are controlled prior to, during, or after the welding processes and then discusses the three control welding systems which are mainly used by manufacturers, i.e. closed loop feedback control of manual welding, and open loop control system and closed loop feedback or feedforward control of automated robotic welding system. **Chapter 3** deals with the literature survey of flexible welding robotic systems, welding robotics work handling, sensors used for robotic seam tracking , and with particular emphasis on limitations of current adaptive robotic welding systems, and the problem associated with the mathematical modelling for the control of welding procedures. **Chapter 4** discusses expert systems, a survey of their general applications, and gives particular emphasis on their application to automated welding systems. Finally PIKBES has been proposed to control quality of component joint prior to welding process. **Chapter 5** describes the hardware and software design consideration for the pre-weld inspection station. It also describes the pre-weld inspection station communication interface with the FWS conveyor, WRAPS supervisory system, and PIKBES via ring communication network (LAN). Methods and algorithms used for feature extraction and joint recognition are discussed. **Chapter 6** deals with knowledge elicitation, formulation and implementation of expert rules for PIKBES. This chapter describes the data management handling between PIKBES rules, joint parameters from the pre-weld inspection station, WRAPS supervisory system and data-base. Furthermore, 'window' and 'linear relationship' techniques to formulate and implement knowledge collected are discussed. **Chapter 7** discusses the assessment, testing and validation of the expert knowledge based rules for modification of welding procedures. The need to reassess knowledge acquired, to implement further knowledge and consequently to modify the rules base is also discussed. **Chapter 8** discusses the further work needed to be done for continuation and extension of this research particularly to a automatic post-weld inspection station and its knowledge base expert system controller (POKBES). **Chapter 9** provides an overall discussion of this research and draws specific and general conclusions.

CHAPTER 2:

Quality Control of Welding

CHAPTER 2 : QUALITY CONTROL OF WELDING

2.1 Introduction

The essential purpose of the research reported in this thesis is the provision of weld quality control in an automated flexible welding system. This chapter deals with the methods by which the quality of welds are controlled prior to, during or after the welding process, and then discusses the three control systems which are mainly used by manufacturers. The motivations behind quality assurance are discussed in the background to this chapter, section 2.2. Section 2.3 looks at the way in which a human welder uses his knowledge and his sensory feedback information system to control quality of the weld being produced. In section 2.4, robot welding systems with no sensory feedback (i.e. open control loop) together with their requirement for tighter control in joint fit-up, tolerances of component, design of component, jigs and fixtures, and welding procedures have been discussed. In section 2.5, further development of these welding systems equipped with feedback and/or feedforward sensing capability is discussed and extended to include the use of expert systems incorporating human skills and expert heuristic knowledge to enable them to be more intelligent and efficient.

2.2 Background

Over the past few years, demands for quality assurance in all areas of manufacturing industry have increased dramatically. In production welding, the term 'quality control' is refer to the quality of welded joint produced by either a manual welder or a machine such as an industrial robot. A weld is good if it meets all strength and aesthetic requirements placed on it by the customer and product application standards. The control of quality was, in the past, often thought of as a simple matter of final inspection, i.e. the acceptance or rejection of the finished product when assessed to a required standard. It is now accepted that quality must be designed and manufactured into a product, a welded joint being no exception. In this respect, an integral part of quality assurance in welding is the qualification of both the welding procedure, e.g. BS4870:part 1 [5] and the welder, e.g. BS4871 [6] and BS4872:part 1 [7], prior to commencement of production welding. In developing a welding procedure for any specific application, it is necessary to define the joint geometry and a set of welding conditions that produce an acceptable weld at the highest possible production rate with a tolerance on each parameter that can be reasonably maintained.

Joint geometry features include root gap (RG), root face thickness (RFT), bevel angles (BV), etc. The welding conditions are the position and orientation of the welding torch relative to the joint, the voltage and current of the welding power supply and its internal characteristics, the filler wire feedrate, and the traverse speed of the welding torch. The type and size of the filler wire and the shielding gas composition might also be varied. The quality criteria that must be satisfied are the penetration of the weld, the subsequent mechanical and metallurgical properties of the joint, and the shape of the weld bead. In addition a number of defects must be avoided such as cracking or tearing in the weld or heat-affected zone, porosity in the weld, slag inclusions, or lack of fusion. Assuming that the welding conditions have been correctly chosen to avoid metallurgical defects then the most likely source of trouble in reproducing welding conditions is an error in the torch position relative to the joint. In manual welding this is dependent on welder skill. In automated welding such errors can easily happen as a result of variation in joint parameters (e.g. RG, RFT, BV, etc), poor initial fit-up or by thermal distortion of the workpiece as well as errors in set-up, fixtures or programming. Thus the first way in which feedback control assists automatic robotic welding is to control the torch position relative to the joint, and there are many methods by which such seam tracking can be achieved. To accommodate joint variations by modifying the welding procedure requires more complex systems of adaptive control, for example, direct optical monitoring of the penetration of the weld pool at the under side of the joint can be used to control the welding power input. Other methods that may be used to control the quality of weld include; spectrum analysis of the acoustic emission from the welding process, and direct observation of the size and shape of the weld pool from the top, or weld pool perturbations.

2.3 Close Loop Feedback Control of Manual Welding

A manual welder brings many qualities to the task of arc welding. He is capable of recognising and inspecting components prior to welding, recording any defects in assembly and faults requiring rectification or special attention during welding. He can orientate the components in the best position for welding and can position himself so as to gain best access to the seam. During the welding process, the welder gathers information about the process with his visual and auditory senses, and after welding the quality of weld produced will add to the experience and learning of the welder for future work. Fig 2.1 shows how the welder is the most important part in the closed loop control of welding. He continually observes the weld puddle in order to control the penetration, and he also observes the geometry of the joint preparation to keep the electrode always in the correct position in relation to the weld seam. While watching

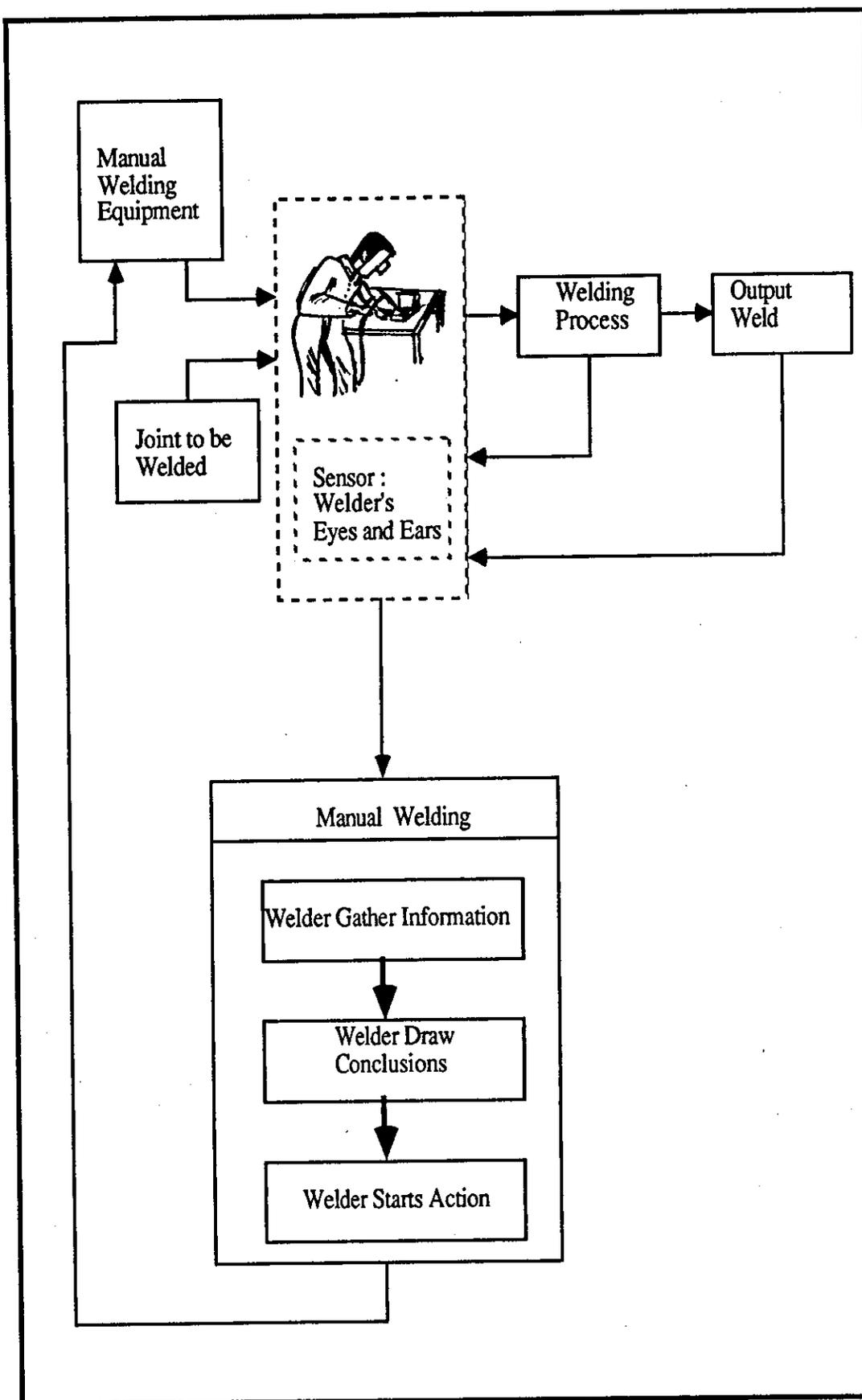


Fig (2.1) - Closed loop feedback control of the manual welding.

the arc and listening to the sound the arc emits, he is able to control the metal transfer. He gathers information during welding and with his knowledge, he draws conclusions and immediately performs necessary corrective actions. The more advanced the knowledge of the welder is, the more problems he can solve and the more corrective actions he can take, i.e. the more difficult work he can tackle.

2.3.1 Welder Approval

As the skill of the welder is a the major controlling factor in final joint quality, adequate welder training is essential if consistent quality is to be achieved. It is common practice to test and prequalify the welder to a specified standard such as BS4872:part 1 [7] which covers a range of applications.

2.4 Open Loop Control of Automated Robotic Welding System

In open loop flexible automated welding systems, the welding robot emulates a manual welder which is regarded as being blind, deaf and dumb, but capable of positioning a welding torch accurately and anywhere within the area of its working envelope. Such accuracy can, moreover, be repeated unerringly, a feat not achievable by the average manual welder. Complications arise, however, if the workpiece and fixtures do not have the same parameters of accuracy, since the welding robot cannot detect these. Repeatable accuracy in the production of piece parts is therefore an important part of these systems. Wadsworth et al [8] have investigated the importance of component repeatability and product design in an open loop robotic welding system and have shown that in industrial practice the repeatability of piece parts dimensions may well be outside the acceptable limits for successful open loop robotic welding system. However, improvement in manufacturing methods can permit successful implementation of sensorless robot welding cell, and many practitioners claim that this is the best approach since it can lead to improved overall product quality and manufacturing performance. During the welding process a sensorless robot, unlike the human welder, is unable to position the welding torch correctly should it deviate from the seam centre line, nor can it compensate for any variation in the joint geometry. Fig 2.2(a), shows the open loop robot welding system with no feedback quality control system. Such limitation of robotic welding system imposes a series of conditions on the designer and user of the installation in order to achieve a satisfactory quality in the weld. These conditions fall into four parts: those associated with the tolerances of components, those associated with the design of component, those associated with the

jigs and fixturing to hold the component while welding is carried out and the repeatability of the robot and any work manipulator.

2.4.1 Components Tolerance

The general levels of tolerance associated with components, while acceptable for manual welding, cannot sustain robot welding. Parts produced from inaccurate or worn press tools, forming or other production processes which result in a wide range of component tolerances and finish, provide the 'blind' robot with a problem of compensation. In order to function well, such a robot must be able to assume that the weld line it is required to follow will be in the same place each time; that parts are produced accurately; that the fit-up of the components is acceptable; and that access to the welding position is possible. Pearson [9] has considered two fundamental laws of robotic MIG welding in open loop system from his practical experience point of view as:

- i) Make sure that the weld joint line is always positioned within half the diameter of the wire being used.
- ii) Make sure that the joint fit-up is always consistent and within the realms of the practical welding techniques.

Moreover, The properties of mild steel may change with time and conditions of storage [10], resulting in a hardening of the steel as time passes. The resulting variation in the hardness will cause variations in the amount of springback that occurs during pressing operations, and thus variations in the final shape of the pressing. Such problem can be reduced by improving stock control, introducing annealing plant, etc. Furthermore, the press dies can be compensated for springback by bending parts to a smaller radius of curvature than desired. The final point with respect to tolerances of component when dealing with open loop automated systems, is that the labour force traditionally handle components roughly. This can result in distortion and hence a loss of accuracy. Although this may be acceptable from human welder point of view, it may be rejected in open loop robot welding systems.

2.4.2 Components Design

When designing a component in an open loop robotic welding system, it requires closer than normal collaboration between designer and production engineer.

The basic principles of design in these systems are broadly similar to those of manual welding in terms of weld size, access and distortion control [11,12], although certain aspects assume greater importance and there may be additional factors to consider. Closer specification of manufacturing procedures and requirements by the designer may well be necessary. Middle [13] has reported that the application of these robots to arc welding may require radical changes in design and manufacturing specifications at not inconsiderable cost, but these costs must be measured relative to the overall improvement in productivity of the welding process and the product itself.

2.4.2.1 Process Tolerance

When designing a component for an open loop robotic welding system, the primary requirement is recognised as; the weld process tolerances (related to the need to satisfy quality standards) should be greater than or equal to the combined errors associated with positioning and orientation of the arc and the variability in joint fit-up. It is argued by Middle [13] that rules of thumb, such as the weld joint line should always be positioned within $\pm 1/2$ electrode wire diameter [10], can grossly under or overestimate the actual tolerances of a procedure. It is important in optimising open loop robotic systems to attempt to maximise and to quantify process tolerance.

2.4.2.2 Closer Dimensional Specification

When dealing with open loop robot welding during the designing stage, a closer control of parts and assembly dimensions than is normally specified for manual welding is required, but this can often be achieved at little cost. Tighter quality control, improved machine maintenance or changed assembly tooling methods may be needed. For example, closer control of shearing machine settings or process parameters in thermal cutting may provide significant improvements. Tighter design tolerances can improve quality assurance. If stricter dimensional specification and control of parts are required, more accurate processing such as CNC plasma cutting underwater instead of optical cutting with oxy-gas, or machined edge preparations may be needed.

2.4.3 Jigs and Fixtures

All assembly or sub-assembly jigs used in the open loop automated welding system require closer tolerances to control the quality of weld being produced.

However, in some applications this has been shown to be impractical, as with the chassis assembly system at Land Rover [14]. In this example, distortion caused by the welding operation led to jamming of various components within the jigs. The problem has been solved by a combination of improvements to the quality of pressed components and a relaxation of jig locations. The important issue is that tolerances must be determined not only by the required quality of the end product, but also by the capability of the process itself. Clocksin et al [10] have discussed the feasibility of using robots as open or close loop welding systems, and have carried out research into two methods: i) Conventional first-generation robots 'without sensors', but with reduced dimensional variation by using different types of press dies, improving jiggling and transportation, and providing extra quality control. ii) Development of a robot that used sensors to find the correct starting and ending points of each weld seam and to track the location of the seam as it was welded. Weaving of the welding torch and appropriate changes in weld parameters was introduced automatically to accommodate any variations sensed in the gap width. Clocksin concluded that it was much cheaper to equip a robot with sensor-based adaptive control, than it was to reduce dimensional variations. Although such statement may be correct for some applications, it does not consider advantages that may be gained in overall product quality improvement through attention to product design and manufacture for the open loop method. Dersin [15] from Ford Motor Company also concluded that with an open loop control method, weld quality cannot be guaranteed with the same degree of certainty. Numerous rewelds have to be performed which has been found to be costly. Furthermore, in order to increase quality and safety with the open loop control method, one is forced to build safety margins into the process by adding pre-weld and post-weld inspection to the system which might have the effect of lengthening cycle time. Finally, the open loop control method imposes a trade-off between line efficiency (throughput), product quality and cost.

2.5 Closed Loop Feedback or Feedforward Control of Automated Robotic Welding System

As discussed in open loop automated robotic welding systems (section 2.4), the welding robots are regarded as blind, deaf, and dumb. However, development of sensors enable these robots to be used more effectively in their manufacturing operations. Sensors form part of a close loop quality control feedback system, fig 2.2(b), and enable the robots to control its welding operation by monitoring the weld pool and/or variation in the joint gap. The application of these sensors in feedforward control systems, provides the robot with an early warning of the variation in joint

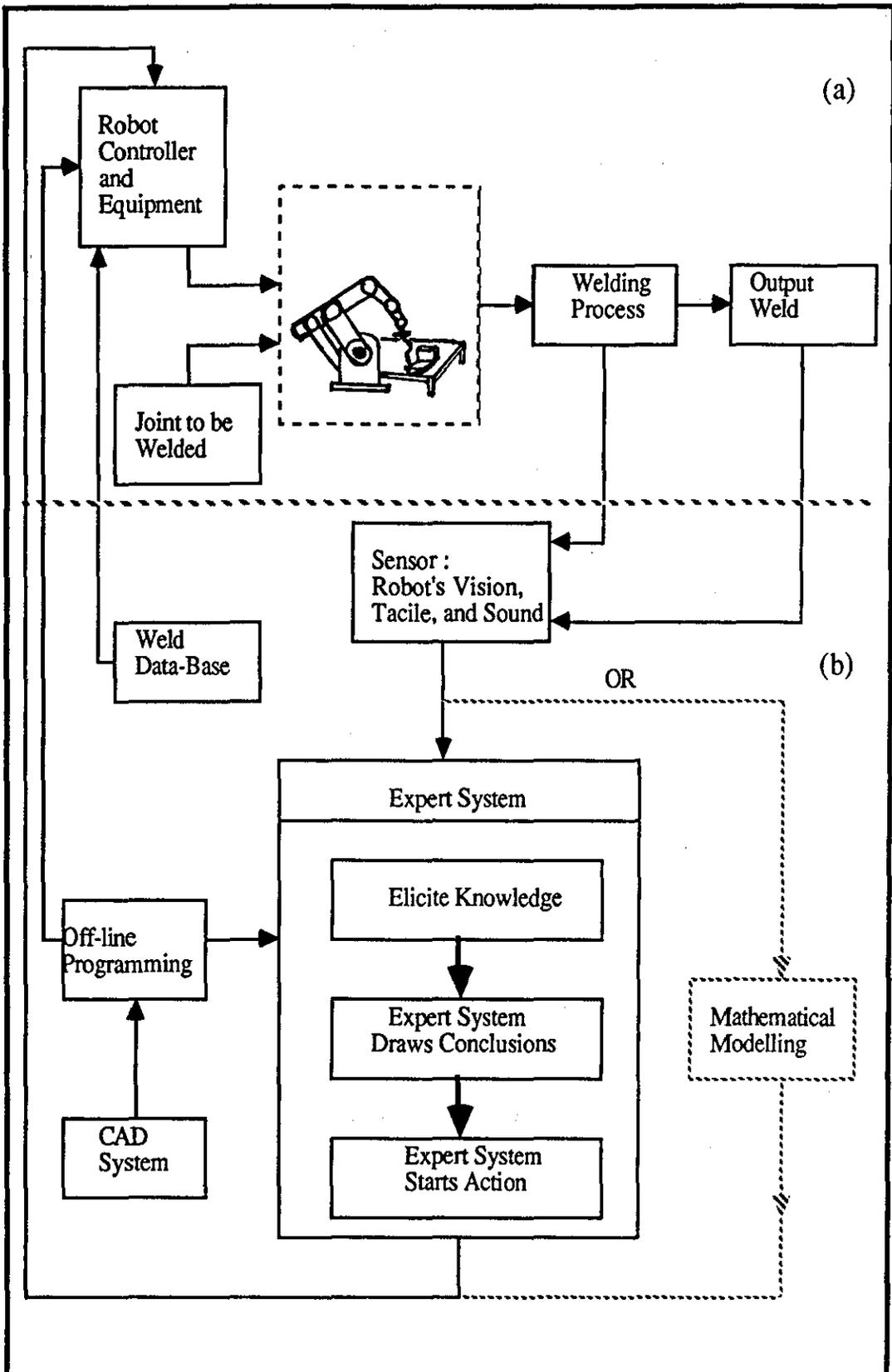


Fig (2.2) - Flexible robotic welding system, (a) - Open loop control system,
(b) - Closed loop feedback control combine with feedforward.

geometry prior to the welding process. That is, disturbances (joint variations) are measured and compensated for before they have upset the process. In-process sensory feedback information (e.g. weld penetration) is used to monitor the welding process and adjust the welding parameters so that an optimum weld bead is achieved. Finally, in post-weld inspection the feedback of sensor information is from the finished weld bead quality. In this case, time lag effects have to be catered for. Each of these three methods traditionally require a mathematical process model [3]. However, robots can be provided with a measure of the skill of a human welder and knowledge of the human welding expert by storing knowledge about different welding process(es) in a knowledge base and manipulating it in an expert system.

2.5.1 Design to Assist Sensors

Adaptive control and seam following together emulate most aspects of the manual welder's control ability and, where they are technically and economically viable, give greater freedom for functional design. The extent to which this is true will, of course, depend on the limits of adaptivity of the robot control system. Design of joint to permit the use of the specific sensing system may be an important consideration as is described in reference [13].

2.5.2 Expert Systems in Welding Quality Control

As welding is a complex manufacturing process, a welder must be trained very intensively to decide how to control the quality of the weld in-process. He must learn not only how to position and move the electrode correctly in relation to the seam and know the parameters for a given task, but his most important task is to react appropriately when unexpected variations occur. For example, if the preparation geometry changes due to tolerances, the process may become unstable or discontinuities occur in the weld. The welder must react immediately to correct these problems. This ability to maintain permanent feedback control, based on his experience, puts the human welder far beyond any machine. Today, by means of artificial intelligence, one can reduce the gap between a human welder and a machine. Further application of artificial intelligence to robotic arc welding, has enabled the dumb robots to be more intelligent, make decisions and provide reasoning for their action. A significant amount of experience and data on how to join similar or dissimilar materials has been gathered over the years. This may be programmed and maintained in a knowledge base of an expert system. Despite the mental capacity of the human

welder and his ability to adaptively control the process, he has a number of limitations. The manual welder is affected by fatigue and loss of concentration and possibly limited memory. Response to deviations from the norm may not be rapid or consistent. A computer based system of sensor and mathematical model or expert system, given adequate computing power, has none of these limitations. On the other hand, capturing large volumes of expert knowledge accurately within a computer program is a very difficult task, but once done such a system will perform consistently. Developing mathematical models for adaptive control is a costly and lengthy process, and they are generally joint specific [3]. There is a need for more generalised modelling [13]. Expert systems are a consequence of such a requirement since they have the ability to handle non-mathematical models. The application of an expert system to a pre-weld inspection station (PIKBES), the subject of this research has shown significant time and cost can be saved compared to traditional mathematical modelling techniques.

CHAPTER 3:

Literature Survey :
Flexible Robotic Welding Systems

CHAPTER 3 : LITERATURE SURVEY : FLEXIBLE ROBOTIC WELDING SYSTEMS

3.1 Introduction

The background and motivation for the application of sensory systems to an automated flexible robotic welding system is given in section 3.2 of this chapter, while section 3.3 concerns the general literature survey into flexible welding system to which this research is targeted. The survey investigates the application of Computer Integrated Manufacturing (CIM) concept to increase communication between a robot control unit and other factory computer control levels e.g. Computer Aided Design/ Manufacturing (CAD/CAM), off-line programming and simulation, and Computer Aided Process Planning (CAPP). Different software packages and their application are discussed. WRAPS off-line programming and simulation package (the overall system core of this research) has been discussed in detail together with its requirements for design and development of the pre-weld inspection station and its knowledge based expert system (PIKBES). Section 3.4 investigates different sensing techniques typically used for seam tracking and adaptive control and their advantages and disadvantages. Consideration of the application of commercially available sensor systems for providing feedforward control data in the pre-weld inspection station which has been developed are covered in section 3.5. Section 3.6 investigates robotic arc welding systems with adaptive process control and the approaches taken in development of mathematical modelling and selection of welding procedures. Furthermore, in section 3.7, the limitation of current adaptive process control systems are investigated.

3.2 Background

Over the past few years industrial robot system have incorporated sensors to improve reliability and quality in the manufacturing of parts. These sensors form part of a close loop system and in the case of welding, are able to provide information for the adjustment of such parameters as welding torch position, velocity, etc. In a welding system, the function of joint tracking sensors are both to find the position of the joint to be welded, and to detect and correct for any misalignment of the seam relative to the robot pre-taught position by adjusting the robot arm and welding torch position to the correct position relative to the joint. However, simple corrections to the

welding path alone are not sufficient for a truly automated welding system. The initially selected welding procedures (such as voltage, wire feed speed, travel speed, torch position and orientation in the joint, etc.) also need to be modified in order to compensate for variation in the joint geometry (e.g. root gap, root face thickness, bevel angles, and joint area). These variations are due to manufacturing tolerances, e.g. component and edge preparation tolerances, cutting and forming, etc, and are compounded with the inaccuracies in fit-up of assemblies due to errors in fixtures, distortion due to tacking, and so forth. Furthermore, in-process thermal distortions can cause a significant movement in the seam during welding. Such variations in the joint geometry can affect the aesthetic and mechanical strength qualities of the completed welds. These causal variations can be partly controlled by improving manufacturing capability and control so that components with closer tolerances are produced and more complex and accurate fixtures are used. They may also be controlled by modification of welding parameters during welding process to take account of the variation in joint position and fit-up. Hence, two fields of adaptive control systems have emerged for the flexible automated welding cell in this research. Firstly, a laser based sensor system which collects information about the joint geometry, e.g. root gap, root face thickness, bevel angle, misalignment, joint area, etc. Secondly, using this information, a system to control welding parameters (voltage(V), Wire Feed Speed (WFS), Torch Speed (TS), Weave Pattern (WP), Weave Frequency (WF), etc.) and compensate for any variations detected in the joint geometry relative to nominal, and achieve optimum weld bead quality. The mathematical modelling approach and the techniques used to determine optimum welding procedures have been surveyed in details in section 3.6 together with their limitations, section 3.7. The author has realised that such approaches are rarely cost effective as they require :

- 1) Extensive empirical experimentation and analysis of a large amount of data,
- 2) Considerable time and cost in the development of the models,
- 3) Mathematical models also tend to have little generality.

Therefore, in this research, the adaptive control of welding parameters is achieved through a non-mathematical knowledge based expert system which can be implemented effectively and in relatively short time.

3.3 Flexible Welding Systems (FWS)

Recent advances in robotic technology have been directed at increasing the flexibility of robot stations by combining robots and work handling facilities in what

can be considered as self-contained manufacturing cells. In such systems robot(s) may be statically mounted, with the work on pallets fed to the welding station by conveyor [16,17,23] or surrounded by fixed stations or manipulators [17-19]. Alternatively they may be mounted dynamically on a track [20], or gantry with the component on fixed stations or using manipulator(s) [18]. Where these welding robots are part of a cell or production line their activities are coordinated and controlled (using the digital and analogue inputs and outputs or other devices such as PLC's) with surrounding equipment such as workpiece positioners, welding power supplies, fixture clamps, sensors, gate interlocks and safety mats. The Computer Integrated Manufacturing (CIM) concept [21] is used to increase communication between robot control units and higher levels of factory control hierarchy, e.g. Computer Aided Process Planning (CAPP) [22,24], Computer Aided Design/ Manufacturing (CAD/CAM) and simulation together with off-line programming [24,26-31]. Computer Aided Process Planning (CAPP) may be added to the system to generate the operation sequence based on input data relative to the workpart and rely on two prerequisites; 1) some form of parts classification and coding system, 2) standard process plans for the part families produced by the plant. By employing computer application tools in process planning the following advantages can be obtained; 1) improved planning, 2) reduction of costs due to better control, 3) selection of optimal production equipment, 4) possible errors are limited due to database function, 5) less routine work and less overlap between different operations. In welding, CAPP tends to be restricted to retrieval and design of welding procedures and such systems can be interfaced with other features of computer integrated manufacturing. Computer Aided Process Selection has also been shown to be viable [32,33]. CAD/CAM systems may be used to model (using 3D wire-frame or solid modelling) and simulate the activities of automated robot cells.

Robots may be 'on-line' programmed using keys on the hand-held teach pendant and a keyboard on the robot system controller. This can be hazardous for the operator during programming of the robot and is not a very efficient and flexible way to program the robot. In contrast to on-line' programming, 'off-line' programming may be carried out from a terminal away from the production line using a computer which converts user's instructions into a format which the robot controller can execute. In this way, a robot program is developed and checked in the computer before it is transmitted to the robot. Two approaches are adapted; textual programming [25] using languages such as AL, VAL, RAIL, AML, HELP, etc. and graphical simulation using packages such as CATIA (from IBM), ROBCAD (from Oshap) [27], ROBOSIM (from Calma) [28], GRASP (from BYG) [29], CimStation (from SILMA) [31], WRAPS (developed at Loughborough University) from which this research arises [1,24], etc. Simulation programming of the system is carried out to assess the

ability of alternative types of robots to meet the requirements associated with a particular application, to check for any collision within the working area, to reduce time during teaching, improve productivity and quality, etc. In robot welding operations, off-line programming and simulation before hand ensures that the programming of the robots, welding sets and handling operations are compatible and fully integrated. In these systems, there can be no exact matching of the 'off-line' modelled program to that of a real situation due to many contributing factor such as; temperature effects, relative positioning errors between robot and component fixtures, accumulative error in the robot joints, etc. Hence, sensory systems [24,26,28] (section 3.4 has discussed a detail survey of sensing method uses in flexible welding cells) may still required to provide corrective action between modelled environments and real world situation. Such corrective action requires a mathematical model or a non-mathematical model expert system of the process so that any variation in the joint geometry can be compensated. Section 3.6 discusses a detailed survey of mathematical modelling, whereas chapter 6 discusses knowledge elicitation and its formulation into the form of non- mathematical models for the pre-weld inspection station in this research. Database and/or knowledge based expert systems have been applied to store knowledge about particular domains, for example, welding procedure selection [24]. However, database applications are limited by their inability to make decisions and to deal with uncertain data. Information about particular problems can not be solved and no conclusions can be drawn. This also applies to conventional computer programs. In contrast to databases, expert systems are used to deal with such limitations. Chapter 4 discusses the general field of knowledge base expert systems and their application to automated welding for welding procedure selection, design, and optimisation.

A number of flexible welding systems have been reported [14,16-24]. A flexible robotic mechanised welding systems is installed at LYCAB by Torsteknik [16] in order to automate welding of car exhausts system, fig 3.1. Prior to this, joining of the complete exhaust system was carried out by manual arc welding or by machines with sets of tooling dedicated to specific models to provide accurately and complicated bend configuration and joint preparation. With the introduction of the new fully automated system (using a computer controlled materials handling store with 51 locations, a pallet transport system, two motoman L106 welding robots each with six axes, and two servo-driven manipulators), the system is able to store up to 249 different tasks in its controller's memory. Several different assemblies are manufactured during a week's production, different jobs are recalled from memory in seconds, sub-assemblies are accurately and consistently produced (resulting in better fit-up and lower scrap rate), and material flow is increased and work in-process is reduced. As the pallet of work arrives at one of the robot workstations a proximity

sensor attached to the pallet and programmed with part number and quantity, sends a signal back to the robot controller which then selects from memory the appropriate program for the component to be welded. Welding parameters and quantity of components welded are continuously monitored during the 24hr operation on two shift.

At Land Rover, an automated flexible welding system was installed [14] for the manufacture of chassis assemblies and to provide improved welding quality compare to manual welding. The system consists of twelve arc welding robots integrated with conveyor and assembly fixtures, fig 3.2. Consideration of component tolerances and assembly fit up was carried out in order to assure proper weld penetration and weld quality. The quality and handling of pressed components was improved and relaxation allowed in the jig. In programming of the system, allowance for robots to be stopped has been considered (e.g. during emergency or stops in mid-work) without always shutting down the whole system. Simulation of the whole automated system was performed to ensure that programming of the robots, welding sets and handling operations are compatible and fully integrated. The safety requirements for personnel and robots, and an area to carry out manual rectification of weld defects caused by faults in the automated welding process, have also been considered in the design of the system. The feasibility of a seam tracking vision system was to be considered for the system.

Perkkeri [17] has described three flexible welding systems which have been installed. In the first system described, fig 3.3(a), The unmanned welding station consists of a welding robot and an ORBIT 500 servo-driven manipulator with components presented on conveyers in turn fed by an automatic intelligent truck which is able to serve several welding stations. The overall supervisory control of the station is performed through the robot controller which also enables the truck to be called up for changing the welding pallets as needed. The welding pallet presented at the station, is lifted to the level of the manipulator and is clamped automatically. At the completion of the welding operation by the robot, the pallet is lifted again and placed on the discharge conveyor. The truck is able to store 150 pallet positions for different operations. The service operation of the system is based on the First In/First Out (FIFO) rule with cycling times of between 6 and 45 minutes. The second system demonstrated is similar and comprises of a four-axes ORBIT manipulator and a robot, fig 3.3(b). The welding pallets are fed to the work station by an input conveyor. At the arrival of a pallet, the pallet is picked up, rotated, and placed beneath the robot for welding. On completion of welding, the pallet is then placed on an output discharge

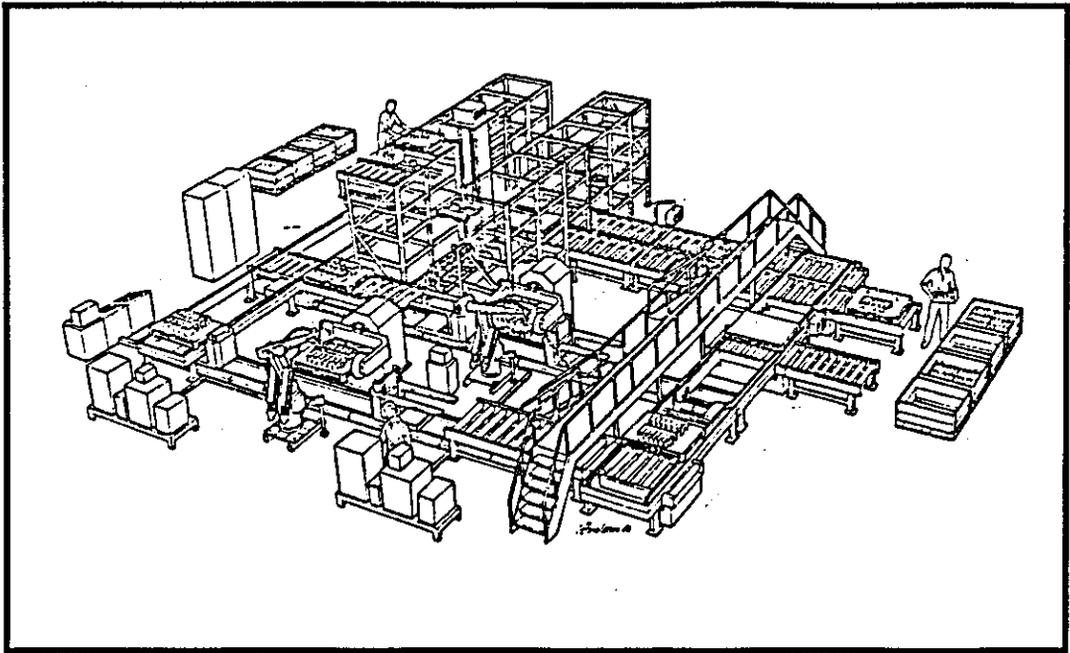


Fig (3.1) - Flexible manufacturing system installed at LYCAB incorporating robotic welding and automated handling [16].

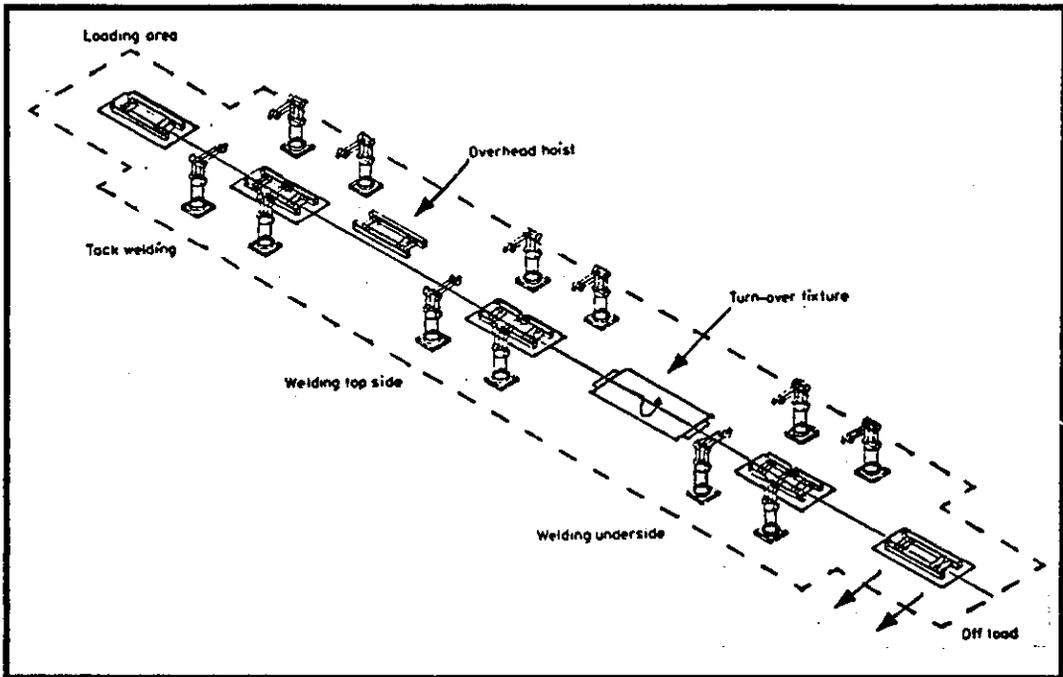
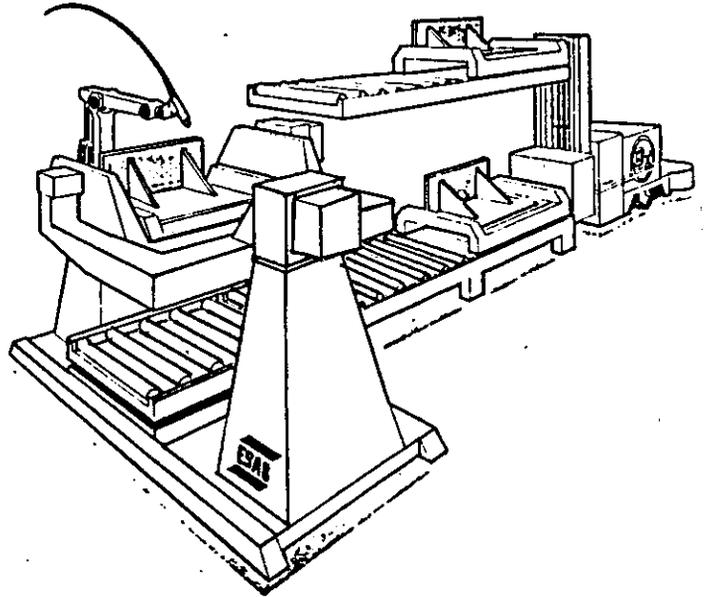
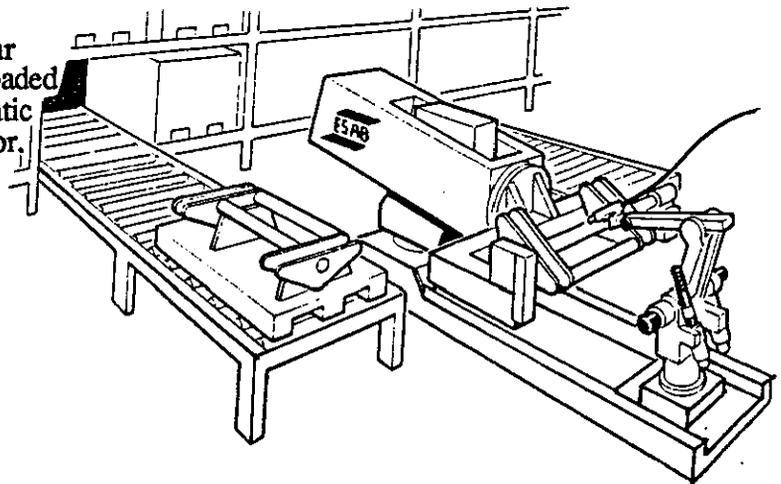


Fig (3.2) - Chasis auto welding line [14].

- (a) - FMS installation with an ORBIT manipulator loaded and unloaded by an AGV via buffers.



- (b) - FMS installation with a four axis ORBIT manipulator loaded and unloaded by an automatic stacker crane via a conveyor.



- (c) - Unmanned FMS installation based on ORBIT with AGV.

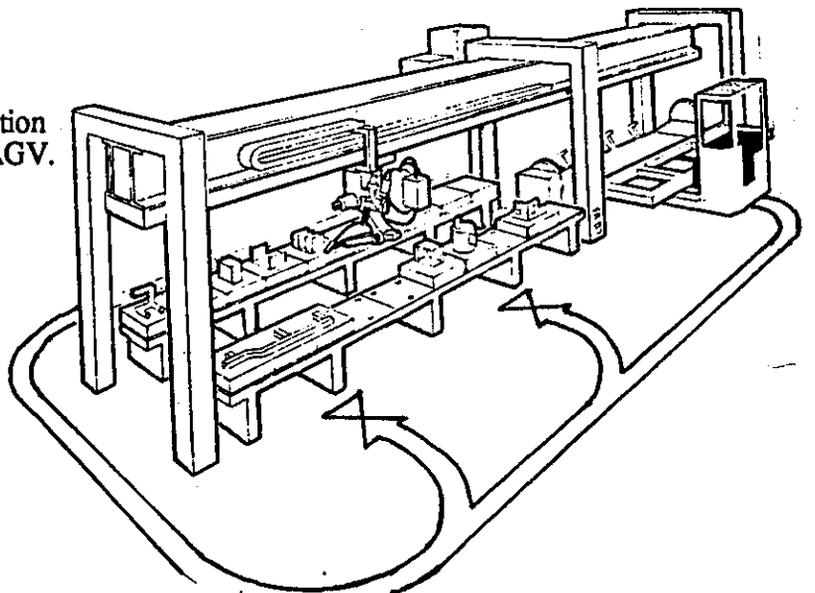


Fig (3.3) - Shows three typical FMS system installed with an ORBIT manipulator [18].

conveyor. The third and more complex system involves a gantry, with robot suspended from an overhead track and able to serve 20 work positions, an AGV loading multiple fixed work stations, and an orbit manipulator, fig 3.3(c). The cell operates for 22 hours per day in three shifts, two of which are unmanned. This welding system has drastically reduced both stock and work in-process.

Smith [18] has reported a flexible welding system consisting of three robots and manipulators together with a manual tack welding station, welding power supplies of 500A, a component transfer carriage, and a central supervising controller. The robots were overhead X and Y cartesian type each capable of detecting component weld joint start positions up to 20mm away from the programmed location, using 400Vac signal applied to the welding wire, and with in-process seam tracking. The manipulators are the 'L' type with two axes of motion and are fully integrated with the robot 16-bit controller. They are able to handle components between 2m and 3.4m long and mass from 296 to 1160kg. Components loading to and from manipulator were done by the conveyor carriage with the speed of 120 m/min between storage. A central controller allow up to 108 different component to be selected automatically and is used to process information on scheduling, tacked components, and availability of the cell robots for loading /unloading. It is reported that the company achieved many benefit from this system, such as; 28% saving in cost, 25% reduction in personnel, and 15% reduction in the number of equipments employed. In addition to these, quality has been improved and workers have been freed to undertake more critical welding task.

A flexible robotic arc welding system has been described by Wilkins [19] for welding seat frames and automotive subframe assemblies. The whole welding system uses two Motoman L10 arc welding robots. One of the robots is used for a variety of different assemblies (in a low production volume) whereas the other is used for large volumes of only one type of component. In case (i), the cell consists of two sub-assembly and one assembly work stations. Station one and three are respectively used for the seat back and the seat base, and station two is used to assemble the completed components from station one and three. Each weld station is operated from its own load/unload door and controlled with a PLC via the robot controller. Approximately 20 minutes is taken to change the fixture at any one station. This is done while the other two stations were in operation and the robot interrupted for only 3-5 minutes. The system operation time for three stations is 133 secs (with average output of 27 complete assemblies per hour for 20 different seat frame designs). In case (ii), three robot cells were in operation. Each cell consisted of a Motoman L10 robot with a 180 degrees index turntable station. All three robot welding stations working 20 hours a day, were implemented to satisfy the desired output of 5000 pieces a week.

The operators load/unload the components into the fixture, an electronic sensor is used to ensure that the components are correctly located before welding begins. The implemented system has shown that the quality of produced components and productivity have both increased, and man machine interaction is considerably reduced.

Boulton [22] has described an approach which should be taken to integrate a robotic welding system into a FMS. Four computer controlled levels within an automated factory hierarchy are considered to perform the planning, scheduling, stock control and coordinating functions at the factory, cell and machine levels. The robot may be equipped with tactile, part position, or laser Seampilot or MetaTorch sensing devices to provide welding torch positional information and to track the seam during the welding operation. The sequence of operation in an automated factory system is described as follows; orders received from customers are used by production engineers to generate master scheduling and production information using the factory mainframe computer (level 4), The information held in the computer at level 4 is then used; i) to design the component and to generate program and part data (e.g. the weld path around a joint) using a CAD/CAM system which can then be transferred to robot (and/or other devices) to form the weld path and relevant positioning coordinates, ii) to access factory controller scheduling system, and finally to simulate the effects of the workload on the cells which then schedules the relevant cell processes, activities, and priorities (level 3). The detailed information of the parts, process data and commands for the factory Process Management System (PMS) or cell controllers are performed at level 2. These controllers perform the relative scheduling and control of the equipment to enable tasks to be carried out on the parts at the machine control level (level 1). The machinery, robots, welding equipment perform the tasks as instructed and return a 'process complete' message.

A flexible and productive MIG welding system developed by Westwood Engineering [23] can accept short runs of a variety of workpieces. The system was developed for the manufacture of parts for garden tractors and it consists of a Fanuc S100 MIG welding robot and its control units, and 10m long conveyor, having two tier roller system together with its control unit. The robot controller can store up to 32 programs in its memory. Hence, after programming it can weld any mix of 32 different components without resetting the system each time. To extend the potential for automatic operation a 'cassette' storage system has been developed to increase the number of loaded pallets that can be held in the system. Sequential control of the operation of conveyor and associated robots is provided by a PLC (Programmable Logic Controller) interfaced to the robot controllers. Control of the welding equipment

is by I/O signal from the robot controller. Work pallets are identified by proximity sensors and a five hole code system on the pallet sides. The loading and unloading of the pallet is carried out on the top tier of the conveyor whereas the bottom tier is used for feeding or storing full pallets. The accuracy of pallet location at the welding station is claimed to be 0.05mm. It is claimed that this integrated system is capable of achieving up to 90% welding time. A development of the Westwood system is reported by Middle and Goh [24] and is also used in this research. This is discussed in detail in section 3.3.2 of this chapter.

3.3.1 Graphical Simulation and Off-line Programming of Systems

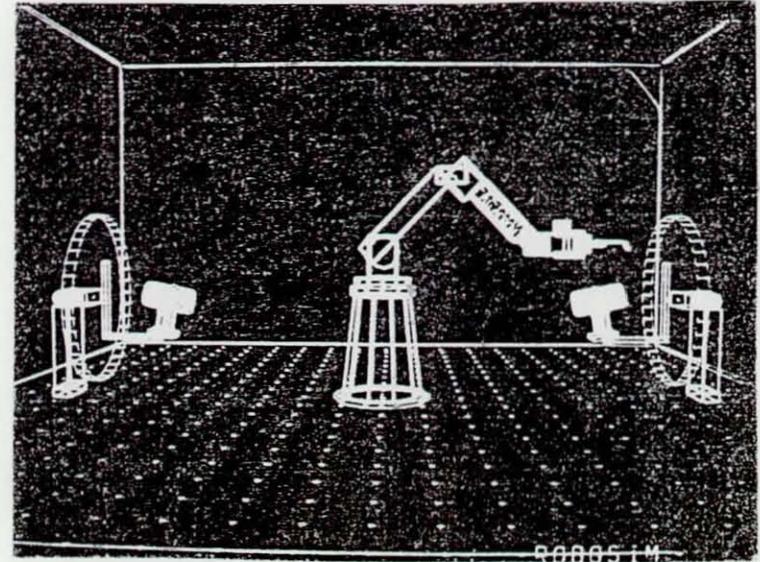
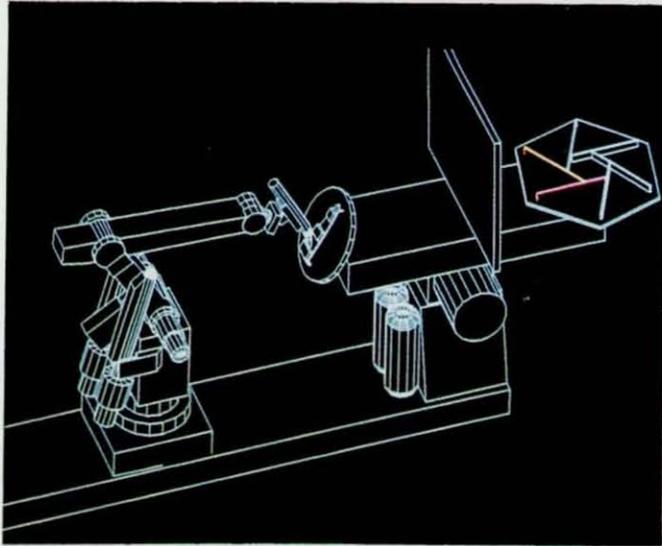
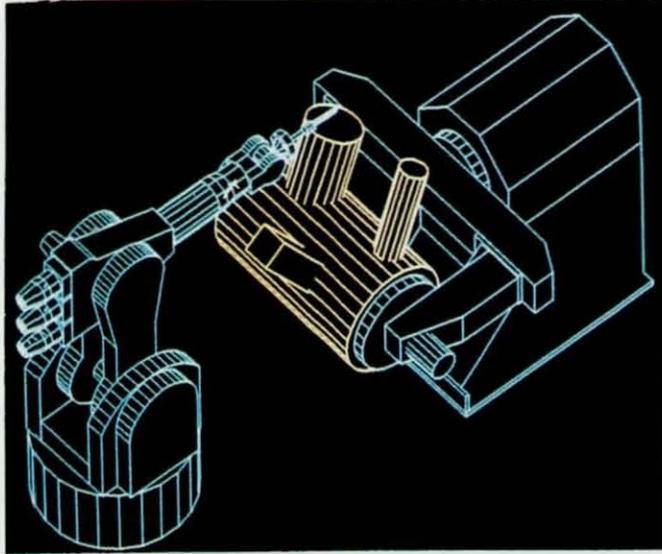
Several software packages [26-31] have been developed for interactive computer graphics (CAD/CAM) in simulation systems which are capable of depicting 3D models and animation of the work cell and assembly lines, and testing event control signals. These packages use mathematical modelling of the serial linkage of the robot arm joints and creates 3D representation of the robot or workcell from geometrical data. Widfeldt [26] reported the application of such a system and its use for off-line programming in a flexible welding system. A CAD/CAM system was implemented in the design and generation of robot programs off-line which was then transferred to the robot control unit. In this way, robot unproductive down-time is reduced within the welding system.

The limitations and delays in the welding system (e.g. breakdown, lack of welding objects, programming) are studied for similar robotic welding systems by two advanced companies, Torsteknik and ESAB [30]. Three different methods for off-line programming were considered ; Alpha-numeric programming based on ARLA (Asea Robot LAnguage) is used to learn some reference positions and tool angles, together with computervision CAD/CAM system for graphical, simulation and programming support (Robographix). Typical graphical simulation and off-line programming for a KUKA IR 160/15 robot and Torsteknik MT1 manipulator are shown in fig 3.4 (a), whereas fig 3.4 (b) shows this for ESAB MHS 150 manipulator and ESAB IRb 6/2 robot. The Tool Centre Line (TCL) representing the weld gun, position coordinates and tool angles are graphically designed and extracted from the CAD system. A MWC (Magnetic Wave Control) inductive seam tracking sensor is used to simplify off-line programming and adjust the difference between the program and real objects. Two different kinds of corrections were made: corrections of an entire program by searching three reference points on the workpiece to establish their actual location compared to the taught points, or corrections of a part of a program due to

dimensional variation which necessitate the seam tracking system.

The practical applications and benefits gained from using computer simulations and off-line programming at the Danish Welding Institute have been described by Christensen [27]. The CATIA CAD/CAM system is used which includes a ROBCAD simulation and off-line programming package and Silicon Graphics hardware. The CATIA CAD/CAM systems consists of 3D-design, solids, surface, advanced surface and wire frame modules, and is capable of sectional views and projections of the models. It contains different modules, such as a robot module, with which the user can define specific robot types, produced data for controlling the robot, etc. The CATIA database contains library functions and data can be transferred to other CAD/CAM systems such as CAEDS (Computer Aided Engineering Design System) and CADAM (Computer-graphics Augmented Design And Manufacturing system). The ROBCAD system is used as a stand alone system designed for simulation and off-line programming of robots. Such systems are used for analysis and programming of new and existing production cells where advantages are realised such as improved quality and productivity, better and more optimised programs, easier-to-change programs, reduction of cycle time by about 25-50% when compared with conventional teach-in programming. The risk of damaging high cost production equipment during run-in, etc. is also reduced. Such systems are limited in usage where complex robot movements in connection with arc welding is involved.

Cook [28] reported the development of a robot simulation system ROBOSIM at National Aeronautics and Space Administration (NASA). The ROBOSIM system is applied to automated robotic welding and contains a data bank of geometrical primitives (i.e. 3D wire frame models of cylinders, cuboids, spheres,etc) which can be combined to form any robot configuration, fig 3.4(c). The system is able to construct wire-frame models of torch, torch mount, fixturing and tooling equipment (e.g. robot manipulator, work positioner) and also of the part to be welded. The system is used for planning, evaluating, and programming and includes several features such as; 1) collision detection, 2) flexibility of view point specification, and 3) generation of digitised views. Planning is carried out to determined the best orientation of the part relative to the robot and worktable, aid fixture design, and to investigate different robot and positioner configurations, etc. A real-time graphics display of the modelled welding operation is produced on the display interface terminal for system evaluation and enabling cycle times and welding costs to be estimated. Programming is done by the generation off-line of entire-path programs which can then be downloaded to the robot and positioner controllers. The system is also capable



Top left : Robographix simulator [30].
KUKA IR 160/15 robot and Torsteknik MT1 manipulator
in simulated welding of a boiler component. Hidden lines
are removed for clarity and improved three-dimensional
representation.

Bottom left : Robographix simulator [30].
Image with hidden lines removed of ESAB MHS 150
manipulator and ESAB IRb/62 robot in simulation weld-
ing trial components to assess feasibility of proposed
works: a) manipulator in first trial; b) manipulator
reversed.

Top right : Typical display of simulated MIG gate valve welder
from ROBOSIM package [28].

Fig (3.4) - Example of graphical simulation and off-line programming of systems.

of determining the optimum angular position of the turntable for best weld pool control and evaluating the positioning requirements of the through-the-arc sensing system.

The GRASP (Graphical Robot Applications Simulation Package) package [29] is one of the early packages developed specifically for robot simulation, and later for off-line programming. It has been used to study and evaluate systems involving spot welding, arc welding, brazing and material handling, and where workplaces involving more than one robot, conveyers, AGVs, and other machines have required modelling and simulation. The GRASP software allows the kinematic structure of serial link manipulators to be modelled, and new structures and/or robot models may be added to the library of existing core models. The robot movement and positioning is controlled by either altering the position of individual joints, or derived automatically from the new desired position of the tool centre point (TCP) which can be directed to move on to an object in the workplace. 3D-solid modelling of the whole system is available in the GRASP software and the detection on robot collision with objects in the workplace can be carried out visually, statically or dynamically. The visual checking by animation is used to detect potential collision problems within a sequence of moves which is then examined using the static collision checking algorithm. By using time frame snapshots, real-time motion pictures can be achieved. Using GRASP, all the information necessary is entered into the model during simulation which then is passed (via the appropriate post-processor) to the particular robot(s). The welding institute [30] has installed GRASP on a PRIME 50 series computer for research and development of computer integrated manufacturing concepts in welding fabrication.

CimStation, is a simulation and off-line programming system, developed by SILMA [31] and used to optimise automatic workcell design and to coordinate the motions between a welding robot and positioners. The user can define the 3D geometry of the workpiece to be welded and the manipulator(s), etc with the program's modelling system, or by transferring to the program, via the IGES exchange standard, the existing CAD models of the workpieces from another CAD/CAM system. The user enters the desired welding speed and lead angle along the weld joint, offset distance from the joint, and other relevant welding variables. The program is able to compute the required coordinate motion of the positioning table to maintain the weld pool horizontal throughout the welding operation. The completed simulation designed program is then translated into ROPS format (Cincinnati Milacron's Robot off-line programming system) and downloaded to the robot controller for welding operation.

3.3.2 The Loughborough FWS

A low cost off-line programming and simulation package for robotic arc welding (WRAPS) has been developed at Loughborough University by Middle and Goh [1,24] together with purposed associated expert systems for the supervision, control, welding procedure selection and optimisation for a flexible welding cell, fig 3.5 and 3.6. WRAPS (Welding Robot Adaptive Programming and Simulation) is used to generate the robot program away from the production line and incorporates the best available welding procedure selected from a database via an expert system. The program is then transferred via an appropriate post-processor to the robot controller. WRAPS is expanded by means of interfacing with CAD/CAM facilities and sensors. It is developed for IBM or compatible micro-computers under concurrent DOS and is written in the 'C' language with GSX graphics and comprises four main modules within an integrated robot welding system, fig 3.6. These modules are:

- 1) Modelling Module - is used to define work components, tooling, the welding system, which are constructed from primitives (e.g. line, cuboids, etc) using 3D wire-frame modelling. It is menu driven and any errors occurring during modelling are displayed. The created models and related data are stored as an ASCII file. The module also allows for some system operation e.g. any deleting or listing of files. Other facilities in the system include such as; showing the coordinates of points graphically, creation of "end of weld" point and pre-defined segments/objects.
- 2) Programming Module - is used to manipulate the models and accept welding programming commands to produce a robot program which incorporates the Tool Centre Point (TCP) coordinates, all robot functions, and welding parameters collected from an expertly managed data base. Files from the modelling module are read by this module and displayed in 3D. Programming of welds is achieved by targeting the TCP to weld end points pre-defined during modelling. Viewing change such as view/rotate left or right and zooming is accomplished through this module together with facilities to assist off-line programming such as examination of distance from TCP to a point on the component and/or between 2 points on a component, etc. Clashes between the torch/component is also accounted for.
- 3) On-line Module - has provided the communication between the micro-computer and the robot controller, post-processing of WRAPS program to robot format, editing and transferring, and on-line monitoring of the welding process in conjunction with the expert module. It also provides for overall supervision of all elements of a flexible welding cell, and to high level factory communication such as MAP (Manufacturing

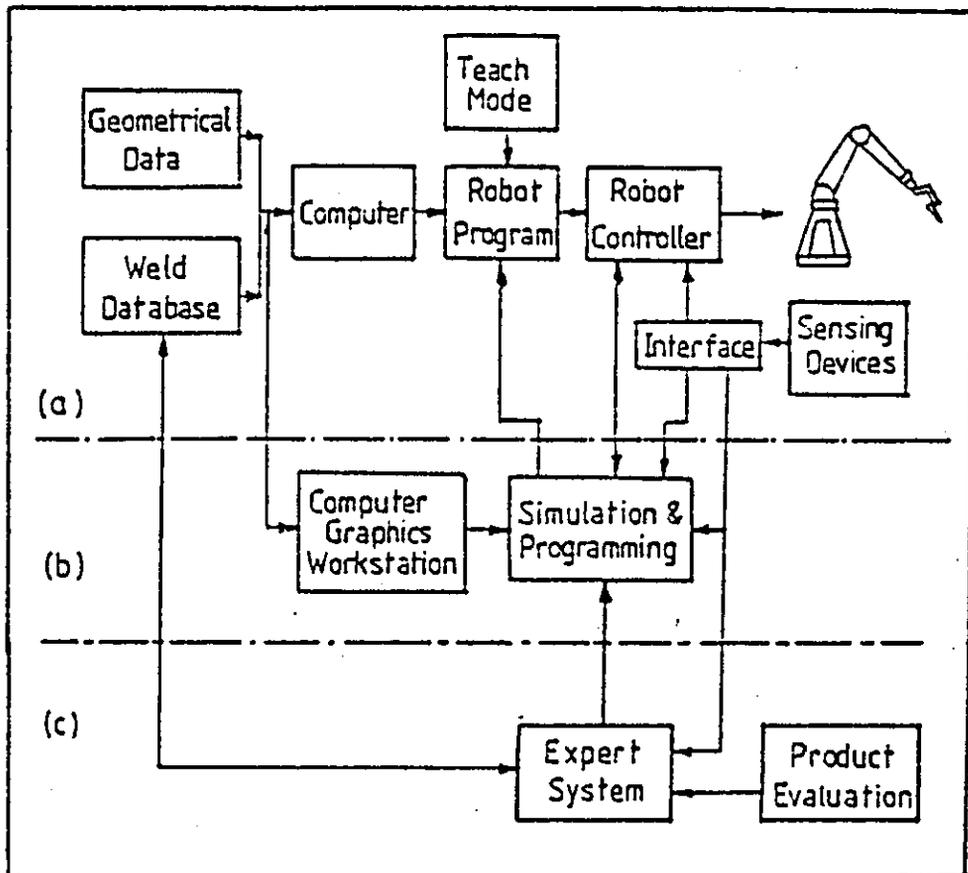


Fig (3.5) - Block diagram of WRAPS integrated robot welding system (a) without and (b) with off-line programming and simulation and (c) with an expert system [1].

Automation Protocol) and TOP (Technical and Office Protocol) [1].

This module provides input/output control capability to enable on-line control of process equipment via a special purpose software, PECIS. PECIS (Peripheral Equipment Control and Interface Software) is an expert system based controller and a simulator console which represent WRAPS flexible welding. PECIS input capabilities are, for example, real time data acquisition for incorporation into the expertly managed data information system, etc, and its output capabilities are such as direct control of PLC, switches, etc.

4) Expert Data Management Module - This module selects the welding procedure for a particular application, if available, from a procedure database. The programming module accessed this database via the expert module during off-line robot program generation. As a standalone module, the weld procedures managed may be interrogated and inspected. The use of KES expert system shell, enables the knowledge which is obtained to be formulated and implemented as rules. This module provides weld procedure selection, but has provisions for extension to:

- a) Prediction of procedures where none previously exist.
- b) Real-time process control.
- c) Adaptive control modelling.
- d) closed optimisation of procedures based on their measured performance in manufacturing operations.

In (a), if during WRAPS off-line programming no suitable welding procedure is found in the database, an expert system is invoked to predict a procedure appropriate to the joint to be welded [32]. This system, which has been the subject of a parallel research study, is designed primarily as a stand-alone procedure design package intended for novice users, hence 'help' facilities and graphical representations are provided in the system. It nevertheless has been provided with facility to interface to WRAPS as part of an integrated flexible welding system. The system knowledge base is partitioned into several sections; material, joint preparation, process selection and welding parameters. Manual Metal Arc, Gas Metal Arc, Submerged Arc and Gas Tungsten Arc welding processes are considered and two types of materials covered are Mild Steel and Carbon-Manganese Steels. The system therefore covers the current scope of WRAPS. Knowledge is represented using two of the KES inference engines; rules in the production rules subsystem or as descriptions in the hypothesis and test subsystem. The research has shown that the expert system can generate welding

procedures for a particular application and can be used as a tool to assist novice engineers, in terms of welding and fabrication experience, as well as welding experts in designing and writing welding procedures.

(b) and (c) are the subjects of further research and development for in-process data collection during an automated welding operation planned for the Loughborough University integrated welding system the concept of which have been described in Goh's thesis [1].

(d) is the subject of the research being reported in this thesis. That is, the pre-weld inspection and feedforward control, and post-weld inspection and feedback control of welding procedures, and the associated knowledge base expert systems (PIKBES and POKBES). The pre-weld inspection station has been designed, calibrated, and implemented on a lower-tier work station of a custom-modified WESTWOOD automatic conveyor within a flexible robotic welding cell, fig 3.7. The whole cell comprises of three robot systems - a CML T3 for handling, a SILVER-REED ARY4 for manipulating the post inspection sensor, and a FANUC S100 welding robot all of which are interlinked to the conveyor system. Three inspection work stations for pre-weld inspection, in-process inspection, post-weld inspection, and manual inspection station have been provided. The component to be welded is first inspected for actual joint geometry such as joint type, plates thickness (T1 and T2), gap or root gap (RG), root face thicknesses (RFT1 and RFT2), bevel angles (BV1 and BV2), etc using a triangulation range finding laser sensor "Optocator" [89]. Collected data from the sensor controller (within an ASCII file) is then transferred to the pre-weld inspection knowledge base expert system (PIKBES). Non-mathematical knowledge based models in PIKBES use this data and compare them with the nominal joint parameters for the joint to be welded held in WRAPS database or WELDSPEC database. The comparison for quality control of subsequent welding of the joint works at three 'levels':

- i) joints within an established tolerance at which nominal welding parameters can apply.
- ii) joints outside expertly established absolute limits which can be considered unweldable by automatic means. In this event the pallet carrying the offending joint by passes the welding station.
- iii) Intermediate level requiring an expert system with appropriate rules to suitably modify the nominal welding parameters and thus enable satisfactory welding.

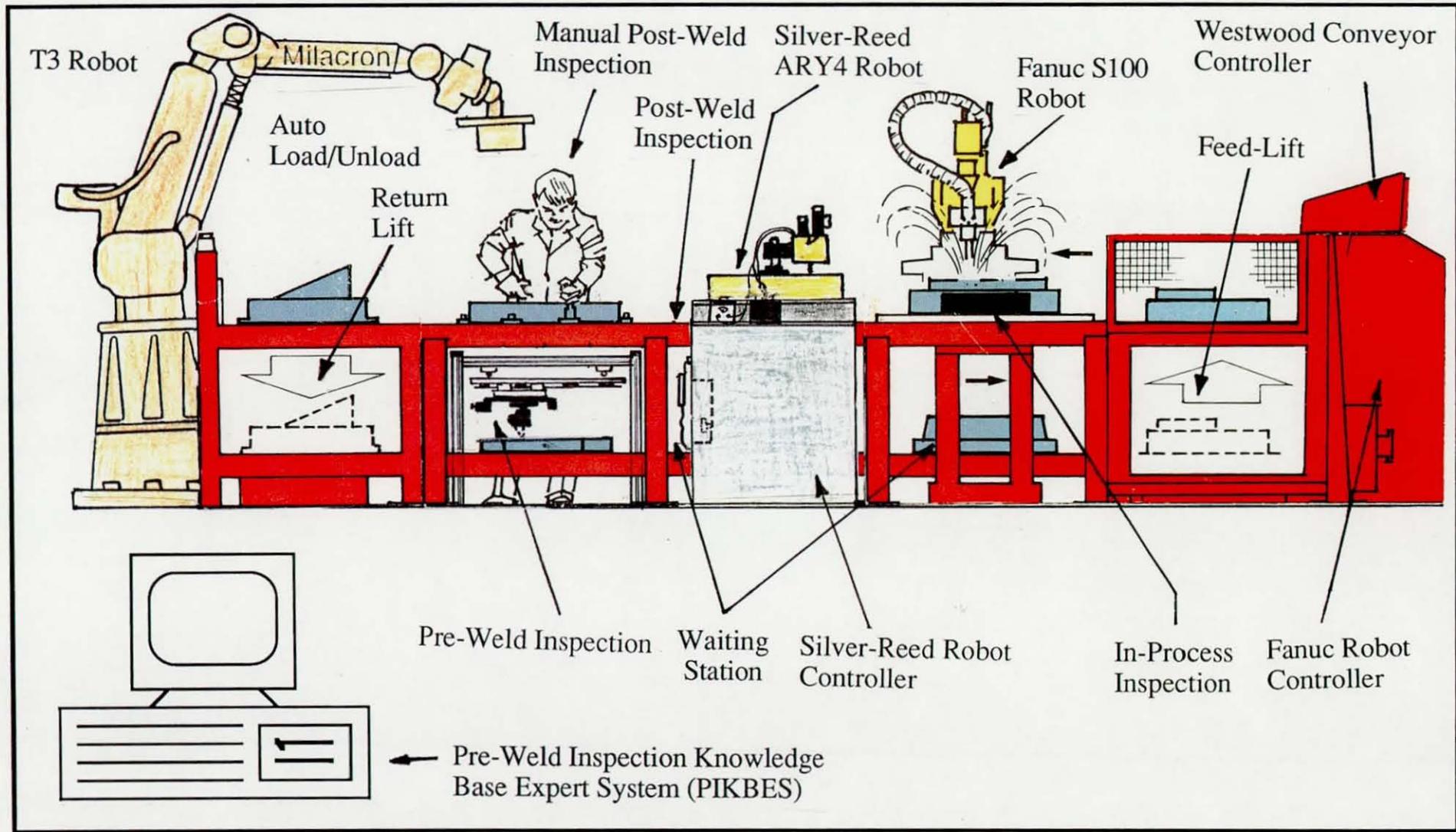


Fig (3.7) - The pre-weld inspection station integration in the Loughborough flexible welding cell.

Where (iii) applies the modified welding procedures will be transferred to WRAPS overall supervisory control. WRAPS supervisory system communication with the welding equipment in the cell is via ring network (LAN). The pre-weld inspection station communication and supervisory system uses a circular-linked list (which is similar to the flow of pallets on the conveyor system) and welding data is stored onto an appropriate slot on the linked list. When the particular pallet appears at the welding station, the correct set of modified welding conditions are used. Chapter 5 gives more detailed information about design, calibration and implementation of the pre-weld inspection station and sensor, and its communication with the conveyor, whereas chapter 6 deals with the knowledge elicitation and implementation of PIKBES.

Research work has commenced on the post-weld inspection system. After welding is completed, the finished joint will be inspected automatically and manually at subsequent inspection stations to establish the effectiveness of the welding procedure employed. Manual inspection will, e.g. refer to weld appearance and surface finish or non-destructive testing (NDT) and appropriate data manually input to the system. Automatic inspection uses a stripe laser sensor, mounted on the SILVER-REED robot manipulator, and weld profile monitoring software to obtain information of the bead geometry (such as bead width and height, etc). The information collected about the actual weld deposited will be manually or automatically consulted by an expert computer system (POKBES). Comparison with quality standards will establish whether further rectification of the welding parameters that produced the weld would have been appropriate. The newly modified welding procedure will then be held in file for use when a joint of similar geometry appears on the system. In this way, the system provides for continual improvement of welding conditions (self-optimisation). It is also conceptually possible that the closed loop of information can be used to modify the rules within the expert systems and consequently produce a self learning system.

3.4 Sensing Systems for Robotic Arc Welding

A variety of sensing techniques have been employed to automated welding systems [34,35] in order to collect information about the joint, track the seam, and control the welding processes. Two main approaches are used by these systems and also have been considered in this research. Firstly, "one-pass" seam tracking systems where the sensor seeks out joint and/or weld data during welding. Secondly, "two-pass" seam tracking systems where the sensor first tracks along the joint to be

welded and stores the path and processed information about the joint in a microcomputer with welding being carried out in a second pass. These systems have a number of advantages and disadvantages which have been discussed in the pre-weld inspection control strategy in chapter 5, section 5.2.

The sensing techniques employed for seam tracking systems are such as tactile sensing, through-the-arc sensing, inductive sensing (or eddy current sensing), optical sensing. The latter uses different methods of sensing such as; structured light, scanning laser range finder, or direct visual sensing techniques. Although these sensing techniques are now well established, a review of the developments will help understanding of the principles applied to robotic arc welding as well as its application to automatic welding systems for Gas Metal Arc Welding (GMAW/MIG/MAG) [36] process. This review was also necessary to establish suitable sensing methods for the pre-weld inspection station in this research.

3.4.1 Tactile Sensing

The importance of tactile sensing (mechanical or electromechanical) in the field of industrial dimensional inspection and arc welding seam tracking have been recognised in the past two decades. An early review of these systems in Tungsten Inert Gas (TIG), MIG, and Submerge Arc Welding (SAW) seam tracking technology [37] showed that these systems used typically rail mounted tractors (tractor units, gantry, or beam mounted equipment) to permit seam to be accurately followed, but were limited mainly to linear seam joints, fig 3.8(a). Such systems were mainly used because of their simplicity and low cost and are classified by Brown [38] as 'first order' welding head manipulates. Further research and development into using electromechanical types of tactile sensing enabled robots to be more flexible in their welding operation. Nicolo'[39] at FIAT's Research Centre has investigated the feasibility of applying a tactile sensing technique to robotic arc welding for seam tracking by mounting the probe on two orthogonal slides driven by stepping motors (in vertical and horizontal planes) and sensing the sidewall of the joint ahead of the arc. The joint position is derived from the set of contact points to keep the electrode position in the seam centreline. The occurrence of contact is detected by the break of electrical circuit continuity inside the probe. A horizontal slide moves the probe from edge to edge of the joint and the information obtained is used to calculate the gap and cross-section area of the joint. The investigation showed that the sensor was affected by the presence of spatter coming from the arc which gradually altered the operation of the sensor. The sensor required to be made of special materials to prevent damage by spatter. The main

drawback of the implemented system was that the robot had to be manually driven to the beginning of the joint and positioned approximately at the correct weld start position.

Bollinger [40] has reported the design of a tactile sensor for the guidance of welding robots in a hostile environment. The sensor is mounted on the robot welding gun 6mm distance from the electrode and at angle of 15 deg. from the plate surface to eliminate spatter problem. The weld geometry is sensed in close proximity of the arc at the leading edge of the molten pool. Probe design involved considerations such as; 1) using a copper stylus oriented with a low approach angle to the pool so that the probe is located at an angle below the "spatter cone" and will be less subject to intense bombardment. 2) mounting the probe to a circulated water-cooled heat sink to reduce the effect of the heat transferred from the welding region. 3) wear resistance which is mainly related to joint surface finish, the mechanical bonding characteristics of the material, the maximum probe temperature, the time that it takes a molten globule to freeze once it is in contact with the probe.

Heitmayer [41] has reported the design of a tactile sensor for seam tracking. The sensor mounted on the robot welding gun consists of a ring with four opto-electronic transducers planar, fitted concentrically to the welding tip so that it has a relatively small parallax in all four directions, fig 3.8(b). Any pressure or movement in the ring during the sidewall contact seam following causes a signal on either of transducers. If the gun moves away from the centre of the joint, an error signal is obtained in one or two monitored directions, this triggers a corrective movement in the robot controller to move the weld tip in the appropriate direction until a zero signal is received from both directions for path correction. A more sophisticated sensor to control an arc welding robot for seam tracking has been reported by Presern [42]. The sensor is mounted 30mm ahead of the robot welding gun and has a resolution of 0.05mm. This sensor consists of two optical sensors which provides displacement measurement, fig 3.8(c). A special mask using the grey code is used to monitor needle displacement and register the reading. The movement in the needle corresponds to a change of one bit and 64 positions are coded into the mask. Two degree of freedom are used for the sensor's needle (10mm displacement in either direction) which is placed at the bottom of sensor with a 30mm fixed distance from the welding gun. The report claimed that the robot is able to find the beginning of the seam by itself, utilising a preprogrammed search routine. More recent tactile sensors, use ultrasound for seam tracking, contact being made via a coupling fluid.

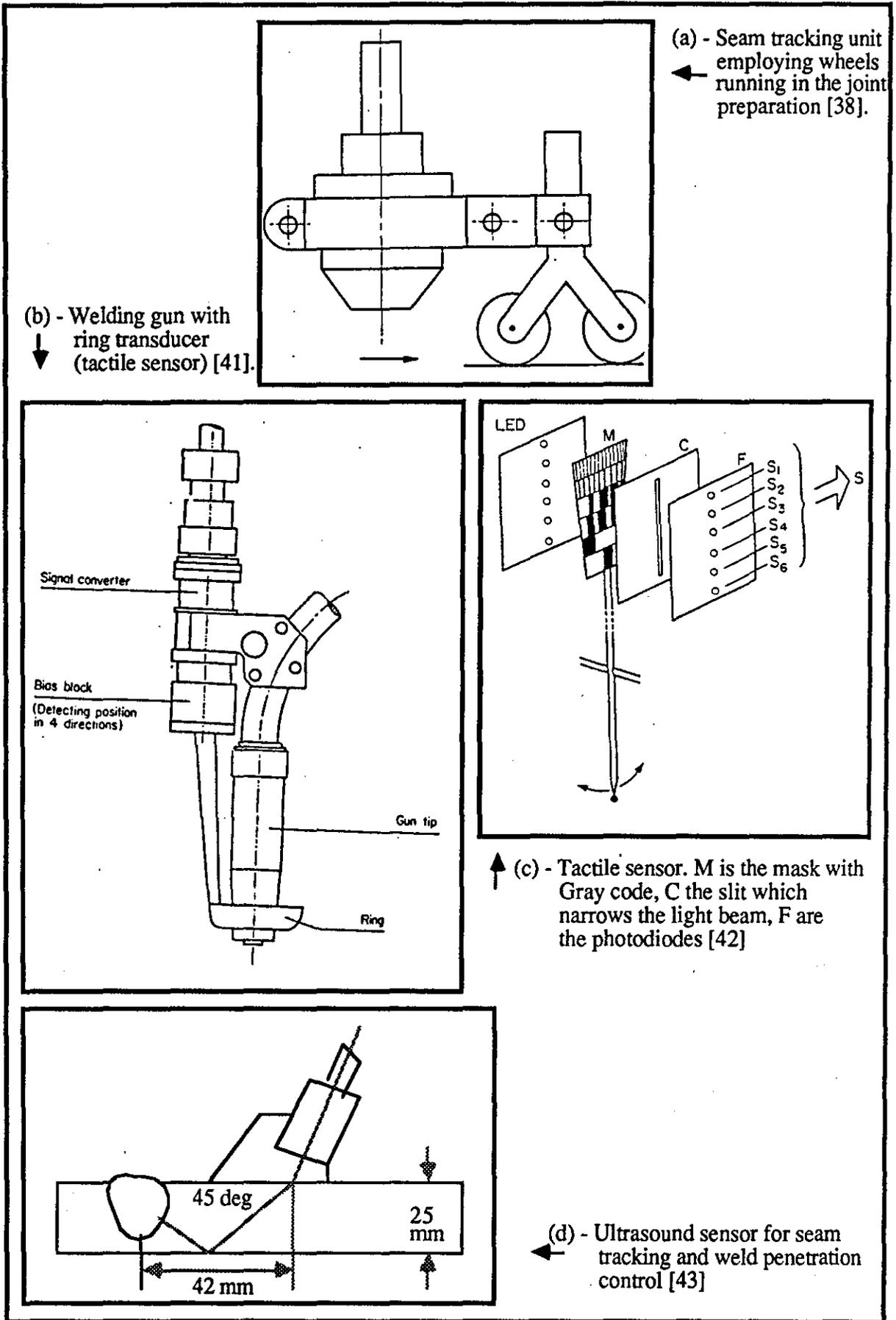


Fig (3.8) - Shows number of typical tactile sensor systems.

Stroud [43] investigated the feasibility of the use of ultrasound for seam tracking and real-time weld penetration control for robotic welding systems. The robot is capable of tracking the seam, measuring the weld bead penetration depth and position, control them simultaneously, and subsequently modify welding parameters. The ultrasound sensor used, is mounted ahead of electrode and molten pool, and uses oil pumped continuously to ensure sonic contact between the sensor and the plate surface, fig 3.8(d). The sensor was a line focused (50mm) immersion type, working at a frequency of 2 MHz. Any changes in the ultrasonically measured beam path length from the sensor to liquid/solid interface at top and bottom edges of the weld pool dictates changes of welding current and measures depth of penetration. Any shortening of detected beam path indicated excess bead depth, while time-of-flight indicated lack of penetration. However, the signal received from the intact top and bottom edges of the plates are used for seam tracking.

The major drawback encountered with tactile sensing for seam tracking when it is applied to robotic are:

- i) Not adaptable to suit a variety of joint geometries.
- ii) Tendency for probe to lose contact with the joint.
- iii) Probes cannot follow complex contours.
- iv) contact sensors limit the welding speed.
- v) Probes are subject to wear and environmental effects.

These type of sensors are not generally viable for most robotic welding applications that require adaptive control sensing.

3.4.2 Through-The-Arc Sensing

Through-the-arc sensing is the most common form of joint tracking used with industrial robots for arc welding. The technique uses electrical signals from the welding arc and requires oscillation of the welding torch, and monitoring of the variations in welding current or arc voltage, fig 3.9. The weaving motion causes changes in the current sensed at the joint sidewalls. These current changes are directly proportional to fluctuations in distance between the surface of the weldment and the tip of the welding electrode. Such sensing methods arose from a technology for tungsten-to-work control via automatic voltage control with the Gas Tungsten Arc Welding (GTAW) process [45] and proximity control via current feedback with the GMAW process [46]. To find the joint positional information from the welding arc, a

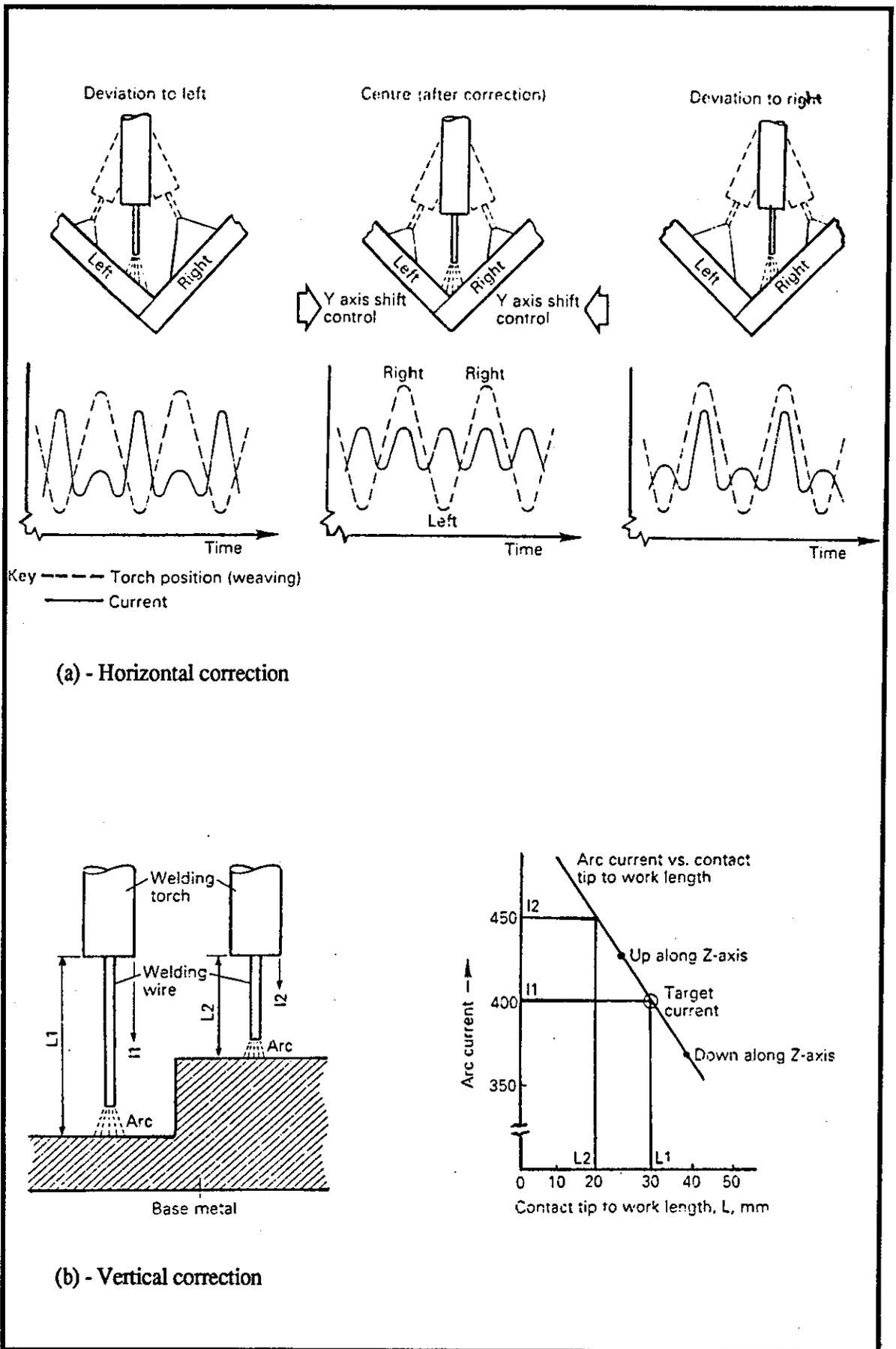


Fig (3.9) - Principle of Through-The-Arc seam tracking [17].

relationship between arc voltage and current to torch-to-workpiece spacing must be known for a particular process. Goldman [47] and Amson [48] have reported such a relationship which was later developed by Cook [49,50] to collect a three-dimensional map of the workpiece for both nonconsumable electrode processes (e.g. GTAW) and consumable electrode processes (e.g. GMAW) and are shown respectively as:

$$V = a_1 + a_2 I + a_3/I \quad (1)$$

$$V = B_1 I + B_2 + B_3/I + B_4 l_a \quad (1 \leq l_a \leq 10) \quad (2)$$

where V and I are the arc voltage and current respectively, and a_1 , a_2 , and a_3 are positive constants which are related to geometrical configuration of electrodes, the chemical composition of the electrode's materials, and the shielding gas used and l_a is the arc length. Referring to equation (1), The total potential of a welding arc (V) falls with increasing current and rises again with a further increase in current and is characterised as a hyperbola curve and a straight line, whereas in equation (2) the relationship is characterised as an approximately straight line for an arc length (l_a) between 1 and 10mm. The contact tube-to-workspacing is equal to the electrode extension plus the arc length where typical values for the constants are $B_1 = 0.013$, $B_2 = 5.2$, $B_3 = 185$, and $B_4 = 0.74$.

In consumable electrode processes for GMAW, this relationship can be shown that the contact tube-to-work distance h is related to the arc voltage V_s and arc current I by the expression:

$$V_s = r[h - l_a] I \quad (3)$$

where r is the average resistivity per unit length of extension wire, and the arc length l_a is also dependent on the contact tube-to-work distance h and the current I will vary inversely with h . Lesnevich [51] showed the relationship between the torch-to-workpiece distance and the arc current for all normal conditions as:

$$W = K_1 I + K_2 I^2 l_e \quad (4)$$

where W , I and l_e are the wire feed rate, arc current, and electrode extension respectively and K_1 and K_2 are constants for the particular operating conditions (e.g. shielding gas type, electrode wire size and composition etc). Cook [52] used digital

signal processing to study the effect of variations in the contact-tip-to-work distance on the electrical arc signals for the submerged arc welding process.

Halmoy [44] used this sensing method for the narrow gap MIG welding of 20-25mm steel thickness and has achieved the sidewall penetration by oscillating the wire electrode and rotating a curved contact tube. But in a deep narrow groove such oscillation causes a difficulty for sideways weaving motion. Therefore, other ways of weaving and oscillation has been attempted by him such as:

- a) Using a pair of twisted electrode wires.
- b) Plastically bending the wire back and forth before it enters the contact tube. The stored tension then produces a wavy motion of the wire as it comes out of the contact tube.
- c) Feeding the wire eccentrically through a contact tube rotating at high speed.
- d) Placing the beads alternately on the left and the right, which has been successful in submerged-arc welding.

Eichhorn [53] has recently carried out the feasibility study of using a through-the-arc seam tracking systems for TIG-narrow gap orbital welding and control the lateral position of the torch during welding process, where the arc scans the groove. Two seam tracking systems have been demonstrated; seam tracking system with constant oscillation amplitude, and seam tracking system with self-tuning amplitude. In the former, the sensor is used to measure average arc voltages (after filtering, integration, and amplification of pulses) at the joint sidewall during scanning. The signal difference is then used to correct for an out-of-centre position of the welding torch. Such a technique is sufficient for welding with small and continuous lateral deviations. In the seam tracking system with self-tuning amplitude, the sensor is used to improve response time and be able to compensate for lateral misalignment by self-adjusting the electrode oscillation amplitude which uses the reversing pulse (from the arc voltage) and correct position of the welding torch.

To compensate for any variation during the welding process by modifying the welding parameters, real-time signal processing and control algorithms are required. Cook [54,55] has shown that this sensing method can provide information for such variation in the weld joint by means of sensing laterally across the joint and matching the "template" with the predetermined reference in order to adjust welding parameters. Three techniques are used:

- i) Matching an average of data samples for the left portion of the weld seam to

an average of data samples for the right portion.

- ii) Comparing an integrated signal corresponding to the leftward portion of the sensed lateral profile to an integrated signal corresponding to the rightward portion.
- iii) Comparing an integrated sensed profile signal to a predetermined reference value which is based upon a reference signal.

Through-the-arc sensing has a number of advantages and disadvantages. Hanright [35] reported that the advantages of this sensing technique far outweigh its limitations and included such advantages as:

- i) Relatively low cost in comparison to other joint tracking alternatives.
- ii) Not affected by smoke, weld spatter, or the arc itself.
- iii) No additional space intrusion in the vicinity of the torch.
- iv) Ability to track and weld simultaneously.
- v) Compensation corrections for heat distortion during welding.

The limitations of this arc sensing include:

- i) Any displacement of the torch in the plane parallel with the joint centreline will usually not be compensated for.
- ii) Incorrect electrode extension will result in erroneous sensing of the joint start.
- iii) Joint sidewalls must be well defined (lap, T- or groove weld joint types) and have typically 3-6mm face lengths.
- iv) All welds must use weaving. This problem has also been reported by Halmoy [44] during deep narrow gap groove joints in MIG welding processes.
- v) Cannot track around sharp corners or turns.
- vi) Heavy rust or mill scale has affected the joint tracking ability.
- vii) Limited ability for non-ferrous material.

Many researches [44-52] have used this sensing technique together with welding wire as a control probe for tracking the seam and collecting information from three-dimensional profile of joint.

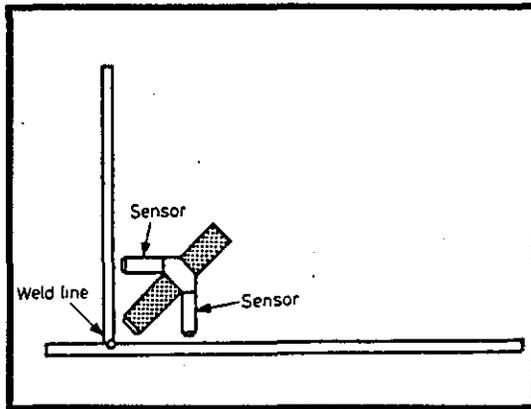
3.4.3 Inductive Sensing

Inductive proximity sensors (or eddy current sensors) consist of an exciter coil, carrying an alternating current with two coaxial pick-up coils connected in opposition. There are basically two types of inductive sensors; those detecting the seam itself which use a high frequency oscillation to generate an alternating magnetic field in the surface of the component [56,57], and those (proximity sensors) predicting the seam position by locating the component surfaces [58,59].

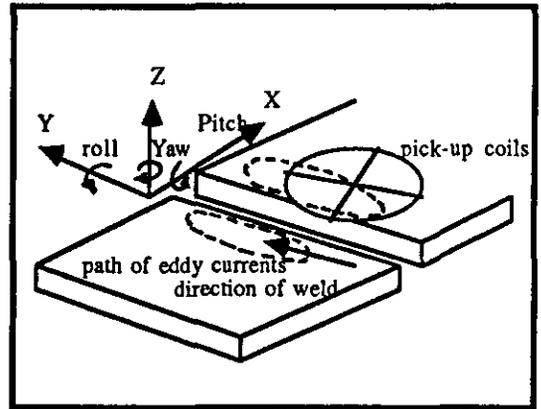
One of the early robots equipped with a seam tracking facility, reported by Ando and Kusmoto [58] from Hitachi is called 'Mr Aros', fig 3.10(a). The sensor consisted of two inductive proximity detectors mounted at an angle of 45 deg. to the welding torch, at right angles to each other, and each capable of measuring their height from a metal surface. In the absence of any metal there is no net voltage induced in the sensor's coils. However, when the sensor is placed near metal the relative magnitudes of voltages induced in the pick-up coils change and so a net voltage is induced which, when rectified and smoothed, produces a d.c. voltage. This voltage increases inversely with the distance from the metal surface. The output depends directly on the amplitude of the induced voltage and is used to modify the path of the robot, the torch, and the sensor back to the correct position relative to the joint.

To obtain more information about the joint than simply height, Howarth [59] has investigated the use of four quadrant pick-up coils positioned below an exciter coil to determine the information about the position of the sensor relative to the joint, fig 3.10(b). The induced voltage amplitude and the phase shift with respect to the exciter coil can determine the pitching in the direction of travel, rolling across the seam and yawing together with height and lateral displacement.

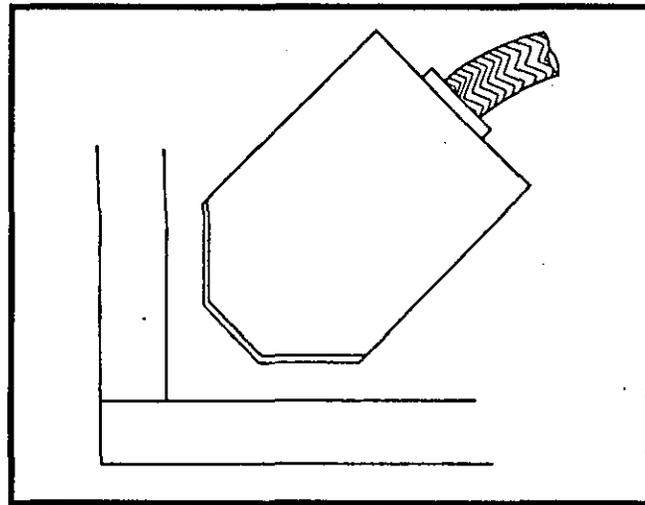
Goldberg and Karlen [56] have reported a seam tracking sensor base on high frequency induction, fig 3.10(c). The sensor is mounted 50mm ahead of the welding gun and is able to measure an area of 40mm width by 15mm long, and 60mm high. It can be used for all types of welding processes as the tracking system is independent of the welding processes. The sensor is applied to butt joints, lap joints, plate edges, and V joints with a maximum gap of 15mm and was able to operate for thicknesses from thin foil to heavy plates at a distance of 15mm above the plates. This distance provides the sensitivity of 5V/mm which gives a tracking accuracy of approximately ± 0.3 mm. To detect the groove or edge of a prepared joint, Drews [57] used a high frequency oscillator to drive an exciter coil placed symmetrically between a pair of sensing coils, fig 3.10 (d), which are connect in series and antiphase, so that net zero voltage is



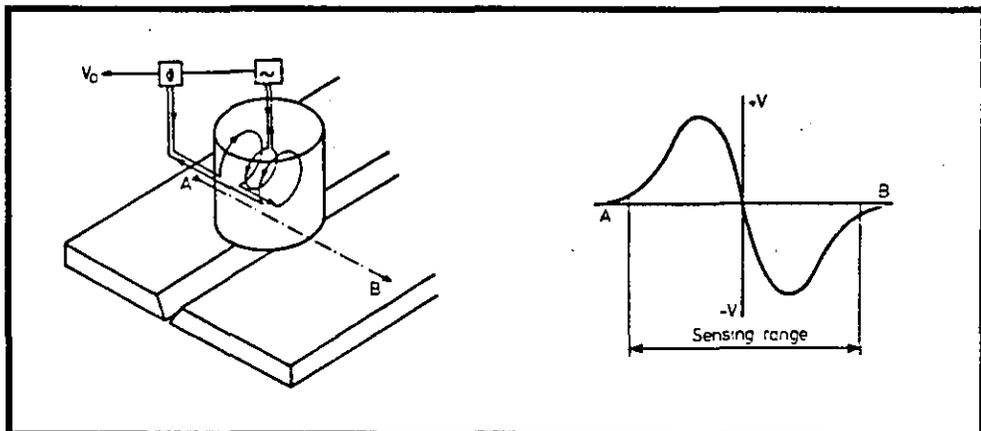
(a) - Inductive sensor developed by Ando and Kustmoto [58,34].



(b) - Inductive sensor developed Howarth [59].



(c) - Inductive sensor developed by Goldbeg [56].



(d) - Inductive sensor, general arrangement and output signal for movement at right angles to the groove developed by Drews [26,34].

Fig (3.10) - Shows number of typical arrangement of inductive sensors.

produced when the weld seam is directly beneath the sensor. The generated voltage from the coils are then used to determine the lateral displacement of the joint relative to the sensor and / or the welding torch.

Nicolo' [39] investigated the feasibility of application of these types of sensors together with a tactile sensor for robotic arc welding systems in order to move the torch toward nominal position. The sensor uses four transducers which are not effected by the arc temperature and/or joint type mounted orthogonally to the direction of movement of the torch gun (and a few centimetres ahead of it). Two external transducers measure the elevation of the sensor on both sides of the joint, the internal ones the lateral displacement of the side the joint centreline and the width. The information collected by this sensor and a tactile sensor for lateral and vertical displacement measurement are then fed back to the robot control software for torch nominal position.

The advantages of these sensors are that they are completely independent of the welding process. The sensors are compact and robust and will even operate under water and are not influenced by rust, paint, or paper that might adhere to the plate surface. It reacts only on metals and will operate on all metal thicknesses. There is no evidence to suggest that inductive sensors are capable of providing precise quantitative information about the geometry of the joint and it seems unlikely that it is possible.

3.4.4 Visual Sensing

To date vision sensing has receiving most attention in automated inspection systems [60] and industrial robot application [61]. Vision sensors can be used to capture detailed information from the seam or weld cross sectional (or three dimensional) profile and spatial position by using visual processing technique [62-65]. Joint types can be recognised, and dimensionally measured, the welding gun can be positioned correctly in the seam centreline, and information on the variation in joint geometry can be use to adaptively compensate by modifying welding procedures. These sensing systems are mainly based on the use of "structured light" [62,63,65] in the form of a projected stripe or plane of light [91], "range finding" [66-68] in the form of projected spot of light, or solid-state camera [83,84,69] principles where direct visual sensing takes place. Visual seam tracking often requires sensing of the seam takes place in a hostile welding environment; this is not a trivial problem. Such an environment can be avoided by using "two-pass" seam tracking [62,63,70,71] where vision sensing is first used to determine the true joint position and orientation of

the joint, and measure its parameters (e.g. root gap, root face thickness, etc.). Welding is then conducted in the second pass. In this way, the sensor will not be damaged by heat, fume or spatters. In "one-pass" seam tracking [65,66,72,73], sensing and welding are done simultaneously. Thermal distortion during welding process is therefore accounted for by modifying welding procedures and torch position. To protect them from the arc environment, the sensors may be shrouded from the arc using a physical or gas shield [82,76] and may include water cooling [76] to prevent damage to the sensor. Complex processing of the signal of the sensor may be needed to remove the effects of the environment, e.g., the light emitted by spatter. Structure light or range finding methods are suitable for the pre-weld inspection station development of this research.

Several researches have been attempted to view the weld pool directly [78-81] by eliminating the intense arc light using the short-circuit phases of the arc [83] or pulsing welding current [84]. Richardson [78] has developed a vision based sensing and control system to view the weld pool. Hanright [35] refers to this as 'direct arc sensing'. The sensor is applied to GTAW and GMAW processes to achieve real-time joint tracking and weld pool control. The weld area is viewed through a bundle of optical fibres housed inside the welding torch coaxially with the welding electrode, fig 3.11(a). The arc light is used to illuminate the weld scene (unstructured lighting) in both welding processes. The image of the active welding area is transmitted to a solid-state camera via a series of lenses, mirrors and filters which digitises the analogue image, and a vision system connected to the camera is used to analyse the weld scene and extract the important features such as:

- a) periphery of the entire weld pool;
- b) boundary between solid and liquid;
- c) solidified weld bead; and
- d) joint geometry.

Welding process information established in a mathematical process model is then transmitted to the robot controller which, in turn, supplies the robot with appropriate corrective actions for welding path and/or joint fill modifications. The system has several advantages relative to conventional approaches:

- i) The bright core of the arc is blocked by the electrode/contact tip, eliminating the overpowering exposure of the imaging system to the bright arc.
- ii) The entire weld area, including the weld pool, the preceding joint

preparation and the following weld bead, can be viewed without obstruction, distortion by a viewing angle, and interference from the bright arc.

- iii) The optical system is contained within, and protected by the welding head housing and shielding gas flow, thus minimising problems with the maintenance of optical surfaces, interference from smoke and spatter, and exposure to abuse.

Corby [79] reported the development of a visual sensor design based on Richardson's coaxial viewing geometry system for use with industrial robots. The optical system is mounted above and coaxial with the electrode, inside the torch cup which is compact and elongated (25mm long by 13mm wide), fig 3.11(b). In this way, the system is able to cover a depth field of 8mm ahead of electrode and capture weld pool visual image and seam profile. The illuminating light source (structured lighting) of 7mv Helium Neon (CW laser) is reflected in the form of a ray which is then moved through space by an xy mirror system. The ray of light is imaged onto one end of a coherent fibre bundle and then emitted at the other end, to be projected onto the surface and profile. The weld pool image received at the Charge Injection Device (CID) camera through fibre bundle after narrow band pass filtering, is then used as 256x256 colour pixel image with 128 gray levels per pixel to provide detailed information about the seam (e.g. lateral dislocation, the position of the edges, etc) and weld pool (e.g. condition, shape, and position of the weld pool relative to the electrode), which later is used for process control.

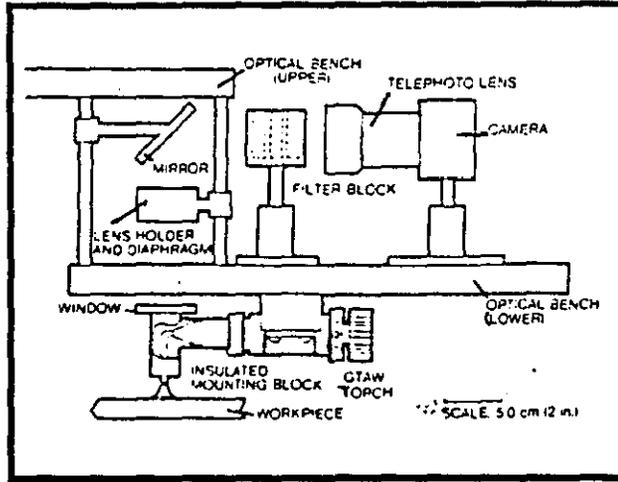
The WeldVision system [80,81] developed by General Electric for seam tracking purposes and closed-loop welding control for TIG arc-welding applications is based on a similar design concept to Richardson [78] and Corby [79]. The scanning dual-parallel stripe laser pattern of light is projected on the workpiece surface through a coherent fibre optic bundle approximately 7mm ahead of torch, fig 3.11(c). Two-dimensional images from the seam are then collected and transferred through the second coherent fibre optic bundle to the solid-state CID camera. The laser stripes are processed to locate the physical features of the joint to be tracked and allowing the torch to be positioned directly over the joint. To control the welding process, weld puddle width, length, area, and position relative to the joint are analysed in real-time.

A research group at University of Liverpool [82] have developed a seam tracking sensor (called TIMTRACKER) for application to robotics in TIG welding. The sensor is based on structured lighting technique and used in a one-pass system. It

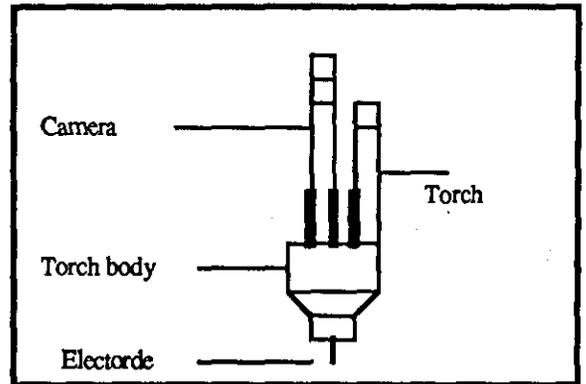
is mounted on the torch so that the light strip is projected 7mm ahead of the electrode tip, fig 3.11(d). The sensor consists of a coherent fibre optic bundle connect to television (CCTV) camera and a tungsten halide light source of 30W which is focused to produced a light strip on the workpiece. The produced light strip is collected and transmitted by the fibre optic bundle from the surface to the CCTV camera. Originally, the image was processed by a low cost, 8-bit BBC microcomputer by means of digitising the picture of 256x256 binary image. At the present time a faster 32-bit processor and high speed framestore are used. In initial development of the system, a problem was realised in that the 256x256 digital picture containing 65536 points of information took an unacceptably long time to process in real-time. Important considerations in the subsequent development of the sensor system were the image resolution and the speed at which the large amount of data associated with each image can be processed. The picture analysis took approximately one second with subsequent interpretation taking only 20msec. Since the digital picture is sampled over one video field of 20msec, the total picture updated time becomes 40msec. this means that robot welding torch position can be updated every 40msec. This sensor system would be suitable for the pre-weld inspection station of this research.

Niepold and Bruemmer [83] have used a conventional solid-state camera system together with a special exposure technique to view the weld pool in the MIG/MAG welding process. The camera and image processing technique is used to provide seam tracking and measure the three-dimensional profile of the seam. It also provides process parameter control by analysing the weld pool shape and position of the electrode relative to the seam. The camera is mounted 30cm ahead of the welding torch and monitors the front surface of the melting pool together with its shape and the electrode position. The seam is tracked (using the geometry of the pool contour line), as a result of the conformity of the liquid metal with the edges of the work pieces which assumes a typical shape according to the actual seam profile, and thus allows the localising of the centre of the seam. The height of the torch above workpiece can be determined by vertically measuring the position of the wire electrode in the binary picture frame of 256x256 pixels. To eliminate the effects of the bright arc during welding, a special exposure technique is used during the short-circuit phases of the arc in the dip transfer mode. The optical shutter of the sensor is worked electromechanically and allows exposure times of 1 msec with a reaction delay of approximately 250 micro second.

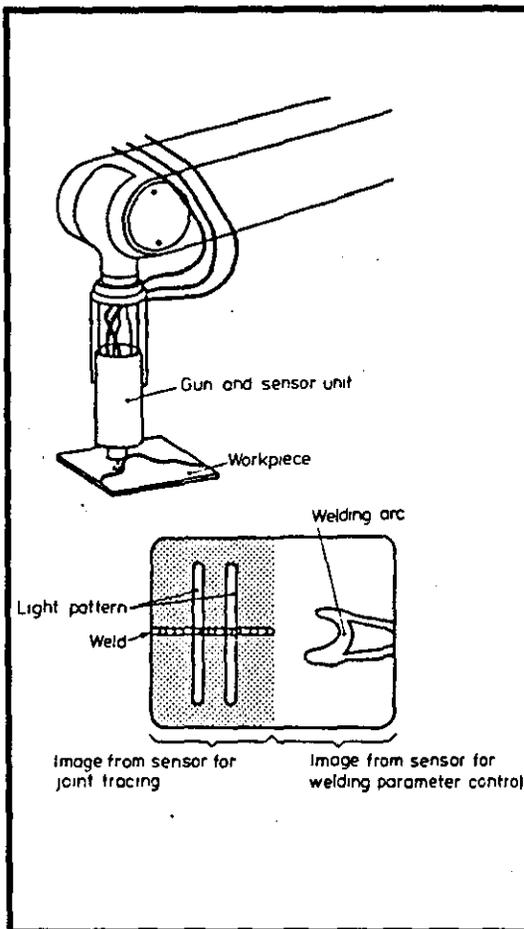
Rider [84] has described similar technique to measure the width and location of a weld pool in the gas tungsten arc welding process. A linear photodiode array is used to capture the information, arc interference being avoided by momentarily extinguish-



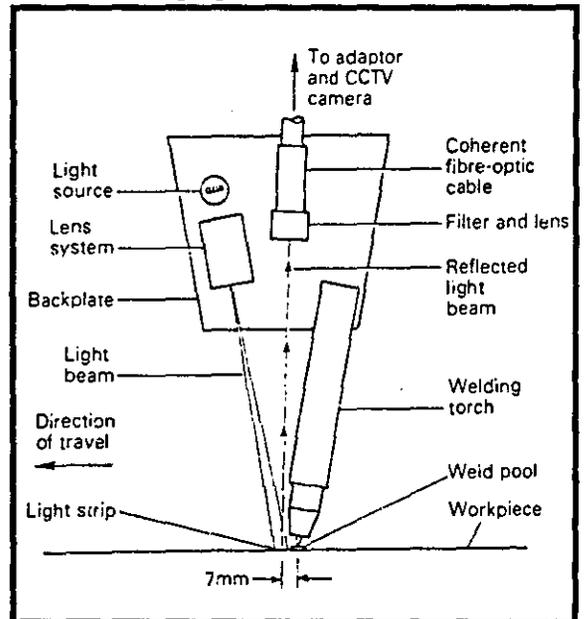
(a) - Direct arc sensor applied in GMAW.[78].



(b) - Thru-torch integrated welding torch sensor [48].



(c) - Weldvision sensor applied in TIG welding [80].



(d) - TIMTRACKER sensor applied in TIG welding [82].

Fig (3.11) - shows number of typical vision sensor systems.

-ing the arc for up to 2ms. The scanning is performed at 7kHz which enabled up to 14 images to be captured repeatedly (at 10Hz) before the arc was restored.

Masaki [70] reported a sensor system which consists of an optical slit pattern projector and an optical fibre bundle. Two-pass seam tracking is performed. The sensor is mounted on the robot wrist and senses the deviation between seam and taught robot path in the first pass. Welding is performed in the second pass. The optical slit pattern is projected onto the workpiece at 45 degree and is detected at 90 degree from horizontal. The deformed image of the optical slit pattern is used instead of the image of the seam itself, because the signal/noise ratio, from the point of view of seam position detection of deformed image, is much better than that of the actual image of the seam itself. The deformed image is collected by the object lens attached to the tip of the fibre bundle and is then transferred to the frame store, and then transformed into the serial binary electronic signal for image processing.

Verdon [71] developed a non-contact television camera seam tracking system suitable for flat horizontal submerged arc welded box section fabrications. The system used two-pass seam tracking by viewing the preparation vertically downwards 300mm ahead of welding gun. The camera is positioned roughly at the start and over the preparation by a joystick. When the welding gun reaches the start point of the preparation, welding is started. The camera collects positional information, volume of the preparation, width and distance from the component edge in its first pass and stores them in a computer. This information is used to control the position of the welding torch when it reaches the sensing region. Experimental results has shown heat distortion does not cause significant changes in the position of the preparation in the time between sensing and welding.

Lacoe and Seibert [69] have reported the use of Robovision with "Partracking" for seam tracking and welding of the sideframe of railroad cars. The sideframes of the car are winched up in a large ring fixtures and presented to Automatrix robots for the welding operation. Two wear plates are clamped in each sideframe. The robot system locates one plate and welds it, then the fixture rotates 180 degrees and the process is repeated for the second plate. The robot is mounted with two solid-state cameras to view the workpiece stereoscopically, fig 3.12(a), and these were 76.2cm apart on the upper arm of the robot. Each camera takes a single picture and sends it to the computer in order to calculate the position of the plates in space and to locate the welding torch on the seam centreline. The vision processing takes less than six seconds.

Several researchers [64,66-68,72] have reported the use of laser range finders

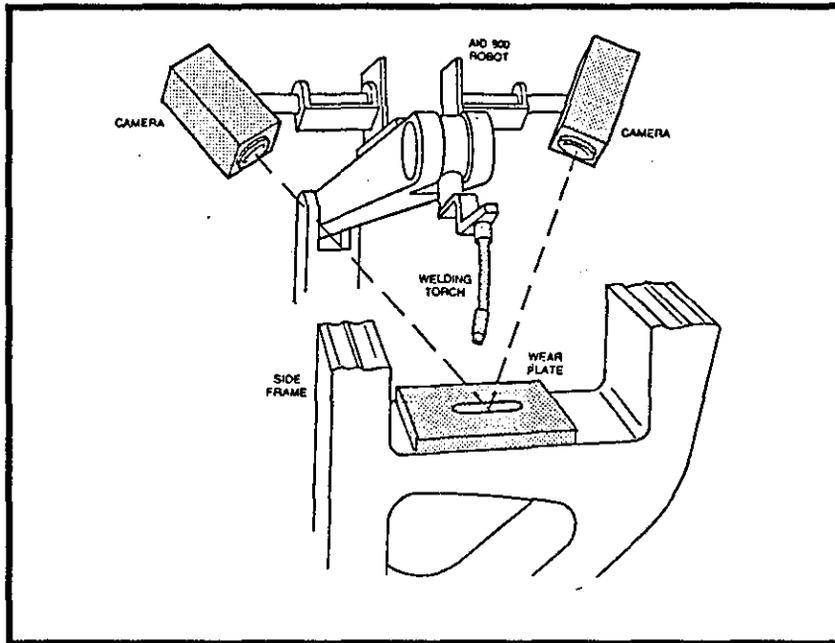
for seam tracking and for the collection of a three-dimensional profile of the joint. These sensors are based on two principles; "time-of-flight" [85,86] where the range is determined from the time needed for laser light to travel to the target and back to the receiver, or "Triangulation" [87,88], fig 3.12(b), which is based on

a beam of light projected onto the workpiece surface. The angle of incidence of this light beam and the reflected beam collected at the detector together with other parameters (e.g. distance between light source and detector lens, etc) are used to calculate the range. Various solid-state array cameras may be used such as vidicon tube, Charge Coupled Device (CCD), or Charge Injection Device (CID).

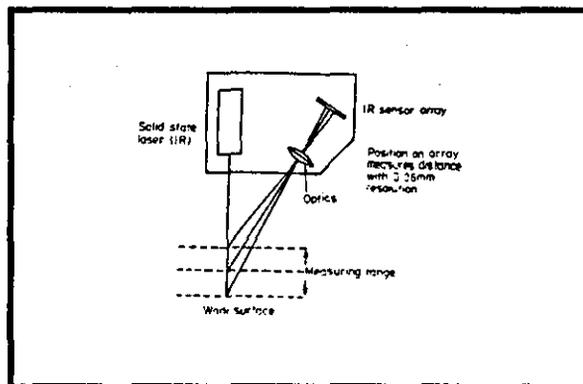
Sthen and Porsander [68] have demonstrated the use of an ASEA robot equipped with a laser range finder "Optocator" [89] for seam tracking in car bodies, fig 3.12(c). The sensor is mounted onto the robot torch holder with the measuring spot approximately 20mm ahead of wire tip, stand-off distance of head is 175mm, and a range of 32mm and resolution of 0.06mm. In the searching process, the joint is defined in three dimensions and the welding gun is positioned simultaneously. A complete search in three dimensions and location of gun takes less than 1.5 secs. The system was able to detect a sheet thickness as low as 0.8mm with search accuracy of less than 0.4mm.

Smati [64] used a laser range finder "Optocator" with scanning range of 70mm for joint finding and seam tracking. The sensor was applied to one-pass MIG welding of pipes and collected two-dimensional profile information about the seam. The workpiece is mounted on a static rotating device with the torch connect to a cartesian configuration above the workpiece enabling the torch to be moved to the required position on the joint. The sensor was mounted under the pipe. It used a laser diode source of light (spot light) projected to the workpiece and scanned across the joints using an oscillating mirror. The collected data was then used to extract features such as joint position, gap size, bevel angle and etc. Any variation detected in the joint parameter is later compensated by means of adjusting welding process parameters (e.g. wire feed speed, torch speed, voltage, and etc) using appropriate collected data in a mathematical process model. The scattered light is imaged by a lens onto the position sensitive photo-detector. The current produced in the device is a function of the position of the imaged light spot, and output is calibrated to remove non-linearities. A narrow band pass optical filter is used to reduce the interference from the arc light and the laser beam is modulated.

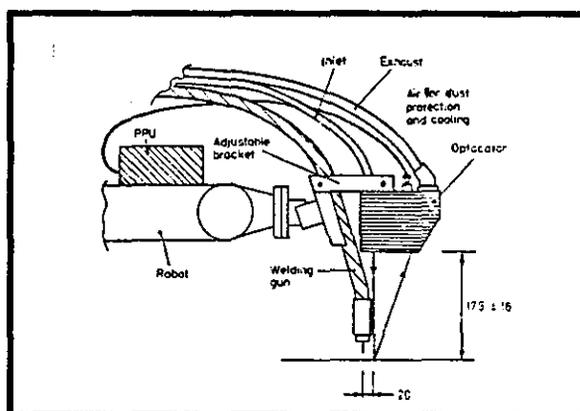
In earlier work by Smati [66], a similar sensor is mounted on the industrial robot arm (acting as a reactor manipulator) for single and multi-pass welds in the radioactive area



(a) - Binocular vision sensor developed by Lacoé [69].



(b) - Triangulation principle [34].



(c) - Laser range-finder system (Optocator) on robot [68]

Fig (3.12) - Shows two typical range finder sensors.

of a nuclear plant where high quality welds are required. It projects a narrow beam of light from a laser diode at a wavelength of 850nm, with a resolution of 1 in 4000, or 4 μ m in an active measuring range of 16mm. The modulated beam of 16 kHz is used for suppression from adjacent radiation sources with a data sampling rate of between 125 Hz and 8kHz. A similar sensor has also been reported in early research conducted between Loughborough University and British Rail [67] to demonstrate the feasibility of one-pass automated welding of the railway bogie side frames using the flux cored arc welding process. The sensor used had a measurement range of 32mm and stand-off distance of 180mm. The sensor was mounted on a Cincinnati robot arm with a xy linear motorised system and scanned the seam 25mm ahead of the torch with a minimum of 3 seconds lapse between the data being collected and processed. The report showed that despite the noise suppression techniques used sufficient noise was still present in the data to make direct measurement of the joint root face thicknesses difficult. A similar problem has also been reported in this research which will be discussed in chapter 5.

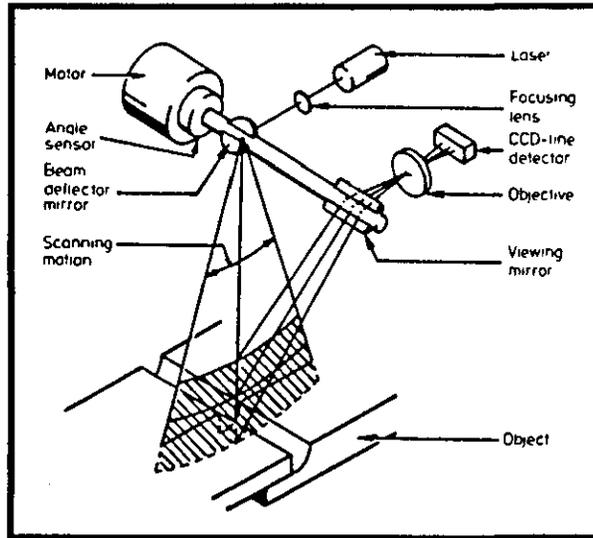
Vavreck and Nayak [90] have recently reported the use of a laser range finder for seam tracking of aluminium welding process in their research. The sensor (Laser Articulated Robotic System (LARS)) is based on the method of triangulation and located at 10.1cm in front of the welding torch. The source beam is emitted from an infrared semiconductor laser light of 750nm wavelength and 5 milliwatt which is projected as a spot of light on the surface of the workpiece and sensed by a CCD camera. A resolved distance of within ± 0.127 mm and nominal stand-off distance of 25.4cm can be achieved from the sensor. The scans are separated by approximately 0.5 seconds. The main advantages of the sensor over other laser scanning sensors is that the position of the beam and the exposure time for CCD camera are programmable. The disadvantage of the system was that the welding torch had to be manually located near to the beginning of the seam and prior to commencing automatic welding.

Betz [91] has described the design of a 3D Robo Sensor vision system which consists of a solid-state array camera and a structured light projector which projects a plane of light onto the surface to form a cross sectional image of the surface to be digitised. Accuracy of ± 0.13 mm and the field view of 50.8mm has been reported for is sensor with a data acquisition speed of approximately 0.3sec. The 3D vision sensor has been applied at General Motors Janesville, to accurately measure the position of the front pillar-roof seams and rear-sail roof seams on the J-cars where the weld paths of Cincinnati Milacron T3 Welding robots are then modified to adapt to the measured seam location and cross section. The sensor is also applied in inspection of a

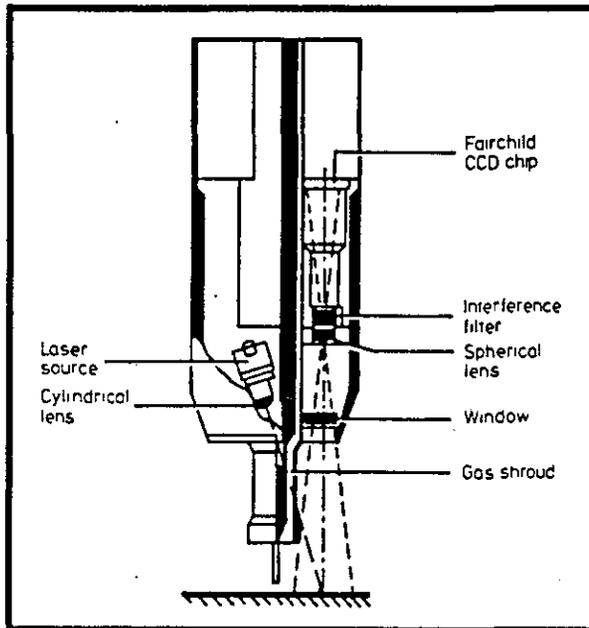
diesel engine and was able to measure over 800,000 data points to an accuracy of 0.25mm in 40 minutes.

Several researches have reported the use of Seampilot sensor for seam tracking for arc welding [72-74], fig 3.13(a). The Seampilot has been designed by Oomen and Verbeek [72] from the Oldeflt company in Holland. It is a compact vision sensor system which is able to detect the starting point of the seam, any tack welds in the seam, and calculate the seam volume for process control (real-time) with lateral resolution of a few tenths of a millimetre. The designed sensor is capable of tracking all types of seam and of modifying weld process parameters (in MIG,TIG) on the basis of weld/joint profile. The sensor uses a 1mW HeNe-laser and is based on the triangulation principle. It is able to collect information from the cross sectional profile of the seam by means of mechanically scanning the laser beam perpendicularly across the seam ahead of the torch. The projected laser beam is detected by a CCD linear detector system and the distance between the camera and workpiece is used to generate the three-dimensional profile of the seam. The sensor is capable of working in very harsh environments (e.g. spatter, arc-light, temperature, etc.). More recent work by Oomen [75] showed the Seampilot used for two-pass automated control of the welding process itself. The cross-sectional area together with volume of the seam is utilised in control algorithms to modify several welding parameters at the same time. Furthermore, the root gap and the asymmetric irregularity of the cross-sectional shape is measured with the sensor and relationship between torch orientation and weld quality is calculated. The system is able to detect tack welds and compensate for the tack's volume.

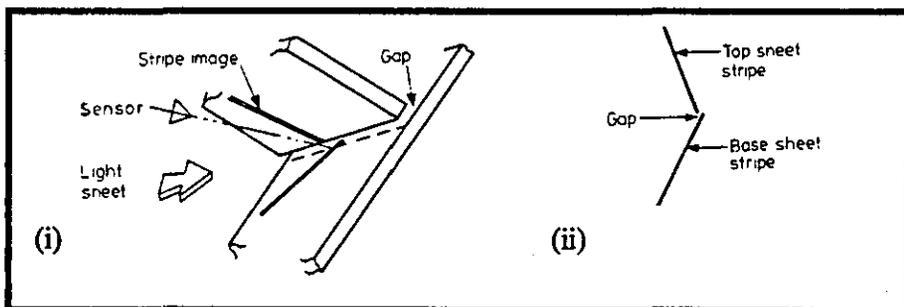
The MetaTorch sensor for joint searching and seam tracking has been reported by many researchers [63,65,76,77], fig 3.13(b) and (c). The MetaTorch was first developed specially for dip transfer MIG welding thin sheet material of thickness 0.8-3.2mm. It uses the structured light stripe technique. The sensor consists of four laser diode light sources (produces a light stripe) and two CCD cameras with 488x380 pixel array (monitors the shape of the work surface) which is packed around the welding torch in a cylinder of 57mm diameter by 200mm long. The sensor is mounted 16.5mm ahead of torch and views a field 16x19mm. The shielding gas shroud surrounding the weld tip is used to prevent the direct arc-glare from entering the optics and greatly reduces the bombardment of the camera's protective window by weld spatter. The sensor is applied to lap and fillet or T-joint. The computer analyses the data collected from the joint and generates appropriate gap, lateral and stand off correction signals. Such information is then used to modify welding procedures using mathematical models of the welding process. Further development by Davey [76],



(a) - Optical arrangement of the Seampilot Camera [34].



(b) - The MetaTorch sensor cross section [34].



(c) - The MetaTorch (i) stripe laser projection on fillet joint (ii) resulting image [34].

Fig (3.13) - Shows number of typical vision sensors.

enabled the sensor to be used for wider range of joint profiles, particularly those arising from curved pressings where there is curvature of the surfaces close to the seam, and on the intersection of the curves locally at the joint. Furthermore, Davey developed a sensor so that the camera image remained sharp over an extended range of distance, and a single frame could be handled by extending the range of light levels along the line segments in the structured light. Koelbl and Morgan [77] recently reported the practical industrial application of MetaTorch (200, 500, TIG series), such as applications in USA, Germany's most prestigious automobile manufacturers, aerospace industry, and at a customer's site in Sweden. Advanced model-based seam tracking algorithms for following complex seams (e.g. the circumferential seam of a suspension unit, or components produced for heavy earth moving vehicles in the USA) were used to produce optimal welds.

A more recent sensor demonstrated at 12th Essen international welding fair 1989 [94] was Modular Vision Systems Laservision. The sensor is a very compact device which utilises laser illumination and a CCD camera, and uses a dedicated image processing system. It is claimed that the position of the torch relative to the seam may be checked 60 times a second allowing rapid correction of tracking errors.

3.5 The Suitability of Commercially Available Sensing Systems for the Pre-Weld Inspection Station

The pre-weld inspection station (two-pass system), the subject of this research, was required to be designed, calibrated and implemented on the Westwood conveyor within a flexible robotic welding cell in order to inspect the quality of the component parts arriving at this station prior to the welding operation. Ideally, the inspection task will provide information such as; the position and orientation of components on the work pallet, identify the joint types, measure the plate thicknesses, and calculate joint parameters such as root gap, root face thickness, bevel angles, joint area, etc. At this point in time it is only possible to collect joint information from an assembly accurately jugged in a fixed location on a pallet. In the prototype system, the component parts and joint under inspection are assumed to be in the flat position with square-butt or one-sided single V-butt preparation and made of Carbon and Carbon-Manganese steels of up to 12mm thickness and produced to British Standard BS5135 [4]. The assembled component parts on the pallet may deviate in root gap and plate edge alignment during fixturing and tack welding, cutting, forming, etc, and/or in root face thickness and bevel angles faces due to manufacturing variations. The thermal distortion during fabrication must also accounted for despite tack welding of the

assembly.

The application of tactile and inductive sensing to the pre-weld inspection station may be restricted. These sensing systems usually suffer from a bulky end-effector and tend to be specialised for particular materials or joint configurations. Tactile sensors have a tendency to wear, lose contact with the joint, and cannot follow complex contours. The speed of inspection is limited which could delay the cycling operation in the system. Tactile seam tracking systems are used where relatively simple linear joints are available and offer a low cost and simple solution. Inductive seam tracking systems are claimed to be usable on aluminium, copper, austenitic and ferritic steels in addition to simple Carbon and Carbon Manganese steel and for both butt and fillet joints [56]. However, the appearance of holes, bosses and tack welds, around or in the seam tend to distort the eddy current path during seam tracking. Inductive seam trackers also have some restrictions over joint configurations but, most importantly, precise quantitative data regarding joint dimensions cannot be obtained and they are therefore not suitable for the pre-weld inspection station.

Through-the-arc sensing systems are the most common sensors used with industrial welding robots. These systems have been successfully applied to real-time seam tracking for both gas metal arc and gas tungsten arc welding processes. The technique is not suitable for the pre-weld inspection.

In the pre-weld inspection station, the variation in root gap and root face thickness was allowed to be between 0 - 2.5mm for unbacked square-butt of 2mm and 3mm plate thickness and unbacked one-sided single V-butt of 4mm to 12mm plate thickness. Bevel angles variation is allowed to be between 20 deg. - 35 deg.. These variations necessitate compensatory action in the welding process which is beyond a seam tracking capability if acceptable weld beads are to be produced. Visual sensing systems are receiving the most attention today for flexible robotic welding cells. The technique is capable of providing much more information than simply seam tracking. It can obtain information such as Seam area and/or volume, 3D profile of the joint, root gap width, weld pool shape, etc, and use this information to control welding process parameters and produced an acceptable weld bead. They can be used for ferrous and non-ferrous materials. The sensing system is also independent of the welding process. Visual sensing systems do not have any contact with the seam during seam tracking. Therefore, the joint can be inspected more quickly.

A number of commercial visual sensing systems based on structured light and the triangulation principle are available, as described in section 3.4.4, which can be

used in conjunction with image processing for joint measurement for two-pass systems. These sensors include; The "WeldVision" [80] from the General Electric company based on the work done by Richardson [78], "MetaTorch" [76,77] marketed by Meta Machines, "Seampilot" developed from the work by Oomen [75] from Oldeflt company, TIMTRACKER developed in Liverpool University [82], "Optocator" laser range finder from Selcom [89], etc. SeamPilot may be applicable to the pre-weld inspection station, but seems to be expensive, bulky, and requires more computational power. MetaTorch may also be applicable (Metatorch 500 series) to pre-weld inspection station. MetaTorch has been successful for real-time seam tracking and monitoring both the joint profile and the weld pool. These sensors may be suitable for in-process inspection. On the other hand, successful similar welding application of the Optocator has been reported by many researchers [64,67] and this sensor requires less computational processing power and time (80 data point/scan). The sensor size of type 2203 (120x97mm) has also made it more suitable for the application to the pre-weld inspection station in this research where there is a shortage of space. Whatever sensor is used, it requires a mathematical model or knowledge based expert system to establish the necessary process parameters compensation for the joint variation. Section 3.6 gives a detailed survey of the mathematical modelling for welding and the motivation for the application of non-mathematical modelling expert system for the pre-weld inspection station. The "Optocator" laser range finding device was selected as offering the most appropriate features overall.

3.6 Robotic Welding System With Adaptive Process Control

As has been described in section 3.2, seam tracking techniques are used to monitor and maintain the desired location and possibly orientation of the torch with respect to the seam, and may also provide information about the joint. To make most effective use of arc welding robots it is also necessary to provide the robot with a tool to control the welding parameters. A high degree of confidence has to be achieved in predicting the weld bead geometry and shape relations to attain the desired mechanical strength in the weldments. Several researchers [93-99] have employed the mathematical modelling technique. Such technique required a large amount of data to be analysed and are not cost effective in terms of development for many different joints type, welding processes, time required to develop the models, etc. The author has carried out a survey of approaches used in development of mathematical modelling together with welding procedures selection using these models.

3.6.1 Approaches in Development of Mathematical Models

Since arc welding began, there have been many attempts to predict the effect of the input or controlled variables (elements of a welding procedure) on the output variables (weld bead geometry, dimensions, etc). Two approaches have been widely adopted [94]; entirely theoretical approach based on heat flow theory, and empirical approach based on actual welding experimentation. In the theoretical approach, the welding process model is built from physical considerations, and particularises to the practical situation by observation, whereas, in the empirical approach data collected from the practical situation is used to develop empirical equations by one mathematical technique or another. Shinoda and Doherty [94] have reviewed the literature and concluded that although the theoretical approach minimises the experimentation, in its disfavour was the difficulty of ensuring that all relevant factors were considered and that the model adequately described every welding situation. Clark [95] confirms this view by stating that predictions of weld bead based on heat flow theory are unsuccessful due to the complexity of the many interacting factors such as convective mixing in the pool, the impact of fused droplets on the pool, magnetic forces, latent heat of fusion, temperature dependence of properties, surface heat losses, etc. Due to the complexity of the problem most approaches to the prediction of weld bead shape have necessarily been empirical. McGlone [96] has also reviewed these approaches and reported that the theoretical approach could not be used to derive equations capable of relating the arc welding controlled variables to the weld bead geometry dimensions. The difficulties in overcoming the complexities of interactions and reactions between the variables, coupled with the vastly over-simplified assumptions prove too great.

The tolerance box technique is more systematic and can be valuable when selecting process settings but is limited as no quality feature can be related graphically to more than three process parameters. It is also expensive, time consuming, provides no statistical information and no data on interacting variables [97]. The traditional experimental technique of studying the effects of several factors is the "one-variable-at-a-time" approach. The technique is used to study for example the effect of two factors wire feed speed (WFS) and torch speed (TS) on the quality of output root penetration (RP). The "one-variable-at-a-time" approach would be to hold TS constant at some prescribed level and then note how RP varies with WFS. This might be repeated for several other levels of TS. Then WFS would be held constant at several levels and the effects of TS on RP studied. Replication of each elementary experiment might be made to get an estimate of the experimental error. This technique is a time consuming and costly exercise and involves too much experimentation. However, the more modern factorial or partial factorial design of experiments

approach have already been successfully used in other areas e.g. chemical engineering, agriculture [96]. In welding, many researchers have also reported [93-98] such experimental design to study weld quality. The approach suggests that the number of elementary experiments called for by the traditional "one-variable-at-a-time" approach of analysis may be unnecessarily large when (1) we have somewhat limited objectives and (2) it appears justified to make special assumptions regarding the factors involved in the experiment and the nature of the experiment errors. In this approach, for each variable the range of interest is represented by a number of levels and experiments done so that each level of each variable occurs at every level of every other variable, e.g. five variables at three levels require $3^5 = 243$ experiments. The effect on the weld bead dimensions of any combination of input variables can be determined from the experimental results by an analyses of their variance. The total variation in the experimental set is computed and then apportioned between interactions. The analysis of variance reveals the important factors for each weld dimension. fitting equation to experimental results may be done by multiple regression analysis; as a test of the goodness of fit actual values are compared with values predicted by equation. Many researchers have found this technique to be valuable in the modelling of a variety of welding processes. Therefore, the first recommendation would be to state clearly the objective of the experiment and to carefully design a set of experiments so that interactive effects between factors can be detected. Doherty [99] confirms this view by stating that anything other than the most carefully designed experiment may provide misleading results as factors may interact in a complex manner. The second recommendation would be to note any prior knowledge that we may have regarding the factors and the technique of experimentation.

Many practical approaches have been carried out because welding is a complicated phenomenon which cannot be described theoretically. Shinoda and Doherty [94] have reported that there are many difficulties in predicting weld geometry by such approaches because the shape of penetration is affected by several factors, including minor element changes in base metal, and a large amount of experimental work is required. In favour of the pragmatic approach is the speed with which any particular problem can be solved. Data gathered directly from the situation enables equations to any desired degree of accuracy to be quickly generated. Its drawback can be a heavy commitment of resources for the experimentation since the data is specific to a particular situation and one problem will not often generalise to provide a solution to the next.

The empirical approach is carried out to provide a relationship between process variables and weld bead geometry. Doherty and McGlone [93] have concluded that on

a statistical basis, acceptable equations can be developed relating welding current, travel speed, voltage, wire diameter to weld bead width and height, and weld penetration, etc. This approach has been successful and widely used by many other researches [3,64,97,98]. In this approach, combinations of welding parameters (factorial experiments) are established to produce welds of a given quality, mathematical techniques such as multiple regression analysis are then applied to correlate welding parameters with weld geometry to establish an appropriate model or equation as a function of all input variables.

In disfavour of this approach is the considerable amount of experiment, time, and cost involved in the development of a model(s) (or equation(s)), which may only be applicable to a single combination of plate thicknesses, joint type, etc [3,93]. Middle [13] has also confirmed this view by stating that "developing process algorithms (or mathematical models) for adaptive control can be a costly and lengthy process, and the resulting algorithm may be quite joint specific. Therefore, there is a real need for a generalised modelling system". Such generality of a modelling system can be provided through the application of the non-mathematical modelling expert systems.

Artificial Intelligence (AI) or expert systems can be used to model mental faculties. Expert systems with their ability to handle non-mathematical data can replace some of the welder's tasks in controlling the welding process and widen the applicability of robotic welding [100]. In this research, information from the joint geometry (e.g. root gap, root face thickness, etc) and/or weld pool, is used in an expert system to enable a robot to react quickly to changes by adjusting its welding parameters (such as torch speed, wire feed speed, voltage, etc). Such adjustment of parameters require a high degree of confidence to be achieved in predicting the weld bead geometry and shape relations to attain the desired mechanical strength in the weldments.

A non-mathematical model expert system [100] in the form of 'if - then' rules can be programmed and feedback to the robot can be used to emulate human judgment with a degree of confidence. In favour of the non-mathematical modelling expert system approach, the subject of this research, the models can be built in a shorter time which also reduces the costs and they can be of a more generic nature. The building of the models involve:

- 1) elicitation of welding domain knowledge from an expert or a welder,
- 2) formulation of the knowledge in the form of rules,

- 3) implementation of the rules in an expert system knowledge base,
- 4) and finally, carrying out test validation on the rules.

In this way, some of the welder's tasks in controlling the welding process are replaced and the applicability of robotic welding is widened.

3.6.2 Mathematical Models for Selecting Welding Procedures

When arc welding is chosen as a method of fabrication, suitable welding procedures must be established. In many instances, especially in manual welding, these are based on established practice, and are no more systematic than reference to a manual. However, with the increase of mechanisation and automation in arc welding, the solution of welding procedures must be more specific to ensure that adequate weld bead quality is obtained. Practically any joint can be made by several welding processes; each welding process can give a different set of weld properties. Doherty selected submerged arc welding process (SAW) for study [99] because the levels of the inputs can be made sufficiently distinct from one another to permit an overall appreciation of the relationships between inputs (such as wire feed speed, torch speed, voltage, etc.) and outputs variables (such as weld bead width, height, depth of penetration, etc). These relationships were later extended by Doherty and Chadwick [101] to cover the MIG process as that of most interest for robotic arc welding. Doherty and McGlone [93] has also concluded that the equations describing the weld bead produced by the submerged arc welding process can be used to predict the bead size deposited by the gas metal arc welding (GMAW) process. This could be achieved by recalculating the partial regression coefficients or by forming a new equation of the form:

$$P(\text{GMAW}) = a_0 + a_1 P(\text{SAW})$$

Where a_0 and a_1 are constants and account for the process differences. Consideration has been given to weld metal metallurgy and mechanical properties, as well as the selection of the most economic welding process from those technically acceptable. Doherty [102] has confirmed this view and reported that the cost effectiveness of any welding procedure will depend on the process chosen and the selection of the parameter levels for that process. Whilst such a statement is acknowledged there is little evidence to show that a systematic approach to the development of such procedures is widely practised [93]. A number of factors may be

defined which could affect the selection of welding procedure. McGlone [103] has discussed these factors by identifying twelve potentially significant process variables for submerged arc butt welding, and several were found to interact with each other. He has included primary variables such as welding current/wire feed speed, welding voltage, and welding travel speed which he claims have major effects on weld quality. Furthermore, mathematical relationships are required to correlate these welding variables (factors) with weld geometry. Several researchers [3,96-98] have reported the development of such mathematical models which relates the weld parameters to the resulting weld bead geometry using techniques recommended by Doherty [99]. These techniques use a carefully design factorial experiment providing combinations of input variables. The results, or responses, of which can be analysed by ANOVA (ANalysis Of VARIance) techniques. ANOVA reveals the important factors for each weld dimension. Multiple regression analysis can be used as a test of the goodness of fit of actual values compared with values predicted by the equation. The form of equation used has been found to give a good fit with different welding processes and is shown as:

$$P = a + b S^{C1} W^{C2} V^{C3} E^{C4}$$

The weld bead dimension, P, is related to two process-determined constants a and b, and the procedure inputs S, W, V, E, are respectively torch speed, wire feed speed, voltage, and contact tip to work distance which are raised to powers (C1 - C4) depending only on the bead dimension of interest. McGlone [103] has followed the same techniques recommended by Doherty [99]. The submerged arc welding process for square close butt joints of 12.7mm and 19mm steel plate was used. The combinations of certain welding factors (wire feed speed (I), Voltage (V), torch speed (S), and wire diameter (D)), are used for factorial experiment i.e. $2 \times 3^3 = 54$ factorial experiments were carried out. After the analysis of variance and the multiple regression analysis, a mathematical model in the form of an equation capable of evaluating penetration (P) as a function of all four input are represented as:

$$\log P = c_0 + c_1 \log I + c_2 \log V + c_3 \log S + c_4 \log D$$

Where $c_0 - c_4$ are constant. This approach was then extended to include, the joint included angle A in the equation as $(1 + \tan A/2)$ so that the bead geometry of welds could be computed. the form is then shown as :

$$\log P = c_0 + c_1 \log I + c_2 \log V + c_3 \log S + c_4 \log D + c_5 \log (1 + \tan A/2)$$

McGlone [96] in his recent research developed mathematical models capable of accurate prediction of weld bead dimension, from input variables of welding current, voltage, torch speed, joint included angle and electrode diameter. Submerged arc welding was used to butt weld mild steel plate of one thickness. A $3^3 \times 2 \times 4$ complete factorial experiment is carried out (i.e. 216 experiments). Hunter et al [104] have also used the same technique and developed a mathematical relationship between the input variables (travel speed, wire feed speed, voltage, and contact tip to work distance) and outputs of the welding process (leg length, bead height, penetration along the joint). These relationships were used to select procedures and to obtain on-line control laws for welding arc process. A carefully design factorial experiment was carried out. In the design, the parameters such as consumable type, wire diameter, gas composition, welding position, root gap, and gun angle which have less influence on weld bead geometry are kept constant and the parameters such as torch speed, wire feed speed, voltage, contact tip to work distance are varied at three different several levels (low, medium, and high). Hence, $3^4 = 81$ experiments were carried out. Experiment sets were carried out and the mathematical models for 2.4 and 1.6mm diameter fluxed cored wire and 1.2mm diameter solid wire with various shielding mixtures were found. Only fillet welding in the flat position was investigated in the research.

Raveendra and Parmar [98] have reported the development of five models to predict weld bead geometry and shape relations for CO₂ shielded flux cored arc welding, as functions of arc voltage (V), welding current (I), welding speed (S), nozzle to plate distance (N), and gun angle (T). The experiments were designed to correlate these independently controllable welding parameters to weld bead quality parameters such as penetration (P), weld width (W), reinforcement height (H), width to penetration ratio (A), and percentage dilution (D). The interaction effects between five variables (VISTN) at two levels (low and high) were tested in a half fractional factorial experiment (i.e. $1/2 \times 2^5 = 16$ experiments). For ease of recording and processing of the experimental data, the upper and lower levels of the variables were coded as +1 and -1 respectively. 13mm thick low carbon structural steel plate was used. The general form of the equation was given as:

$$\begin{aligned}
 P = & b_0 + b_1V + b_2I + b_3S + b_4T + b_5N + b_6VI + b_7VS + \\
 & b_8VT + b_9VN + b_{10}IS + b_{11}IT + b_{12}IN + \\
 & b_{13}ST + b_{14}SN + b_{15}TN
 \end{aligned}$$

Where $b_0 - b_{15}$ are the constants. Modification of the model gave further models for weld width, reinforcement height, width to penetration ratio or percentage dilution. Shepherd [3] has developed a similar mathematical modelling technique to that reported by Doherty [99] and Hunt et al [103]. The models were developed to express the levels of controllable welding factors as a function of the joint geometry, such that acceptable weld beads are produced. The self shielding flux cored electrode arc welding process was used to weld plain carbon steel of 12mm thickness with a single J preparation in the horizontal-vertical position. The root face thickness of the joint preparation varied between 0.5mm and 2.5mm whilst the root gap varied between 0 and 1.5mm. To develop the mathematical models, 2187 experiments were required (seven welding factors at three levels low, medium, and high i.e. $3^7 = 2187$). This amount of experimentation was reduced to 243 with a carefully designed fractional factorial experiment (i.e. $1/9 \times 3^7$). These models were used to relate the weld bead geometry, incidence of porosity and the occurrence of electrode stubbing to a function of up to seven factors. Hence, the model represented in the form of:

$$R = a_1 + a_2 \text{ WFS} + a_3 \text{ TS} - a_4 \text{ SO} - a_5 \text{ POJ} - a_6 \text{ WFS(TS)}$$

Where $a_1 - a_6$ are the partial regression coefficients and shows how the response was affected by changes in factor levels. The equation shows that the response (R) increases as wire feed speed (WFS) and torch speed (TS) increase and decreases as the stand off distance (SO) and/or electrode position on the joint (POJ) increases. Furthermore, simplified models relating uncontrollable factors to controllable factors were shown as the following form:

$$\text{SO} = b_1 + b_2 \text{ RFT} - b_3 \text{ RG} + b_4 \text{ RG(RFT)}$$

Where the root face thickness (RFT) and root gap (RG) are related to the stand off distance (SO), and $b_1 - b_4$ are constants. Such a model shows how the stand off distance must vary as the root face thickness and root gap change in order that acceptable weld beads are produced.

The more recent development carried out by Chandel [105], uses a computer program written in 'Smalltalk' which is able to compute the weld bead geometry. The program provides the user with the bit mapped graphics featuring windows, panes, stroke control, and pop-up menu. After all weld process parameters such as current, voltage, electrode diameter, electrode extension, travel speed, electrode polarity, and shielding gas are entered by either a user or external program, Smalltalk then computes

the nugget features such as bead width, reinforcement height, penetration, nugget area, etc and draws the weld nugget graphically to scale. The calculation of the weld bead shape utilises the mathematical models developed over 205 weld experiments. The program is capable of dealing with 19mm thick steel for the gas metal arc welding process. The welding consumables of 0.89, 1.14, and 1.59mm diameter were used together with two shielding gases; M-2 (2% O₂ + 98% Ar) and C-25 (25% CO₂ + 75% Ar). A total of 205 welds experiment (24 regression equations) were carried out with different weld parameters for each weld. The welding parameter ranges used in the experiment were; arc voltages between 24 and 32 volts, welding current from 140 to 400 amps, electrode diameter from 0.89 to 1.6mm. The travel speed ranged from 3.8 to 6.35 mm/s and, the electrode extension ranged from 15 to 35mm. From the forging the vast amount of experimentation needed for modelling and the highly joint, material and process specific nature of the models will be appreciated.

3.7 Limitation of Current Adaptive Control System

The cost effectiveness of any welding procedure will depend on the best availability of knowledge about the process and the selection of the best parameter levels for that process. Such knowledge and selection of parameters levels requires a large amount of experimental work, analysis, and consequently generation of mathematical models. However, mathematical models for welding procedure selection is restricted by time and cost involved in developing them and a large amount of data also has to be dealt with. Several researchers [3,93-99] confirm this view and show that the development of mathematical models for one or two different plate thicknesses, welding processes, or joint types would required at least a few years of intensive research and development. Hunter et al [104] has concluded that although such a technique is useful and may be used in industrial environments, a general framework is required to extend the other input variables, materials consumables and welding processes. Such requirements, in the author's opinion, is the consequence of heavy investment and man hours to research and develop mathematical models. Doherty and McGlone [93] have developed mathematical models which are capable of only dealing with the square butt of 12.7mm plate thickness for the submerged arc welding process. There is no evidence of the time and cost spend in development of the models. Early research and development at Loughborough University by Shepherd [3] showed that more than three man-years of research was spent to develop mathematical models capable of only dealing with flux cored electrode arc welding for plain carbon steel of 12mm thickness with the single J joint type with little potential for generalisation. Shepherd concluded that "the experimental effort required to generate the predicative

models was considerable, despite the use of fractional factorial experimentation. This effort may prove prohibitive to the exploitation of adaptively controlled robotic arc welding unless the development costs can be reduced or the costs spread over many robot systems. Alternatively, The use of intelligent knowledge based computer systems to capture the skills a manual welder possesses should be explored in an attempt to reduce the cost of developing the simplified adaptive models (rules)". As stated previously this is a view confirmed by Middle [13]. Therefore, there is a real need for a generalised modelling system. Such generality of a modelling system is provided through the application of the non-mathematical modelling expert systems. Kuhne et al [100] has reported that in welding manufacturing, the knowledge that cannot be mathematically described is approximately 80% to 85% of the whole knowledge. By representing this knowledge in computer programs such as expert systems and connecting these programs to the manufacturing process, a major step can be taken to improve the adaptive control in automated welding manufacturing environments.

CHAPTER 4:

Literature Survey :
Expert Systems for Automated Welding

CHAPTER 4 : LITERATURE SURVEY: EXPERT SYSTEMS FOR AUTOMATED WELDING

4.1 Introduction

This chapter contains a general survey of expert systems and their application into various areas with particular emphasis on automated welding systems. It starts with the background of expert systems generation and the requirement of flexible robotic welding systems (section 4.2). The general issues of these systems have been discussed in section 4.3. These are; features and components, motivation behind their development, problems associated with them, etc. Furthermore, the comparisons between conventional computer programs and expert system software, and commercially available expert system shells have been investigated. The KES expert system shell has been selected for PIKBES and the reason behind its selection has been discussed thoroughly (section 4.4).

This chapter also investigates the application of expert systems as an intelligent tool in welding operations (Section 4.5) and looks at five main areas; welding procedure generation, welding design, process/electrode selection, process/equipment diagnostics, and process control.

Finally, the proposed design of expert system and its implementation (PIKBES) has been discussed (section 4.6). Five stages of building the knowledge has been considered as; problem identification, conceptualisation, elicitation, formalisation, implementation, and testing as well as the need for reformulations, redesigns, and refinements.

4.2 Background

Since the establishment of the Alvey directorate [106,107] for the implementation of information technology programmes into areas of software engineering, man/machine interface (MMI), intelligence knowledge base systems (IKBS), and very large-scale integration (VLSI), the application of expert systems has shown to be very successful in many different areas of science and technology such as medicine, education, science and engineering, design, fault diagnosis, financial and

legal, military and space, manufacturing, etc [108-110].

The field of welding is not an exact science and it is difficult to predict the exact outcome of a welding operation. This characteristic is partly responsible for the limited applications of conventional software in welding. The ability of expert systems to cope with uncertain data and to be able to reason problems out probabilistically means that 'reasoned' judgments can be made about such an imprecise area.

There is increasing interest in the use of expert systems for mechanised and robotic welding applications to provide procedure generation, process, consumable and equipment selection, process/equipment diagnostics, etc, and as part of computer integrated systems. For their use in process control to be successful, sensors at the welding station capable of detecting what the skilled welder previously sensed will be required in the system. Their outputs can then be used to drive suitable rule based systems, or models of the welding process, to execute appropriate decisions. Various sensory systems can be applied. For example, machine vision has been used in order to give 'sight' to a blind robot for seam tracking, correction of joint mismatch and for general improvement of quality. Similarly proximity and tactile sensors can be used to provide 'feel', arc noise can be analysed and heat and light sensitive devices can be used to monitor the weld pool. Available sensor technology has already been discussed in section 3.4 of chapter 3.

4.3 General Issues in Expert Systems

4.3.1 Features of Expert Systems

An expert system is a computer program which embodies organised knowledge concerning some specific area of human expertise sufficient for it to perform as a skillful and cost effective consultant. An expert system may emulate the external behaviour of an expert (i.e. gathering information and producing solutions to problems). Alty [111] has argued that expert systems are a development of traditional data processing. He added that all programs contain human knowledge of some form, even a payroll program. However, There is a common agreement on the distinctive features [112] which expert systems have. These are:

- (1) An expert system is limited to a specific domain of expertise. A specific expertise area has to be chosen and all of the KNOWLEDGE about that area has to be collected. This involves interviewing experts in the field, collecting information from books, journals, etc.

- (2) Expert systems can REASON with uncertain data. They are able to recommend a course of action even if the user does not know answers to some of the questions. Uncertain data in the form of 'probably' or 'unlikely' to a question can be handled by such systems. A question may typically be of the form : 'How sure are you that the voltage has to be 21 volts?' The answer may be numerical, such as between -5 to +5 where -5 rates as 'extremely unlikely' and +5 rates as 'almost certain'.
- (3) They can explain their train of reasoning in a comprehensible way. In the same way as a human expert explains his line of reasoning. The computer should be able to answer the questions such as 'what', 'why', and 'how', for example, 'How have you arrived at that conclusion ?'.
- (4) Facts and inference mechanism are clearly separated. In this way, if the facts need to be changed or added to, it can be done quickly without any need to change the inference mechanism.
- (5) They are designed to grow incrementally. As more knowledge is gathered, this can be coded and added to the knowledge base. In this way, knowledge about a particular domain can be grown.
- (6) They are typically rule-based. Knowledge elicited from experts in the field or from other sources is coded in to a form of rules or heuristics and placed in the system knowledge base.
- (7) They deliver advice as their output, not definitive data. They will recommend a certain course of action rather than specify parameters, although parameters may be included in the advice. This is similar to the way a human expert would state conclusions, for example on, the remedial solution to a problem.
- (8) Within their scope of application they can be highly cost effective. Goodall [117] has discussed the application of expert systems which have increased turnover in VAX computer company (XCON/R1), saved time and money in oilfield decisions (Drilling Advisor), saved money on equipment selection (DENDRAL).

The key word are knowledge and reasoning. Clearly, the objective of an

intelligent problem-solving system (like a human) is to cut out blind or random searching. To do so a computer system has to exploit the same advantage that the human expert has over the novice - i.e. he processes expertise or organised knowledge. Knowledge about facts, knowledge about rules of inference and knowledge about solution strategies. However, up to now the biggest problem has been getting the knowledge from an expert into machine-manipulatable form.

4.3.2 Components of Expert Systems

Expert systems are basically constructed of three components, a knowledge base, an inference engine, and a user interface, fig 4.1. However, there is an important prior stage in the development of an expert system, i.e. knowledge elicitation or acquisition.

4.3.2.1 The Knowledge Acquisition

Knowledge acquisition is probably the most time consuming stage in the development of expert systems and is usually carried out through dialogue between one or more domain expert and the knowledge engineer. Knowledge may also be obtained from published sources, etc.

- i) Domain expert - is a specialist in a particular field with the ability to apply knowledge to solve problems and make decisions.
- ii) Knowledge Engineer - knowledge engineers are first concerned with identifying the specific knowledge that an expert uses in solving a problem. Initially, the knowledge engineer studies human expertise and determines what facts and rules of thumb the expert employs. Then the knowledge engineer determines the inference strategy that the expert uses in an actual problem solving situation. Finally, the knowledge engineer develops a system that uses similar knowledge and inference strategies to simulate the expert's behaviour.

The knowledge engineer will develop a working knowledge of the domain field, relying on introspection to articulate the requisite knowledge. The knowledge engineer then encodes the knowledge into computer language or uses an expert system shell. The enclosed knowledge becomes the knowledge base of the expert system. The

knowledge engineer is therefore responsible for "translating" and implementing knowledge.

The difficulty lies in eliciting knowledge from a domain expert and encapsulating such knowledge in the computer in a suitable form. The knowledge is usually heuristic, judgmental, subjective or intuitive in nature and the domain expert must be totally committed to the concept of expert systems to make his contribution meaningful. Yazdani [114] has described three types of knowledge as:

- i) Factual (declarative) Knowledge - this knowledge represents a particular case and is usually gathered through a dialogue with the user to establish what facts are true at the present time. The way such information is represented is important, as the structure of the representation contains information.
- ii) Procedural Knowledge - this knowledge is usually collected in advance from the domain specialist and forms the core of a knowledge base. This also forms the reasoning part of the system in order to infer conclusions. Such procedural rules can generate facts on demand. Furthermore, these rules need to be open to manipulation by other rules at the run time.
- iii) Control Knowledge - the system needs to have a variety of control strategies available to it so that alternatives can be tried out at run-time and be able to deal with failed attempts.

The collection of knowledge about the domain and the important sources of information are mainly : 1) direct interviewing of experts in the field, 2) rule induction from examples, 3) information from book, journals, etc.

There are a number of guidelines which assist in knowledge acquisition from domain experts. Olson and Rueter [115] have reviewed the literature and reported that there are two classes of knowledge acquisition methods; direct and indirect methods. The 'Direct method' asks the expert to report on knowledge he/she can directly articulate. This set of methods includes interviews, questionnaires, simple observation of the task performance, protocol analysis, interruption analysis, etc. In contrast, 'indirect methods' do not rely on the expert's abilities to articulate the information that is used; they collect other behaviours, such as multidimensional scaling responses. This technique provides similarity judgments on all pairs of objects or concepts in the domain of inquiry. The analyst can then make inferences about what the expert must

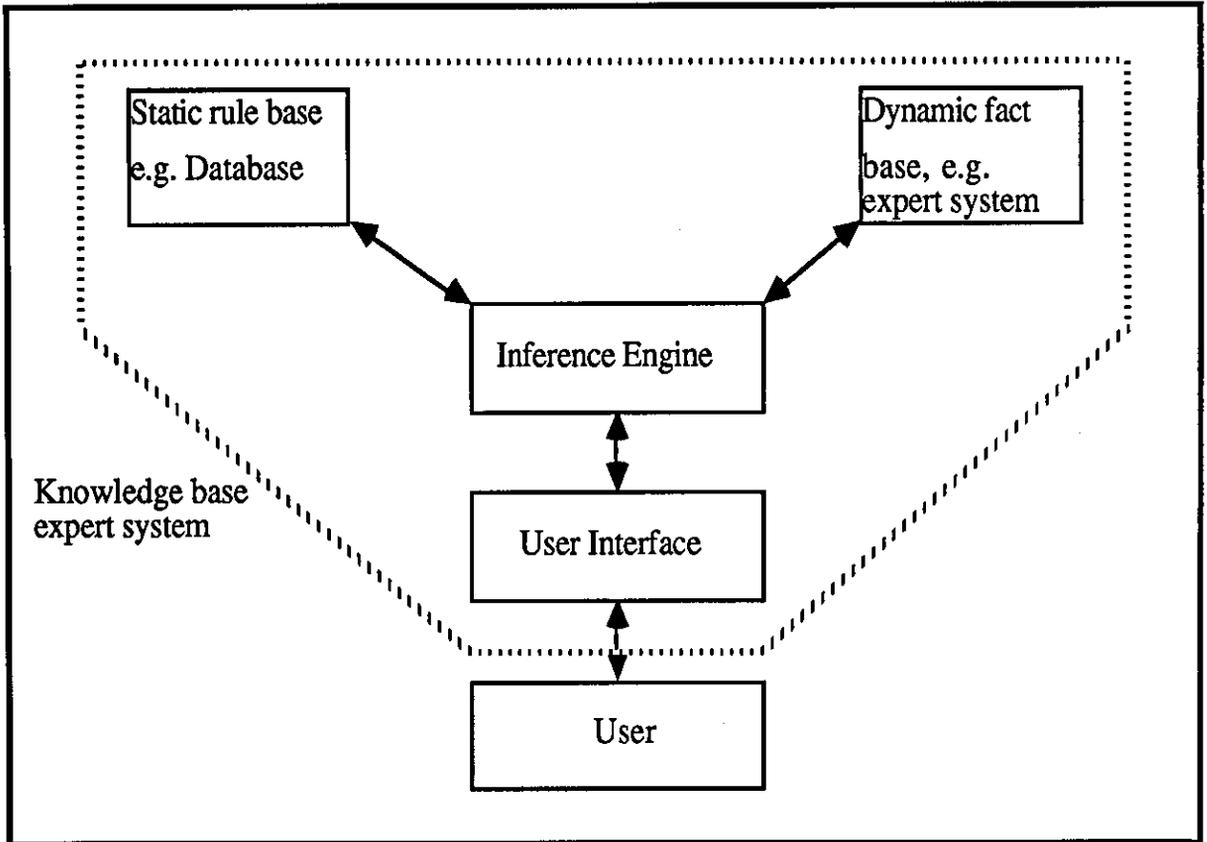


Fig (4.1) - Components of an expert system [123].

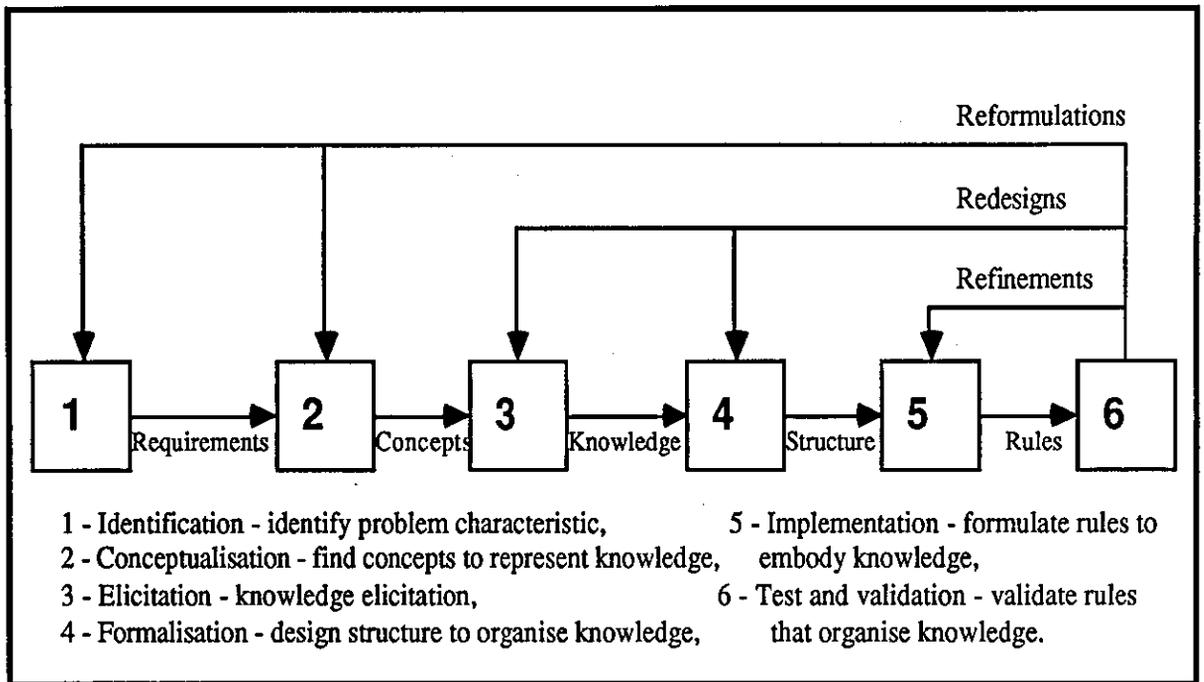


Fig [4.2] - Stages of knowledge representation (developed from [116]).

have known in order to respond the way he/she did. During building of an expert system, one has to realise the problems associated in the develop of such a system. Heng [116] has reported that there are mainly four crucial problems when developing an expert system, namely:

- i) The problem of defining system requirements,
- ii) The problem of extracting expert knowledge,
- iii) The problem of organising and structuring expert knowledge for machine manipulation,
- iv) The problem of maintaining the interest and enthusiasm of the domain experts.

The author considers that a fifth stage, representation of the knowledge, is also required. The stages in which knowledge has to be acquired and represented, i.e., formalised, implemented, and tested are given in fig 4.2. Furthermore, Heng has concluded that a better understanding of the structure of the knowledge, especially expert knowledge, will enhance our ability to build expert systems. He suggests a comprehensive "periodic table" of expert knowledge which technique can provide enlightening clues for organising and manipulating knowledge. The author of PIKBES also found that a tabular method of knowledge categorisation was valuable in this research.

4.3.2.2 The Knowledge Base

The knowledge base stores information collected from the subject domain. A knowledge base contains facts and rules. Facts may be either permanent, for example the composition of mild steel, or may be variable depending on the state of knowledge during the course of a consultation, for example, the level of certainty associated with an opinion can change as more knowledge is gained. Rules are the longer-term information about how to generate new facts or hypotheses from what is presently known (fig 4.1). In the knowledge base, the knowledge is stored as statements about facts and rules and may include numerical values, and as more information becomes available the knowledge base grows. If the information about a particular problem is missing from the system database or knowledge base, it tries to obtain the missing information, for example, by requiring input from the user. However, the task of the knowledge engineer is to select appropriate means of storing such information symbolically. It is appropriate, therefore, to examine some of the methods of knowledge representation used in common systems [117-119]:

- i) Dynamic knowledge - Production rules are used to formulate and represent expert knowledge which are in the form of;

RULE 1: IF (conditions or antecedents)
 THEN (conclusion or consequence).

Each rule has two essential parts, the conditions or antecedents and the action (or conclusions or consequences). The conditions may be a single condition, or may be a Boolean expression. Conclusions may also be compounded. The separation of knowledge and control permits the run-time facility of providing on-demand explanation and justification.

- ii) Dealing with uncertainty - two methods are mainly used in expert systems for handling uncertainty; Bayes' theorem and fuzzy logic. Bayes' theorem provides a means for continually 'weighing up' the chances of a hypothesis being true, as fresh pieces of evidence relating to it become available, whereas fuzzy logic is an extension to Boolean logic (truth = 1, and falsity = 0) which allows logic to be defined in probabilistic terms by using real rather than integer numbers. The boolean operators AND, OR, and NOT must be used in order to cope with real values.

- iii) Static knowledge - In contrast to production rules which represent 'dynamic knowledge' and are used within the knowledge base, there is static knowledge which is always true and can be accessed from an external database to provide the knowledge base with more information about the particular situation, e.g. WELDSPEC database [120] is used with PIKBES to contain factual weld procedure data. There are three ways static knowledge may be presented: Triples, Frames, and semantic nets. Triples consist of three parameters to describe an item, these being the name of item, relevant attribute, and value of the attribute which can be respectively related to, for example; a welding procedure, current, current value. Frames are an extension of triples, in which many pieces of information may be assembled into a predetermined pattern. The frame provides a framework for organising the information, and contains 'slots' in which the information resides. For example, this can be found in a welding procedure of a process where for instance plate thickness, current, voltage may have values in the current frame but material type or electrode represent other frames, in which more information about them resides. Semantic nets represent the relations among objects in the domain by links between nodes. In this way, the knowledge gives

common sense to a system.

Whatever method is used to implement such knowledge (described above), the sorted symbolic information is then used by the inference engine to perform logical deductions.

4.3.2.3 The Inference Engine

The inference engine is a program that applies domain knowledge rules to known facts in order to draw conclusions. The knowledge base contains no information about how to find the rules that apply and when to evaluate them. However, the inference mechanism is used to 'fire' an individual rule when the rule is selected for evaluation. Such mechanism for selecting which rules to fire and in what order, uses two alternative strategies, forward chaining and backward chaining. Forward chaining is a line of reasoning that starts from known facts (data) and fires rules to infer conclusion (hypotheses), while backward chaining starts with a conclusion and then fires rules which can establish that conclusion. These mechanisms have to also deal with uncertain data. There are many ways of dealing with uncertainty such as fuzzy logic, Bayesian logic, multi-valued logic and certainty factors, etc [112,113,119].

4.3.2.4 The User Interface

An effective human/machine interface is essential in operating an expert system. A survey suggests [118] that of a typical expert system's code, 44% deals with user input/output. Two types of facility are usually provided to a user during consultation with an expert system, explanation and/or graphical facilities.

1) Explanation Facilities

It is important for an expert system to be able to explain why it reached certain conclusions. The degree to which the expert system is accepted by the user will depend significantly on its ability to explain its reasoning. Explanation facilities are particularly important in domains where the expert system is asked to make judgments. The diagnosis will not be accepted without detailed explanation. The basic explanation facilities provided by an expert system should include why it came to a particular conclusion and how it is going to achieve a particular goal. In the 'why'

explanation the rules which have been used to derive the conclusions should be presented to the user, whereas in the 'how' explanation the rules that will be used to achieve the goal should be presented to the user.

Explanations in current expert systems [121] typically consist of tracing the rules in the reasoning process. Such tracing only provides the user with a logical proof of the correctness of conclusions made by the system. However, explanation of some of these conclusions or interrogation during consultation may be represented by graphical means.

2) Graphical Facilities

Another class of tool is concerned with the display of knowledge and inference processes, so that the user can better understand them. Graphical representations may be used to maximise the understanding of questions during interrogation, or the reasoning of a solution. For example, in welding design, the system may ask user about type of joint which he/she would like to design and at the same time display types of joint.

4.3.3 Motivation Behind Expert Systems Development

Whatever the application area of expert systems are, there are common motivations behind their use including:

- i) To make expertise widely available throughout an organisation.
- ii) To free experts for less routine activities which demand their specialist skills.
- iii) To provide expert education and training across a wide spectrum.
- iv) To provide surrogate experts in those areas where experts are in short supply or required only infrequently.
- v) To provide a standardised or methodological approach to solving important, fairly unstructured but usually routine tasks that require expertise.

- vi) To provide interfaces to complex systems. An example of this is the application of an expert system in this research which involves the interfacing of expert knowledge held in a knowledge based system (PIKBES). This system is interfaced to the WRAPS overall supervisory system and off-line programming system of a flexible welding cell in order to provide optimisation of the welding procedure to account for measured variations in the joints presented to a robotic welding work station.

- vii) To provide more consistent and high quality evaluation and monitoring. For example, humans tend to lose concentration and become fatigued over a working period whereas machines do not. This is a major reason behind AI applications, such as the use of robots, sensors, expert system, etc, in this research.

- viii) To reduce cost and speed up the development of process and system modelling. The application of various mathematical modelling techniques [93-99] has shown very little encouragement for their generality of use. For example, in weld processing, they have been found not to be cost effective [3,13]. The application of expert systems to the research reported in this thesis with their ability to handle non-mathematical models, has demonstrated the time and cost effectiveness of these research and development tools in problems requiring generalised solutions.

4.3.4 Problems Associated with Expert Systems

A number of problems and limitations exist in the building of expert systems [127]. Some are unique to this new type of software tool and some common to almost all software developments. These problems include:

- 1) Lack of Resources - Articulate, competent and confident domain experts who are eager to expose their knowledge while experimenting with a new form of software technology are not always available as one might hope. Competent knowledge engineers, appropriate software tools and/or research capital may not be readily available. Knowledge Engineers need training and experience and this only comes with exposure to many different projects.

2) Useful expert systems can take a long time to build. Although this has been acknowledged as one of the limitations of expert systems, as quoted above they can still represent the most efficient methods for solution of problems.

3) Planning and developing the expert system project can have many problems:

- i) The problem that the expert system is designed to solve is too complex.
- ii) The gap between an expert's knowledge and that of a non-expert user is so narrow that the expert system does not contribute much to the problem application.
- iii) The expert is not a suitable one for the system development, for example, he is not a rule expert, he is inarticulate, his reasoning is shallow.
- iv) The domain expert has insufficient time to devote to the project.
- v) The domain expert has become so demotivated that his interest can no longer be refired.
- vi) The domain expert and knowledge engineer cannot establish a suitable harmonious and understanding relationship.
- vii) Where multiple domain experts are employed as sources of knowledge, contradictions and arguing the basis of knowledge can seriously hamper progress and reduce the confidence in the knowledge employed.
- viii) The knowledge engineer is insufficiently trained for the job.
- x) The users find the system difficult to use.
- xi) The system becomes so large that is difficult to modify or amend.

4) Maintenance of the expert system - the system will lose its power once the knowledge it holds is outdated which will result in loss of credibility. Therefore, facility must be provided to update an expert system's knowledge base.

5) Identifying a meaningful application, defining the problem scope, and selecting the appropriate tool for building the expert system are difficult decisions that need to be made. There are mainly two types of tools currently available for constructing expert systems, namely expert system shells and high level programming languages. Section 4.3.5 and 4.3.6 will discuss the these types of tools.

4.3.5 Comparison of Conventional Computer Programs and Expert Systems

Expert systems can be distinguished from conventional computer programs;

the former has a reasoning mechanism fed from a knowledge base and its output consists of numbers, possibilities, probabilities and advice.

A conventional program manipulates logic preset by code to give answers as output data, fig 4.3. It is built to perform some useful task and is expected to perform the task correctly or to arrive at the same answer every time. Expert systems can perform no better than the experts that provide the knowledge on which they are based and they can therefore exhibit "human frailties". Conventional programs are highly procedural; the computer is instructed exactly how to solve a problem. Expert systems, on the other hand, are 'declarative' - no instructions on how to solve the problem are given. Instead the knowledge is represented as a collection of facts accompanied by a collection of rules for using them. An inference mechanism finds

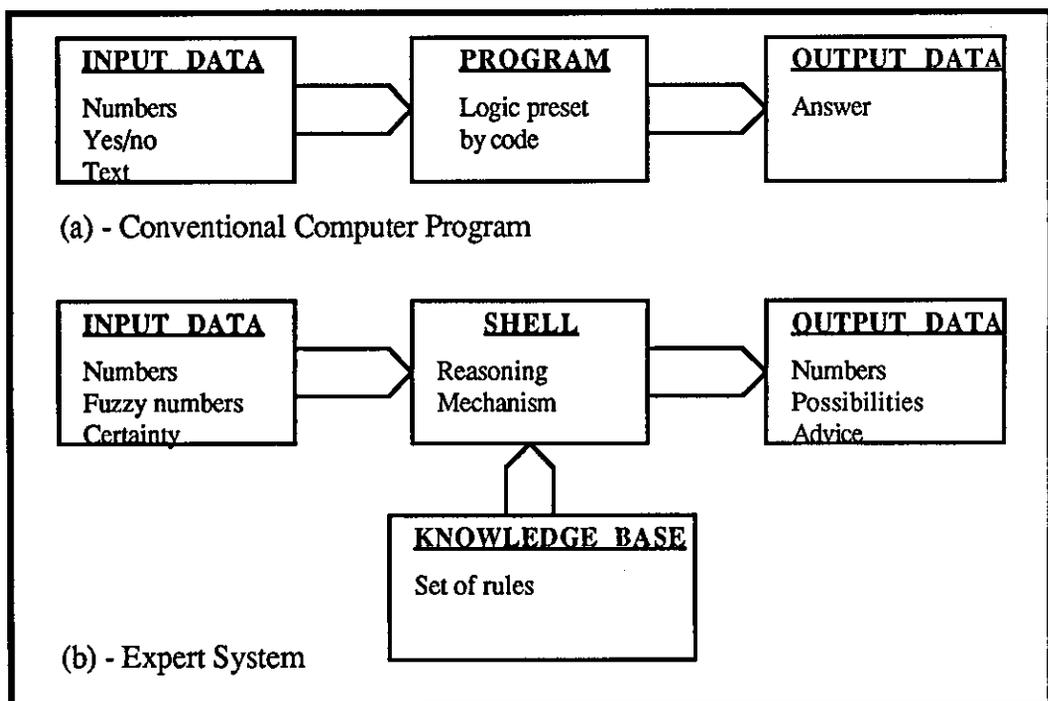


Fig (4.3) - Schematic comparison of conventional computer program and expert system.

the appropriate solution to the problem from the facts and rules. The inference mechanism or 'inference engine' which provides the expert system with its ability to deduce new facts and conclusions from the input data, provides the expert system with its power and potential. Conventional computer programme languages such as PASCAL, FORTRAN and C have a rich set of data structures for non-numerical computations, for example, lists, arrays, strings, words, procedures, processes, and so on. Their data structures are type-free. So, for example, lists can contain arbitrary objects, and code can be treated as data. However, AI languages as well as having

some features of conventional languages, have the capability of making decisions, solving problems, and justifying their course of action. They are also embedded in environments (programs) and these language features and their environments together help the programmer to cope with complexity. AI languages take advantage of the fact that, as manpower costs for programming rise, hardware costs are falling, for the languages certainly need powerful computing systems, for reasons that will become apparent.

The comparison of conventional computer software (1) and expert system software (2) perhaps can be abbreviated as [112]:

Data + Algorithm = Program (1)

Knowledge + Inference = System (2)

4.3.6 Languages and Shells

There are two alternative types of software for developing expert systems: general purpose programming languages, and expert system 'shell' software packages. Although it is possible to write expert systems in conventional procedural languages such as BASIC, FORTRAN, PASCAL, or C, it is acknowledged that the two most powerful AI languages are LISP and PROLOG [110]. There are many books available on these Languages [110,112,113], which provide information about their operation. LISP is used extensively in the USA for building large scale expert systems, whereas PROLOG has been adopted more extensively in Europe for building medium size expert systems and in Japan for research into fifth generation computers [106]. 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. However, standard features such as inferencing mechanisms, fuzzy logic [112] and explanation facilities which are available with most expert systems are not provided in LISP and the programmer must write these himself. PROLOG, on the other hand, is more structured but less versatile than LISP. It is provided with in-built knowledge representation and deduction, in the form of a database and production rules and works by backward chaining. Both of these languages have the advantage of versatility but they have been shown to be very expensive [119]. Also, these languages lack the run-time components of an expert system shell. PROLOG has a built-in inference mechanism but if the rules of the knowledge base are encoded in 'raw' PROLOG, they are not available for inspection by run-time facilities [113]. It is necessary, therefore to build a rule-interpreter and to

code the rules as data. This means that PROLOG (and LISP) are not as suitable for prototyping as an off-the-shelf shell. However, their powerful data structures, built-in search mechanisms and interpretive nature makes them a better building tool than conventional procedural languages such as FORTRAN, PASCAL, C, etc.

In all expert systems the knowledge is separated from the inference engine which is used to carrying out logical deduction, and user interfaces which are used to provide explanation and debugging facilities. This provides the basis of an expert system shell which is essentially an expert system without any knowledge installed. Therefore, to put briefly [107]:

A Shell + Specialist Knowledge = An Expert System

When building commercial expert systems a large percentage of the programming effort is taken up in designing and implementing the human interface. The production of expert system shells was an attempt to overcome this burden. Using programming language to develop an expert system will only give the user limited textual interface facilities. However, the knowledge engineer can build the expert system using graphics packages which can be integrated with the programming language. Even with good graphics packages a large amount of time will be taken in implementing the interface. In PROLOG this would add further complications since they do not usually have direct access to graphics packages [113].

There are a large number of commercially available expert system shells. One of the first shells to be constructed and put to use was EMYCIN ("Empty MYCIN", derived from the MYCIN medical expert system by removing the application-specific knowledge) [121,122]. Shells now available include [107,119]; SAGE, MICRO-EXPERT, KAS, EXPERTEASE, Savoir, EXTRAN, CRYSTAL, Xi plus, ART (Automated Reasoning Tool), KEE (Knowledge Engineering Environment), M1, ESP-advisor, Reveal, OPS5, OPS83, S1, Knowledge Craft, KES and ENVISAGE/SAGE. Reference [128] provides some information about the specification and cost of some of these shells which may be useful for expert system builders.

One of the major limitations of many shells is the lack of a powerful representation formalism. Many of them are equivalent to programming languages supporting only simple Boolean and numeric variables.

The Savoir shell (from III Lad) has been reported [119] to be used by the

Welding Institute for welding procedure generation. This shell is rapid in execution, can handle large numbers of rules, incorporates several different types of inference and allows individual control mechanisms to be built in. It is capable of handling simple arithmetical operations. External programs written in PASCAL can be used for complex calculations. Other facilities of this shell include; good explanation facilities and a good user interface. The limitations of Savoir shell are; relatively high cost, it does not contain any means of incorporating static data, not easy to use, a considerable amount of training is required. Explanation of other shell packages can be found in references [107,119].

Lucas and Brightmore [123] have discussed that compared with the number of expert system tools, the number of published applications or commercially available systems especially in the manufacturing sector is small. This may be due in part to the nature of expert systems in requiring possibly confidential knowledge or expertise which is a valuable asset to a company, and if made available commercially could be accessed by its competitors.

4.3.7 Application of Expert Systems

Knowledge based expert systems are becoming more widely utilised both in the financial and manufacturing sectors of industry. Earlier applications of expert systems were limited to consultive or diagnostic activities involving no immediate external feedback into the expert systems to effect their inferencing. These applications [107,117] were for example:

- (i) MYCIN - This is an expert system which was developed to assist physicians with advice on diagnosis and treatment of bacterial infection. Its goals were therefore concerned with the identification of the offending organism and with the treatment of the disease.
- (ii) PROSPECTOR - This expert system is used for the evaluation of geological prospects. The system provides three major types of advice; The evaluation of sites for the existence of certain deposits, the evaluation of geological resources in a region, and the selection of the most favourable drilling sites.

Both systems have been designed with relatively simple control structures. The architecture of both systems is based upon the production system approach and

consists of; a collection of facts, a set of production rules, an inference engine which is either forward and backward chained (or both), a mechanism for drawing inference from uncertain or incomplete evidence.

Other application areas are found to be as follows [107,111]:

- 1) **Medicine** - expert systems have been developed for advising on general internal medicine (INTERNIST), diagnosing the eye disease glaucoma (CASNET), assisting in the design of genetics experiments (MOLGEN), respiratory intensive care (PUFF), pregnancy advice (GRAVIDA), blood disorder (CLOT), ventilation management (VM), treatment of oncology out-patients (ONCOCIN), diagnostic planning for Hodgkins disease (HODGKINS), psychopharmacology advisor (HEADMED), etc.
- 2) **Chemistry** - expert systems have been developed for advising on inferring the structure of chemical compounds (DENDRAL and Meta-DENDRAL), protein crystallography (CRYSALIS), logic and heuristics applied to synthetic analysis (LHASA), synthetic chemistry (SYNCHEM), etc.
- 3) **Education** - teaching purposes (GUIDON), geography tutor (SCHOLAR), electronics troubleshooting tutor (SOPHIE), logic and set theory tutor (EXCHECK), identifying student's basic arithmetic misconceptions (BUGGY), learning environments (LOGO), animation system (DIRECTOR), message-passing (SMALLTALK), teaching logic, probability, decision theory and geometry (WUMPUS), cause of rainfall and geographical process tutor (WHY), guided discovery (WEST), etc.
- 4) **Science and Engineering** - expert systems are used to organise and manipulate large bodies of information and analysis processes used in mass spectrometry analysis, biological classifications, metallurgy, mathematics (MACSYMA), engineering structure calculation (SACOM), etc.
- 5) **Design and fault diagnosis** - XCON/R1 (a configurer for VAX computers), fault diagnosis system (FALOSY), fault diagnosis for computer hardware and software (CRIB), etc.
- 6) **Financial and legal** - expert systems are used to assist in the analysis of capital investment, new product analysis, etc, e.g. TAXMAN used as a tax law advisor, Mees (Macro-economic expert system) used for teaching economics, tax planning recommendation for businessmen (TAXADVISOR), sit planner assistant (XSITE),

aid manufacturing (IMACS), aid scheduling (ISA), IPMS, aid project management (IPMS), refining and organisational procedures (XPRESS), etc.

7) Law and administration - expert systems developed to assist lawyers to search for legal precedents in various comprehensive databases. For example, LRS expert system is used to perform knowledge based legal information retrieval, DSCAS expert system is used to analyse differing site condition claims in the area of contract management.

8) Military and space - expert systems are used by the military for equipment diagnostic, planning systems and training personnel, the guidance of autonomous vehicles, large battle management systems. In space, expert systems are used for controlling, monitoring and diagnosing various space-borne systems, mission planning, etc, e.g. teaching naval engineers (STEAMER), understanding signal systems used in navy (SUS), planning military air-traffic movement (AIRPLAN), tactical air targetteering (TATR), etc.

9) Other area of application of expert system are: water resource management (HYDRO), fault diagnosis for hardware and software (DART), etc.

In keeping with the current emphasis on increasing productivity, potentially high pay-payoffs for knowledge system investments is the key issue in the industrial environment. The application of expert systems in industry particularly in manufacturing, is an emerging technology for industrial problems. Examples of these industrial applications [110] are:

- i) Production planning and scheduling,
- ii) Inspection,
- iii) Quality control and analysis,
- iv) Tuning of closed-loop control systems,
- v) Group technology,
- vi) CAD/CAM
- vii) Flexible machining systems, etc.

More recently, the potential for expert system applications to Robotic and Vision systems has been realised. Robots have been described as being clumsy, and stupid [9]. It is difficult to teach a robot to perform even the simplest human tasks. The major limitations are found to be [100]; Insufficient material-handling capability, open loop control, inability to detect and correct errors, restricted mobility. Equipping

robots with sensors, possibly interfaced to expert systems, improves the accuracy and repeatability of the such systems and reduces their limitations. In welding fabrication, expert systems are used to equip robots with the knowledge of skilled welders.

4.4 Selection of KES Expert System Shell for PIKBES

Expert system shells have significant potential for application in manufacturing environments. The system developer has a difficult job evaluating and selecting one for a given application from the many available. The products can be differentiated by the problems for which they are commonly employed. The majority of shells [113,127,107] address the provision of 'performance programs' by concentrating on run-time capabilities, whereas others address the problems of knowledge-base development and refinement. However, the application of expert system shells in process control has been hampered by their limitation in real-time feedback control capabilities. Such limitations do not affect the application of these systems to the pre-weld inspection station of this research, as the system is designed to provide information on the basis of on-line feedforward control.

In the selection of an expert system shell for the pre-weld inspection station (PIKBES), the author has carried out a survey and there were over 20 expert system shells available for use on microcomputers. The search was constrained to shells used on microcomputers since PIKBES was required to integrate with WRAPS [1] and its subsystems all of which were developed on microcomputers. The KES (Knowledge Engineering System) shell from Software Architecture and Engineering Company [129] has been selected for the pre-weld inspection station. The main factors contribute in selecting the KES shell are:

- i) The interface capability of KES with other software packages. PIKBES is constructed within KES shell which is written in 'C' language and detailed interface information to embed KES into other software packages or to embed other 'C' software into KES are provided. In this research, the application of a non-mathematical model expert system to provide welding procedures modification base on performance data, there has been need for the interfacing of the expert system to external programmes and database(s), such as 'C' program ('sear.c') used to retrieve data from WELDSPEC database.

- ii) As KES is written in the 'C' language, this provides the knowledge base builder with many advantages such as the ability to integrate with other software packages (as mentioned above), minimal memory requirements, high performance, and machine portability.
- iii) The ability of KES to easily communicate and pass or receive information between different systems or knowledge base programs. In this research, PIKBES is required to provide information on modified welding procedures and pass this information to the WRAPS supervisory controller. This has been done through a communication ASCII file. PIKBES was required to be compatible with WRAPS and other systems in a flexible welding cell.
- iv) Many expert system shells within a modest price bracket provide only the production-rule logic as their inference engine. The production-rule logic, however, may not be the most suitable in cases where uncertainty of data is involved. An alternative logic system is based on Bayesian, fuzzy, triples, and frames theory [112,113,121]. Section 4.3.2.2 (ii) has explained these alternative logics briefly.

KES provides multiple inference engines because a single approach may not be well-suited to all expert system applications. The three inference engines are PS (Production Rules), HT (Hypothesise and Test), and BAYES (Bayes Theorem);

- i) Production Rule (PS) - a modular knowledge structure representing a single chunk of knowledge in the form of "if-then" or antecedent-consequent. It uses deductive reasoning where conclusions follow from the premises.
- ii) Hypothesise and Test (HT) - provides reasoning through hypothesis formulation and subsequent verification. It uses abductive reasoning where the conclusion is a likely explanation of the premises, i.e. the domain knowledge is represented in the form of "descriptions". It is suitable for minimal set covering, i.e. the inference engine determines the smallest number of causes represented by "descriptions" in the knowledge base, that explain all known manifestations of the problem of interest.
- iii) Statistical Reasoning (BAYES) - performs statistical pattern classification based on Bayes' theorem. This theorem relates the probability of a

hypothesis being true before receipt of extra information, to the probability of a hypothesis being true after that information has been received. BAYES inference engine is well-suited for applications where there is a large body of pre-existing data expressed as probabilities.

The main features of each inference engine are provided in the table 4.1. There are two major criteria in selecting the inference engine; the way knowledge is represented, and the way information is processed. The selection of an inference engine for use in particular environments are provided in the KES Knowledge Base Author's Manual [130] chapter 5 "Designing a KES Expert System". In PIKBES, the production rule (PS) inference engine was selected, as this inference engine was appropriate where:

- a) The knowledge required is to be represented by rules, which may also use certainty factors. This is a way of expressing conditional relationships between attributes giving an answer with degrees of confidence.
- b) Good control over inferencing is required. This has been achieved by a combination of controllable forward and backward chaining.
- c) Classes and class inheritance may be used. Classes allow reasoning about groups of objects with the same characteristics. Classes inheritance expresses hierarchical relationships between classes.
- d) Communication with the outside world is required. KES uses an externals command to call other expert systems or application software.
- e) Forward and backward chaining is required. KES uses a demons command which allows event driven forward chaining and a backward chaining mechanism for rules. This combination provides a powerful inference engine for the expert system.
- f) Consistency maintenance is required - in this way, the dependent values can be updated (or modified), so that they are consistent with the new attribute values.
- g) Embedding with other applications software is required.

Appendix A1 provides more explanation of the above KES PS features. The advantages of the PS production-rule inference engine may also be explained as :

- a) Mature (well formulated and understood).
- b) Natural representation for many application domains. Branching logic. Knowledge expressed in 'if - then' format.
- c) Modular: Easy to construct and maintain.

- d) The development and run-time systems are separate.

Chapter 6 discusses in more details the interfacing (embedding) of KES shell to 'C' programs which were developed to control the knowledge base for different joint types.

KES Features	PS	HT	BAYES
Backward chaining	Rules	Minimal set covering	Bayes Theorem
Forward chaining	Demons	Demons	Actions
Procedural control	Actions Demons	Actions Demons	
Certainty factors	Numeric -1.0 to 1.0	Symbolic always to never	Probability 0.0 to 1.0
Class inheritance	Yes		
Class with variables	Yes		
Embeddable	Yes	Yes	
Externals	Yes	Yes	Yes
Explain	Yes	Yes	Yes
Help	Yes	Yes	Yes
Justify	Yes		Yes
Trace		Yes	
Why	Yes		
Frame-like representation	Classes	Description	
Handle Unknown values	Yes	Yes	Yes
Numerical calculations and functions	Yes	Yes	Yes

Table (4.1) - The main features of KES [129].

4.5 Welding Software Packages

A requirement for arc welding procedure selection and generation [93,99] has long existed as a basis for advice to welding engineering practitioners and researchers. A number of different database and other welding software packages have been developed [133-135] to provide arc welding procedure selection, but were

only limited to static knowledge and incapable of problem solving, decision making, or dealing with uncertainty. Some of those are described briefly below.

One of the early static knowledge base packages developed for welding procedure selection, was WELDQUEST database [133]. WELDQUEST was implemented on mainframe or large minicomputers at The Welding Institute. It has been reported that the system has a flexible database structure and comprises of six pages of information each being assigned to one visual display screen. The format of data entry is similar to the Welding Procedure Data Sheet given in BS 4870 format [5]. The pages content is describe briefly below:

Page 1 contains general details of the procedure, base material specifications and joint/weld definitions. Page 2 contains information on consumables, including where applicable those used for root runs, and specifications of fluxes and shielding gases. Page 3 defines the configuration of the electrodes, and their longitudinal and lateral angles and separations. Page 4 details the welding conditions and summarises the mechanical test data to be expected from a weld made using this procedure. Page 5 contains the more frequently used welding parameters, particularly those relevant to non-pulsed welding. Page 6 contains the less frequently used welding parameters such as pulse and weave parameters and bead width.

Data are entered directly at the keyboard, under control of the entry subroutines, to the 314 data fields, each of which has a corresponding 'box' on the screen display. Editing data is much the same as entering data, except that the user may select one or more particular fields instead of all fields. search subroutines are 'menu-driven'. Key feature used for searching are; qualification, material type, process, joint type, thickness (mm), position, special features, welding mode.

A-Weld database (produced by Marshall Marlow Associates) [134] is reported to have a similar data entry format. Screen layouts are designed to reproduce the format commonly found in Welding Procedure Data Sheets. It integrates procedure design, includes a variety of calculations, data storage, retrieval, analysis and output together with accessibility in respect of future program developments. A-Weld programs are included for selection of both the procedure specification (WPS) and procedure qualification records (PQR). Each qualification record is related to its master WPS and this relationship is maintained by the program at all times.

Queen [135] has recently reported the development of a database called 'Weldpool' for welding procedure storage/retrieval. The database is used for the

construction, repair, maintenance or improvement of offshore structures and facilities operated by Shell UK Exploration and Production in their sea gas fields. The A-Weld software was chosen as meeting the concept envisaged for the 'Weldpool' system. For searching purposes, the user requires to enter a certain minimum amount of information in order to conduct a data search. The 'Weldpool' database uses a standard Shell UK Search Request form to search for welding procedure records. Having identified a number of potential welding procedures available, these are closely reviewed in conjunction with the design drawings, and specification requirements to confirm an appropriate selection.

A number of packages have been developed in order to help welding engineers to select welding procedures, carry out calculations and to analyse standards. They are also used for estimating the cost of welded fabrication, and give advice on welding parameters. Lucas [136] has reported a number these packages developed at The Welding Institute to assist welding engineers. These are:

- i) **PREHEAT** - Calculations and analysis of standards and the recommendation of preheat or minimum heat input levels to avoid hydrogen cracking. It applies to the arc welding of carbon and carbon-manganese steels having carbon equivalents within the range 0.32 to 0.60.
- ii) **WELDVOL** - This package is used to calculate the volume of weld metal in any joint type as well as the amount of consumable quantities required. The user has to enter information concerning the joint/weld type, the weld dimensions, the material type and details of the welding process or processes to be used.
- iii) **MAGDATA** - This package is used to give Advice on welding parameters for the MIG/MAG welding of steels.
- iv) **WELDCOST** - This package is used to calculate the cost of depositing weld metal, examine effects of varying individual parameters of the welding cost, and make economic comparisons between different joint design/process/procedure options.
- v) **WELDERQUAL** - Database for the storage of welder qualification records providing a constant up-date of when welders must be requalified.

- vi) WELDSPEC - this is a database for storage/retrieval of welding procedures. It is used in this research to provide PIKBES with nominal welding procedures plus some other additional information. The information stored in the database is in the format of a Standard Welding Procedure Sheet, BS4870, i.e. component details, welding variables, consumables and results of inspection and mechanical testing. Further details of this package together with its searching operation and so on will be discussed in chapter 6, section 6.5.3.

4.6 Expert Systems for Welding Applications

In conjunction with static database packages mentioned above, dynamic knowledge base expert systems can be used in order to provide a more powerful computer programs. Expert systems are used to handle the problems associated with welding procedure selection, design and/or generation, and optimisation.

Expert systems have been applied across a wide range of welding technology, from selection of welding processes to prediction of weld quality [131,132]. Several researchers have reported such applications in: procedure selection [1], procedure generations and/or welding design [32,136-142], process, consumable and equipment selections [144-148], equipment/process diagnostics [149-153], welding process control [149,154], risk evaluation [155,156], etc.

An equally important area in which decisions based on experience are required is in the control of the welding operation itself. Fusion welding may be performed by either manual or mechanised methods. In the former, the welder, acting largely from past experience, may determine not only the best method and technique of welding, but will also employ his skill to control the welding process to produce a satisfactory weld. In mechanised welding operations, the operator is placed in a completely different situation. For example, the component must be designed specifically for machine welding, noting that the machine is substantially less flexible than a manual welder in accommodating component variations and access or position restrictions. The welding variables selected are often completely different from those employed by a welder and, during the welding operation itself, periodic adjustments to the machine may be necessary to accommodate parameter variations.

4.6.1 Expert Systems for Welding Procedure Generation

In the absence of a suitable welding procedure it is necessary to generate a new procedure complying with relevant standards and codes of practice. This forms a major part of the work load of many welding engineers. Several expert systems have been developed to assist in the task of procedure generation. These systems usually prompt the operator for information about the joint to be welded (such as material thickness, material composition, joint type, etc) and use the inference techniques, described above (e.g. production-rule, and/or Bayesian, etc), to produce a suitable procedure.

Several researchers have reported the application of expert systems for welding procedure generation [123,137-142]. Lucas and Brightmore (from TWI) [123] have reported the development of an expert system in collaboration with British Alcan Aluminium Ltd. The system generates welding procedures for manual MIG welding of aluminium and aluminium alloy T joints. The Savoir expert system shell was selected because of its interface capability with other software packages such as external database or graphics facilities. The system builder did not need to write the user interface. The task of generating a welding procedure is divided into five sections each of which are further subdivided into the individual items that make up a welding procedure specification. The user of the system may either progress completely through a consultation or simply use a single section of the program if, for example, information is only required on which consumable to use for a particular combination of parent metals and service conditions. As the program proceeds, it requests information from both the user and external data files. The result of the consultation can be displayed on screen as a graphical representation, and/or written explanation of the advice and recommendation made to the user. At any point in the consultation, the user can request hard copy of the advice in a format similar to British Standard BS 4870.

Alberry [137] has also adopted an expert system approach to generate welding procedures for a low alloy creep resistant material. The expert system is a prototype version developed at CEGB Marchwood Engineering Laboratories. The system uses a Savoir shell. The input follows a question and answer format such as joint type, position, thickness, material composition, etc. Request for further information to amplify the meaning of any question is possible. The output from 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.

Taylor et al. [138] have reported the development of an expert system to assist welding engineers to produce welding procedures for SAW in a shipbuilding environment. The system is designed for BS 4360 structural steel in the range of 5mm to 55mm plate thickness. Two types of joint, butt and fillet, are included and electrode size of between 3mm to 6mm has been considered. The Savoir expert system shell has been selected. The program is structured in a modular form which facilitates future expansion of the system. The user is expected to input details of the joint such as plate thickness, joint type, etc, and give answers to questions on the consumables (e.g. electrodes size and type of flux). The interaction between the system and user is on the following basis;

- i) The system estimates the value of parameters based on available information,
- ii) The system recommends the most suitable values to the user,
- iii) The user chooses a preferred value,
- iv) The system comments on the selection,
- v) The system processes the chosen value, and
- vi) The system may advise reselection.

The final output of the expert system program is then displayed giving welding current (250A-700A), arc voltage (24V-46V), travel speed (2.5mm/s-25mm/s), preheat temperature (0C-300C), and edge preparation (single/double V, square edge). This outputs are based on the production of the correct bead geometry as well as the avoidance of defects such as hydrogen induced cracking, solidification cracking, etc.

Dorn and Majumder (from Technical University of Berlin) [139,140] have reported the development of an expert system package called 'WELDEX' to design and generate welding procedures. WELDEX is written in Turbo-Prolog and structured in a modular form. It is designed to operate through a pull down menu by which the user can select an option using cursor keys and activate the desired module. WELDEX contains four modules as described below:

- i) Process selector - this module includes a range of process options from Manual Metal Arc Welding (MMAW) to Plasma Arc Welding (PAW). The user has to enter joint type, type of preparation, and whether manual or mechanised welding will be used.
- ii) Joint design selector - this module displays drawings of different joint

designs to the user and recommends the type of preparation with dimensions.

- iii) Process parameter selector - when the recommended joint preparation (ii) has been displayed, the system will also display a table of recommended welding parameters for that particular joint.
- iv) Defect analysis - this module informs the user regarding defects and their causes in general. This module uses 'natural language' and provides the user with a list of probable reasons for a given defect.

The system is reported to be under development (1988), and will incorporate the facility for handling information with uncertainty.

Abu-Bakar [32] has reported the development of an expert system for designing welding procedures. This system has been the subject of a parallel research at Loughborough University and has already been discussed in chapter 3, section 3.3.2.

4.6.2 Expert Systems to Assist Welding Designers

Development of knowledge based expert systems can assist designers to be more flexible during welding design. Several researchers [141,142] have reported the application of expert system for welding design.

Baker et al. [141] have reported the development of an expert system concerned with design to avoid brittle fracture in Carbon and Carbon-Manganese steel vessels while it is operating at low temperatures. The system gives advice on material selection for the avoidance of brittle fracture in as-welded and stress-relieved pressure vessels. CAMS expert system shell is used as a tree structure, containing sequence of pages of information which can be linked together in a complex network. These pages can be displayed one at a time on the screen, and each page can contain text or diagrams, allow data to be input, perform calculations, and display results either as numerical values or in the form of graphs. The user is asked for information, on the basis of which a reference thickness (shell thickness) and a minimum design temperature are defined. Nomograms are then entered to interpolate a material reference temperature. This is the form of the maximum testing temperature at which a minimum required value of impact energy is wanted, using a Charpy v-notch test. The required material can thus be selected from the existing material standards on the basis of the

information provided by the system.

Fukuda et al. [142] have reported the development of the expert system 'Welda' which determines a welding design plan tailored to a welding engineer's need within his limitations in terms of materials, equipments, costs, etc. Welda provides advice on the appropriate selection of a welding method, a cutting method and a bending method based on the input data about the function, size, geometry, etc of the structure to be built. The system is implemented on micro VAX II under VMS operating system, 9 Mega byte memory and uses OPS83 language. Welda is a rule-based system and contains 14 kinds or groups of rules about manufacture. It is linked with Fortran subroutines which evaluate distortion. There are four kinds of rules for controlling the processing of those 14 groups of rules in the knowledge base, but the report gives only a very brief explanation of the system and there is no evidence of what these types of rules are.

The procedure design expert system reported by Abu-Bakar [32] includes a module capable of calculating the size of weld required to meet the specified service loading conditions.

4.6.3 Expert Systems for Welding Process Selection

There are a very large number of processes available in the welding domain from which welding engineers must select the most appropriate for a particular application. He must be sure that the process can make the weld and that it will do so to the required standard. A number of processes may be equally capable of making the weld, but costs and defect rates will vary from process to process. Hence the engineer needs to decide which of the available processes can make a satisfactory weld and then which of those is the most cost effective. After the final selection of process has been made, it is desirable to allow the engineer to go on to a more detailed analysis in order to determine the optimum settings of the process parameters and whether or not these will influence his decision.

Several researchers [144-148] have reported the application of expert systems as an advisory system for welding process selection. Triouleyre and Grand [144] have reported the analysis of welding process selection in order to verify the agreement between the characteristic, criteria, and application field of each process. The criteria considered were; sequence of welding operations, material, shape, dimensions, preparation required, quality levels, energy aspects, and economic aspects. Triouleyre

and Grand have concluded that availability of such knowledge is not exhaustive, but the main advantage of an expert system is the ease in completing the knowledge base and justification provided by these system when the system reaches final conclusions.

Ribeiro et al. [145] have developed an expert system for welding process selection. The system uses Naylor's expert system shell [143] with a Bayesian inference engine. The expert system program is written in BASIC and implemented on an Apple II microcomputer. The developed system was limited to the welding of aluminium alloy sheet of up to one inch thick. It has been reported that the system supports nine different types of welding process.

Further development of the work of Ribeiro et al. in collaboration with Marchwood Engineering Laboratories of CEGB [132], produced the package called WELDEX II [146]. WELDEX II was written (in BASIC) as an advisory system for the practising welding engineer using Naylor's expert system shell. Its aim was to help in selecting the most appropriate and cost effective welding process for joining thin walled stainless steel pipes. The program consists of two modules:

- i) The actual process selector module - where a number of predetermined questions are answered by the user and decisions are made by the program as to which processes are the most appropriate.
- ii) The cost and failure analysis module - where the information collect from (i) is passed to this module and together with the user information, an analysis is made of the probable total cost per weld of each processes. Failure of the weld also effects the total cost per weld of each process, therefore, the system analyses the rework costs of rejected components and advises the user whether or not it is cost effective to perform rework on a particular component.

More recent developments of WELDEX II, includes the use of AI language, to produce a new and more robust version called WASPS (Welding Advisory System for Process Selection) [147]. WASPS is written in LISP and run on IBM/PC microcomputer. The knowledge representation of WASPS is divided into three modules;

- i) Question knowledge - this is concern with which question is asked to obtain a piece of information, and a list of possible responses if appropriate.

- ii) Decision knowledge - this is the knowledge about how to decide between processes. The representation used is that of production rules which include a test option.
- iii) Process knowledge - this module contains information about different processes. The data structures used are lists. The production rules must find matches with this knowledge in order to fire the rules.

The inference engine of WASPS uses only forward chaining. WASPS provides the user with a display of possible welding parameters and allows him to select what he feels might be appropriate values. Tolerance boxes are used to display possible values for current, voltage, and travel speed, and the user selects appropriate values by positioning a cursor on a graph. These values are transferred to the main program and allow an optimisation of process choice.

Although most of the above research which has been reported was used for process selection, there are a few expert system packages which are also designed to incorporate selection of welding electrode based on some other additional information such as base metal, etc. As the science of welding encompasses hundreds of base metals, welding electrodes, welding processes, etc, the choice of right combination is critical to the strength and safety of welded objects. Research carried out by the Colorado School of Mines in the USA [149], showed the application of expert systems with their capability to solve such problems. The development is called WELDSELECTOR and is based on Personal Consultant expert system shell and contains 150 rules. WELDSELECTOR is capable of recommending welding electrodes based upon key criteria such as base metal, welding processes, etc. The program asks the user a series of questions regarding the welding to be performed. As the user answers the questions, the program searches the database to find suitable welding electrodes, based upon the user's input.

4.6.4 Expert Systems for Process/Equipment Diagnostics

There are number of reports which show the application of expert systems in welding for process [149,150] and equipment [151-153] diagnostics. These systems are developed to assist welding engineers to identify failures and to take remedial action.

Kuhne et al. [149] have reported the development of an expert system called WELD-ASSIST for weld defect diagnosis. WELD-ASSIST is used for the gas metal arc welding (GMAW) process. It can be used with mild and low-carbon steel. WELD-ASSIST uses expert system shell Personal Consultant plus to build the system. WELD-ASSIST provides the user with choice from three program sections:

- i) **Welding Schedule** - the purpose of the welding schedule section is to provide the necessary welding data to the welder so that he is able to perform the welding task. For example, the user will be asked for input data concerning type of material, joint type, thickness and welding position. The output data of the program details preparation with all dimensions, contact tube-to-work distance, number of passes, and welding parameters. The module provides facilities such as print out, program recommendation, save the result in a file, explanation of result, "help" feature, written text, graphics, etc.
- ii) **Discontinuities** - this module provides recommendations to prevent and correct circumstances where discontinuities or defects may appear in the weld joint, e.g. cracks (hot cracks, cold cracks, etc), geometry discontinuities (undercut, overlap, etc.), incomplete fusion, porosity, etc.
- iii) **Improve Process** - this module is concerned with the weld shape. If no defect appears in the weld but the weld joint does not look acceptable because of the weld shape, the amount of spatter, etc, the program will give appropriate recommendation. Graphics are used to facilitate the user input.

The user performs the consultation. He decides whether he wants to weld with the recommended data or not. The recommended welding data can be fed automatically to the power source, wire feeder, and robot controller. The scope of the system is GMAW of mild steel. The possible thickness range is not reported but it appears to be limited to thin sheet (2/3mm).

Smati et al. [150] have reported the development of a prototype expert system shell. In order to demonstrate the feasibility and suitability of the system, the system was applied first to the diagnosis of weld defects (such as porosity, lack of fusion, lack of penetration, etc). The shell is written in LISP and implemented on an IBM PC/AT. It provides a means of identifying the main causes of a given weld defect and

then recommends solutions in order to avoid the same problem recurring again. The welding processes considered are Metal Inert Gas (MIG) welding, Tungsten Inert Gas (TIG) welding and Manual Metal Arc (MMA) welding. The user is asked to input the type of defect observed, welding process used, joint position, etc. The program then outputs the remedial action to improve the defect together with some recommendations.

Perozek and Brightmore [151] have investigated the feasibility of application of expert systems to diagnosis in the welding domains and concluded that characteristics of expert systems make them ideal tools for the often imprecise nature of welding.

Several researchers have reported the application of expert systems to system diagnosis [152,153]. Although conventional logic may be used to identify the failure of equipment, 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 system to know where to look for more 'clues', and to assess the cause of the problem based on the information collected.

A knowledge based expert system has been developed by Bonnieres et al. [152] to help engineers to resolve malfunctions and failures encountered using the automatic hot-wire TIG welding process. Two main malfunctions have been considered; wear or failure of various system components and incorrect setting of equipment parameters, which in turn can lead to two types of problem; welding machine malfunction and weld defects. 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.

Budgifvars [153] has reported the development of an expert system for diagnostic applications. The developed system is capable of diagnosing malfunctions occurring in the ESAB A21 orbital TIG welding automat when used with the programmable Protig 250 power source. The system has been designed to mimic a maintenance expert. The input information to the system is performed by interrogation of the user. Each answer is used to test the different components inside the machine and the faults will be ranked in such a way that if a particular set of symptoms implies more than a single fault, the most regularly occurring fault is investigated first. The system also incorporates many diagrams to help the user. A help function has been built into the system in order to give the user the opportunity to perform procedures such as altering the answers given or testing the system, etc.

4.6.5 Expert Systems for Welding Process Control

There are a number of reports which show the application of expert systems to welding process control. Data collected before, during or after welding can be used to expertly interpret the process and adjust the welding parameters [140].

Kuhne's et al. [149] report a system which requires visual inspection of component joints prior to the welding process. The user then consults the situation with WELD-ASSIST (described in section 4.6.4) which provides the user with recommended welding parameters. The user then decides whether to weld the component or not. WELD-ASSIST initialises the robot, and welding parameters (voltage, current, travel speed, etc) are then directly fed to the robot controller and equipments (the power source, the wire feeder, etc), and starts the robot. The robot performs its task using the welding data provided by WELD-ASSIST. After the welding process is completed, the user visually inspects the resulting weld and decides whether the weld is acceptable or not. He may then call up one of the other two options of WELD-ASSIST to diagnose any defects found.

Although such a system can be a useful tool in quality control of welding, it lacks sensing capability or system integration which is necessary to provide automatic process control as would be needed in a flexible welding system. It is also limited in material thickness capability

Reeves et al. [154] have reported the application of expert systems to adaptive control of the welding process, and remedial solutions to problems in naval shipbuilding. Two elements have been used to adaptively control a welding process in this small-batch manufacturing operation; expert systems, and what Reeves terms as sensor fusion. In sensor fusion, a combination of sensors is used to gather the information during welding progress. By combining the input of two or more sources, sensor fusion derives an intelligent picture of events transpiring in the target environment. For example, sensor fusion plays a role in making intelligent fill-rate decisions. For materials sensitive to heat input, the fill-rate decision requires combined support from both vision and temperature sensors. A vision sensor is used to capture the joint geometry and torch-to-workpiece location. The information collected is then transferred to an expert system module to provide the mechanism for making decisions based on the above interpretation; it uses sensor fusion output in conjunction with a rule base to preset weld procedure, analyse the conditions and modify the welding procedure accordingly i.e. reconcile competing goals, such as cost, quality and

productivity.

4.6.6 Expert Systems in Weld Risk or Defect Analysis

Several other research have recently reported application of expert systems in weld cracking analysis. Willoughby et al. [157] have reported the development of an expert system for assessing the significance of flaws in welds. Three 'Levels' of flaw assessment have been considered for the system. The level used depends on the complexity of the fractured part. The CAMS4 shell is used to facilitate the development of the expert system. The shell provides three different types of page, namely; text, calculation, graphics pages. The developed expert system knowledge base contains;

- i) The CAMS4 pages - approximately 220 pages of information, all of these being either calculator or graphic type pages. The input data for an assessment of fracture are; applied and residual stresses, stress concentration, etc. For fatigue: flaw dimension, geometry, etc.
- ii) External procedures - seven external procedures are used for complicated calculations, for example, calculation of stress intensity factor, curve-fitting, iteration, etc.
- iii) Database files - ten database files are used for storing data and passing data between the shell knowledge base and the external procedures.

Shaw and Bourton [158] have reported the development of two diagnostic expert systems together with the knowledge acquisition and the design philosophy adopted for them. One of expert system developed is called 'WELDCRACK EXPERT', and is used to decide which cracking mode caused a crack in a weldment, the other is used to locate malfunctions in an orbital TIG welding machine. WELDCRACK EXPERT system is designed for use with ferritic steels. The user enters the characteristics of a fabrication crack, e.g. appearance, size and location. WELDCRACK EXPERT responds by indicating which cracking mode is most likely to have induced the crack. Five cracking modes are considered, solidification cracking, hydrogen cracking, reheat cracking, liquation cracking and lamellar tearing. The fault diagnostic expert system is designed for use with an orbital TIG welding machine. When the user enters the characteristics of the malfunction, the expert system responds by informing the user of the most likely cause of the malfunction and the necessary remedy.

4.7 Proposed Expert System - PIKBES

A knowledge base expert system containing non-mathematical models is proposed for the pre-weld inspection station (PIKBES). PIKBES was designed and implemented with a view to providing a cost effective means of quality control of welded joints by compensating for detected joint geometry variations by modifying pre-planned welding procedures. The system inspects the quality of component joints against three criteria 'levels'. Based on these 'levels', components will either be rejected, accepted for welding employing the nominal welding procedures selected by WRAPS [1], or accepted but requiring the welding procedure to be modified.

Six stages of knowledge engineering were adopted in the design and development of PIKBES. These are shown in fig 4.2 which is modified from that originally proposed by Heng [116] who suggested only five stages. These six stages are:

- i) Analysis of knowledge requirements.
- ii) Knowledge elicitation.
- iii) Structuring the knowledge.
- iv) Formulation of the knowledge.
- v) Implementation of the knowledge.
- vi) Evaluation.

Stages (i) - (v) are discussed in more details in chapter 6 whereas chapter 7 will discuss stage (vi). The KES expert system shell was selected for the PIKBES system. The reason for this selection has already been discussed in section 4.4 of this chapter. Furthermore, WELDSPEC database was also selected for welding procedure data storage and retrieval. The reason for selection of this particular database will be discussed in chapter 6 section 6.5.3.

CHAPTER 5:

**Data Acquisition and Processing in
Pre-Weld Inspection Station**

CHAPTER 5 : DATA ACQUISITION AND PROCESSING IN PRE-WELD INSPECTION STATION

5.1 Introduction

This chapter details the overall design consideration (section 5.2 and 5.3) undertaken in the pre-weld inspection station together with its calibration test (section 5.4.3) and hardware and software implementation (section 5.4, 5.5, and 5.6). Square-butt and V-butt joints are dealt with. The sources of error in the laser system is highlighted and discussed in section 5.4.3.3. The pre-weld inspection communication via the ring network with the WRAPS supervisory system, conveyor controller for job and pallet recognition and PIKBES with its data format requirement has respectively been discussed in section 5.5.3, 5.6, and 5.6.4 .

5.2 The Pre-Weld Inspection Control Strategy

There are a variety of control strategies that have been employed for quality control / process control of components in flexible automation systems [159]. The two main control strategies which have been used [60,160], particularly in on-line quality control and real-time adaptive control in flexible automation of welding systems, and considered in the design of the pre-weld inspection station, are :

- a) On-line Adaptive (Feedforward) Control Systems [161] - In feedforward control the disturbances are measured before they have upset the process and anticipatory corrective action compensates completely for the disturbance, thus preventing any deviation from the desired output value. If this ideal can be reached, feed-forward control represent an important advantages over feedback control (as explained below). The essential features of a feedforward control are illustrated in fig 5.1.
- b) Real-Time Adaptive (Feedback) Control Systems [64,67] - Real-time adaptive control systems represents a combination of feedback control and optimal control. A real-time adaptive control is one which operates in an environment that changes over time in an unpredictable fashion, and the system must compensate for this unpredictable environment by monitoring its own performance and regulating some portion of its control to improve the performance. This strategy is also shown in fig 5.1.

There are a number of advantages and disadvantages with these control systems:

On-line Feedforward :

- i) Advantages - In the feedforward control system of the pre-weld inspection station the component is inspected prior to the welding process and any out of absolute tolerance (as explain in chapter one section 1.3) detected, this will cause rejection of the component preventing wasted processing time. Also delays to the welding cycle may be prevented. In this control strategy, the sensor is also removed from the very harsh welding environments, in order to: a) avoid the possibility of damage by intense arc light, fume, smoke, flying spatter, very high temperatures and also during teaching of the robot. b) eliminate the effect of arc noise .

- ii) Disadvantages - In the feedforward control system of the pre-weld inspection station, compensation for variation in joint geometry is determined from measurements taken prior to welding process. This cannot therefore compensate for changes to the joint geometry that may occur after the measurements, e.g. distortion during welding, and requires careful attention to jiggling and tacking to control such changes. For complex components shape requiring inspection time longer than welding time delays in the robot cycle can occur.

Real-time Feedback:

- i) Advantages - In real-time feedback control systems, the compensating action is taken instantly accommodating for any deviation detected in the quality of welding or characteristic of the weld pool.

- ii) Disadvantages - In practice many feedback control systems introduce a time lag effect such that the disturbance has effected the process output before compensating action is taken. Also (i)-a and (i)-b in the feedforward control system may not be avoided.

This investigation necessarily uses feedforward control strategy in the design of the pre-weld inspection station. The requirements of WRAPS to receive information of the joint geometry prior to the welding process and for its control of an automated welding cell system also require feedforward control. Furthermore, it increases the productivity by means of eliminating cycling delay time and taking early action in rejection of component for any out-of-absolute-tolerance found in the prepared workpiece joint.

5.3 Design Consideration of Pre-Weld Inspection Station

In order to achieve the primary objective of this research a pre-weld inspection station has been designed and implemented in a flexible automated welding cell. The three steps requirement in the design procedure was; 1) Conceptual design, 2) Functional design, and 3) Material requirements. The following criteria of the system has been adopted:

- i) The system cost should be kept to minimum. Costs are mainly associated with computer and processing power and/or speed requirement to collect and process the data, the x and y linear motorised axes of appropriate accuracy to manipulate the sensor in a scanning motion across the joint to collect the 3D profile of the joint, and the x and y positioner, and its accuracy, used to position the sensor system in different parts of the pallet. For the purpose of this research the costs are minimised by constraining the inspection to a small area of the pallet and limiting the component size to a 45mm joint length, i.e. reduces computer power requirement.
- ii) The system accuracy should be within $\pm 0.01\text{mm}$. This accuracy was chosen as a minimum accuracy requirement by the system because geometrical data to be collected from the prepared joint required to be accurate to this level.
- iii) The sensor system should be free from vibration during data collection (vibrations were mainly generated by the conveyor and T3-robot while they are in operation). This can be achieved by isolating the supporting structure of the inspection station from the conveyor.
- iv) System calibration and alignment should be carried out. The calibration test on the gauge probe systems should be carried out to eliminate or minimise the existence of any error in the system. It was also necessary to convert the output units of measurement of the gauge to give direct linear metric units. The alignment of laser probe xyz planes relative to the pallet should be carried out in order to eliminate any misalignment and non-linearity error in the system. This uses the laser probe mounted on the x and y position holder and moved to four corners of the pallet while the pallet is in the clamped work position. The frame structure was then adjusted until its xyz planes were parallel to those of the sensor. Fig 5.2 shows calibration of the pallet and laser probe xyz planes.

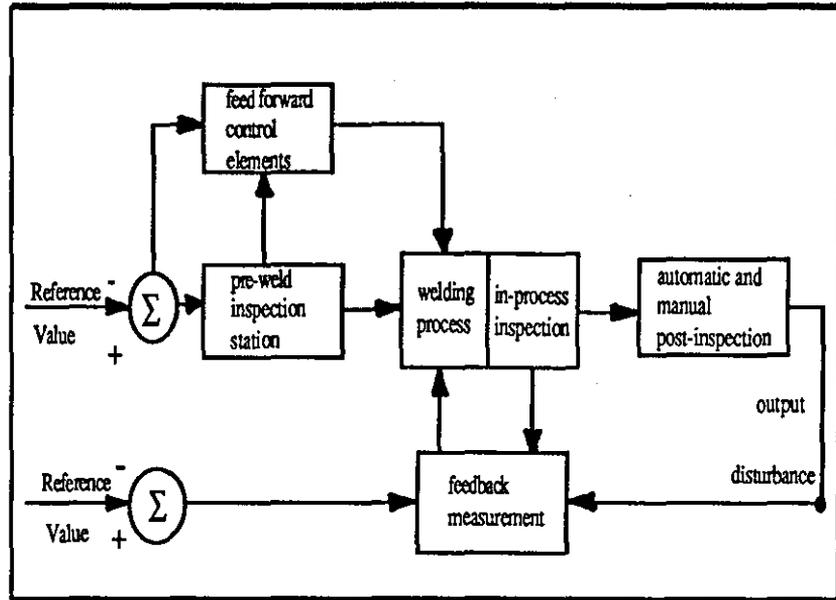


Fig (5.1) - Control strategies.

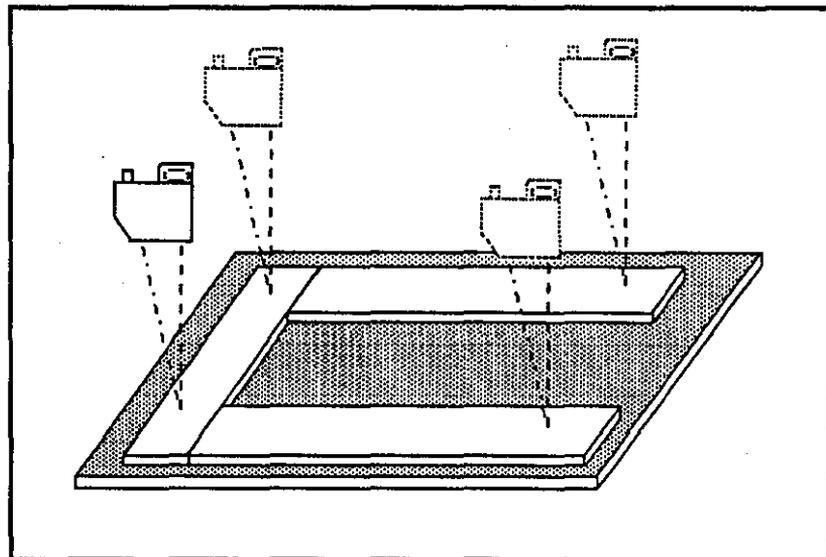


Fig (5.2) - Alignment of laser probe xyz planes with the conveyor pallet.

- v) The designed system should have an easy accessibility to various components for inspection, and also future expansion capability. Ideally, xyz linear axes plus two additional axes such as rotary and yawing axes for manipulation of the Optocator were required for the inspection station (see appendix A2). Because of the high cost of such a system, it was decided that, for initial development of a prototype system, an available Optocator system [89] and x and y motorised axes were to be used. Flat square-butt and single V-butt joints only are accommodated, since the geometrical shape of these joints does not constrain the manoeuvrability of the Optocator around the joint for data collection. Therefore, the sensor and its x and y motorised scanning axes are mounted on a further x and y coordinate system (position holder) which have an accuracy of about $\pm 0.01\text{mm}$. The system enables the sensor to be positioned manually at any point in the pallet area, but also has capability of being fitted with stepper motors to allow this to be achieved automatically at later date.

5.4 Configuration of The Pre-Weld Inspection Station

The overall design of the pre-weld inspection station together with its interfacing and communication ring network for a flexible automated welding system is shown in fig 5.3 and 5.4. The system is comprised of the following equipments:

- 1) A PDP11/23 minicomputer with 8.8 Mbytes hard disk and floppy disks, 64 I/O parallel line interface card (DRV11-J), a programmable real-time clock card (KWV11-A), and VDU terminal (VT52) [171].
- 2) Two Unislide's motorised linear axes [163] model U2504MP (x-axis) with 25mm travelling movement and U4006MP (y-axis) with 50mm travelling movement, and accuracy of 0.0012mm.
- 3) A Digiplan stepper drive control unit [164] comprised of SD2(x-axis), CD20 (y_axis), PM1200 power supply and an IEEE 1217 port interface card.
- 4) Selcom Optocator systems [89] - model 2203 with 32mm measurement range and 180mm stand off, Probe Processing Unit (PPU), Central Processing Unit (CPU) fitted with a 125Hz averaging output board.

5.4.1 Ancillary Set Up and Equipment

The main set up necessary for pre-weld inspection station were:

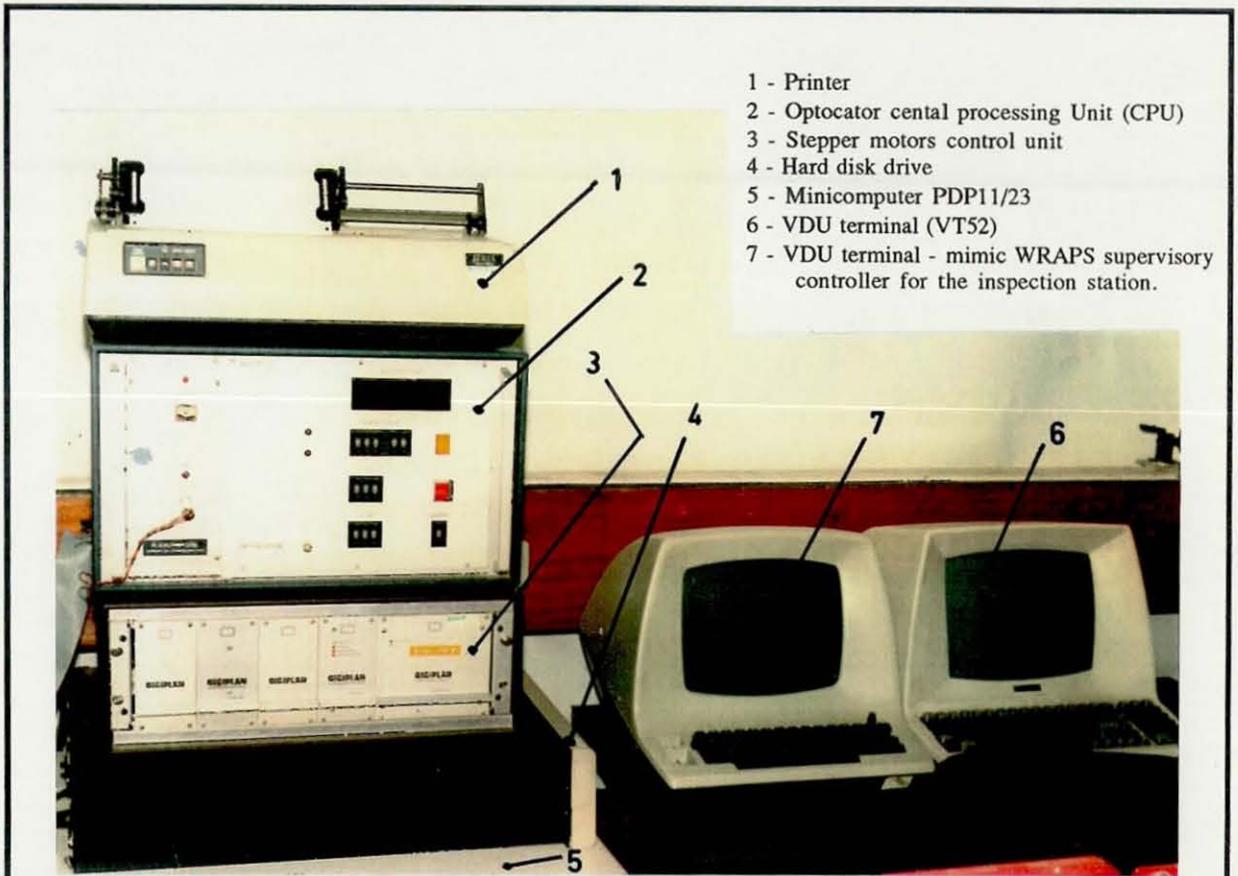
- i) The frame structure - The inspection station frame structure has been designed and implemented on the conveyor pre-weld inspection station and accuracy of ± 0.1 mm along its length. The frame is constructed separate from the conveyor body in order to minimise transmission of the vibration generated by the system during its operation.
- ii) The pre-weld inspection x and y position holder axes - The position holder is used in order to mount the xy motorised linear axes, the Optocator, and PPU which is "piggy-back" mounted on the y-axis slider, so that the whole set up can be moved to different sections of the pallet. A high accuracy shaft and recirculating ball bearing were desired in order to make the system compatible with the required accuracy for the Optocator and motorised axes and to eliminate non-linearity during scanning with the Optocator. Therefore, 20mm and 12mm diameter shaft and ball bearing with an accuracy of ± 0.01 mm are respectively used for x and y position holder in the design of the inspection station. Appendix A3 provides more information about the shaft and ball bearing specifications.

5.4.2 The Optocator System

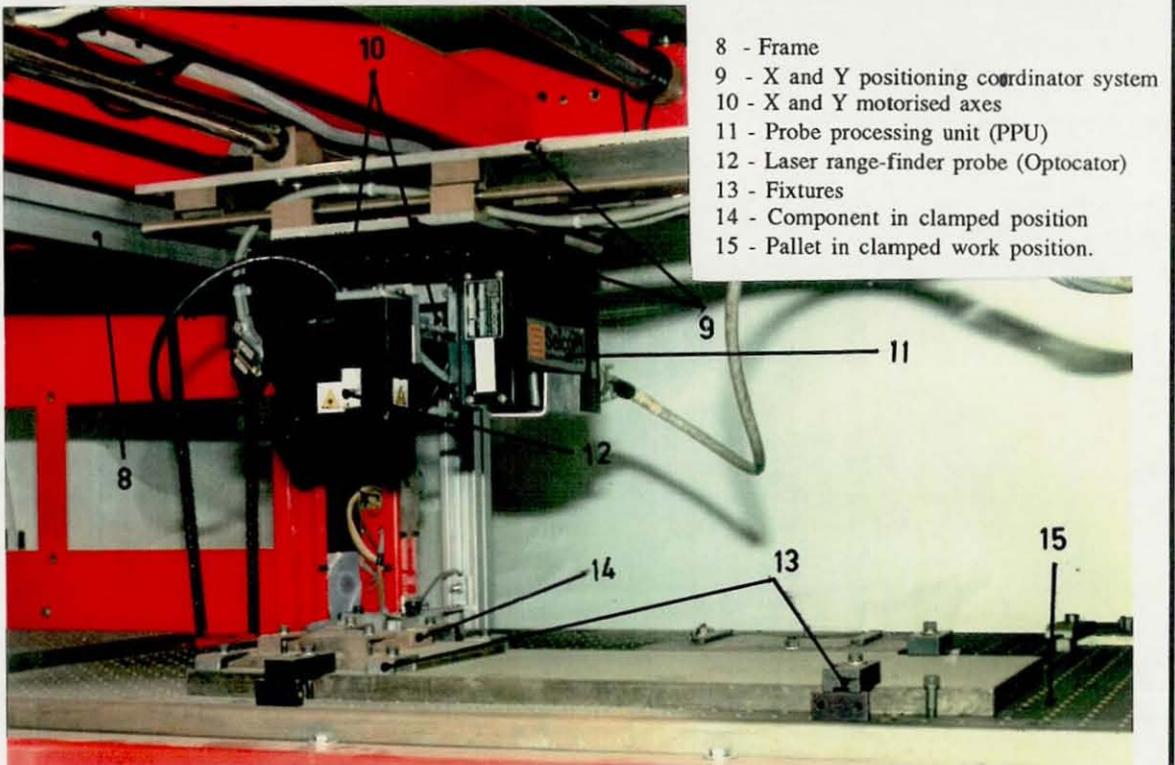
The laser range-finder Optocator systems have a widespread industrial Application [165]. They are used as a high precision, non-contacting measurement system in process control applications such as:

- i) Thickness measurement of hot steel strip.
- ii) Width measurement of hot steel bars.
- iii) Flatness measurement of hot steel strip.
- iv) Road surface profile measurement.
- v) Three dimensional measurement of car bodies.
- vi) Profile measurement of tire tread.
- vii) Seam tracking for adaptive control welding.

Several researches have reported [66-68] the use of such a sensor for seam tracking (of one-pass or two-pass systems) in arc welding. In chapter 3 section 3.4.4 a



(a) - The pre-weld inspection station control units.



(b) - The pre-weld inspection station.

Fig (5.3) - The overall configuration of the pre-weld inspection station in a flexible welding system.

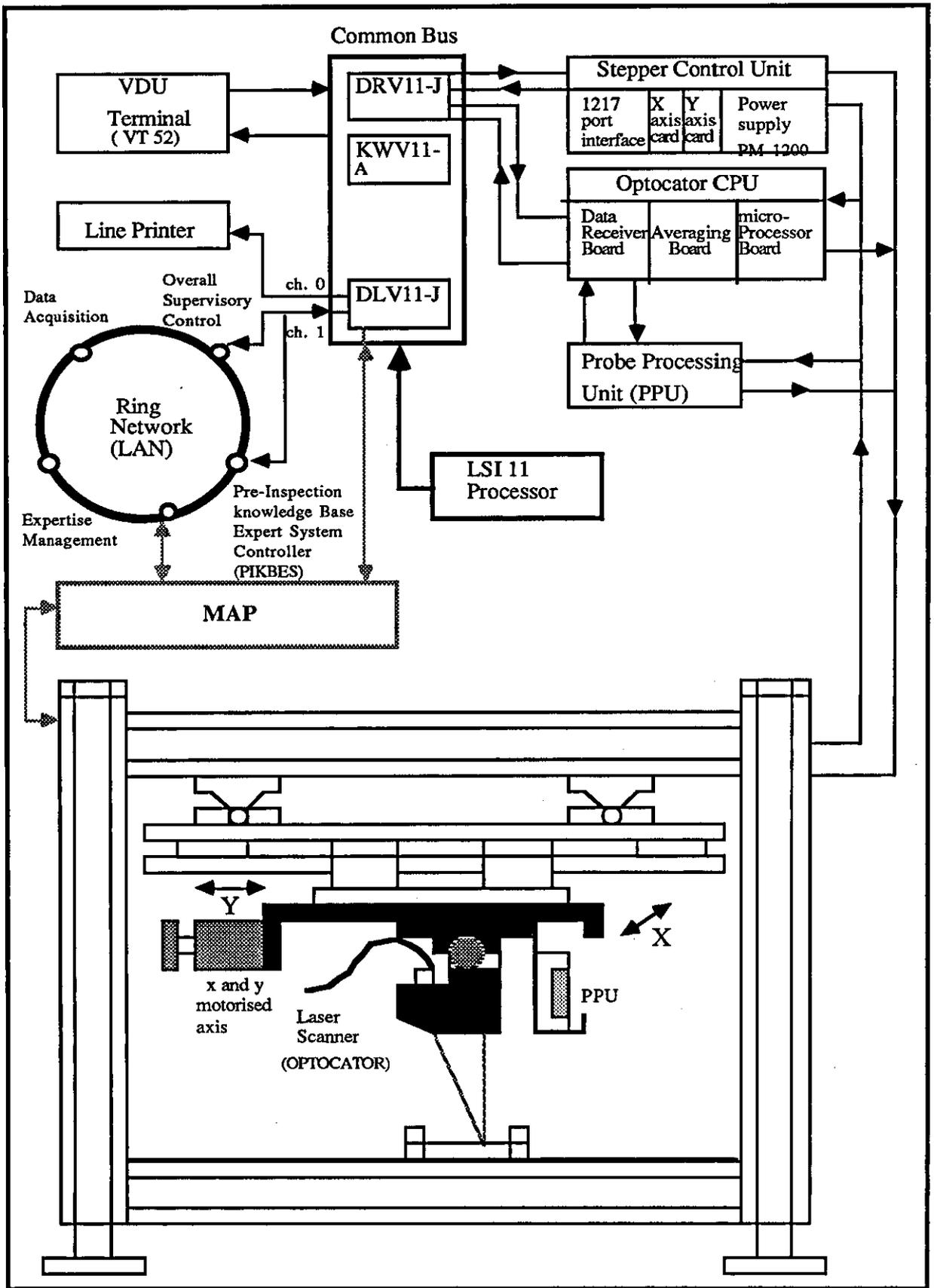


Fig (5.4) - The overall pre-weld inspection station interfacing with its control units and ring communication network (LAN).

detailed survey of this sensor has been carried out. The gauge probe head of the system contains the emitter light source, an optoelectronic photosensitive detector and signal conditioning amplifier. The additional signal processing electronics enables the the Optocator to be used as a stand-alone device. The output of the probe is a linearised signal in a serial digital format. Digital format processors convert these into analogue DC voltage signal and TTL compatible signal for computer uses. The processor also provides a digital display of the measured variable and out-of-tolerance information for monitoring and early warning of the sensor operation. Appendix A4 provides the technical specification of the Selcom Optocator probe.

5.4.2.1 The Optocator Operating Principle

There are two general principles applied in using the range-finding based sensor:

- i) The range-finding principle using the phase or " Time-of-flight" measurement - where the phase measurement of laser propagation is used by means of the time needed for the laser light to travel to the target and back to the receiver [166,167].
- ii) The range-finding principle by triangulation - is based on structured light, where a beam of light is projected onto the workpiece surface. The angle of incidence of this beam collected at the detector together with other parameters (distance between light source and detector lens, etc) are used to calculate the range [86,87].

Fig (5.5) demonstrates the Optocator triangulation principle based on technique (ii). The infra-red laser source diode S emits a light beam onto the surface of the measurement object M by means of the F1 lens system. The scattered light reflexion at point A is focused through F2 lens system and detector D which are at an angle of 30 degrees relative to the incident beam. If the distance S from the gauge probe to the measured surface is changed by X, the light beam from the light source will hit the surface M1 of the measured object at new point B. The picture of point B on the detector in point B' is displaced from the previous point A' by X'. The relation between the distance change X and the move by X' of the light spot on the detector is determined by the geometrical arrangement between the light source and the detector, this relation is not linear [168].

$$X = \frac{K1 \times X'}{K2 - X'}$$

(where X is the position on the detector and X' is the vertical position of the reflective surface.)

Since the light source, the lens and the detector are mechanically and solidly attached together the relation between X and X' is known and can be used to linearise the measurement results.

For the Selcom Optocator, the Measurement Range (MR) is 32mm. This distance can always be considered as a scale with 4000 divisions (resolution level). Therefore for the 32mm range, the resolution is $32 / 4000 = 8$ microns, and measuring accuracy $32 / 2000 = 0.016$ mm.

5.4.2.2 Probe Processing Unit (PPU)

The PPU electronics consists of an A/D Converter (ADC or analogue part) and A/D Converter Control Unit (ADC-CU or digital part), fig 5.6. After the light source is modulated to give a light beam of 16kHz, the output signal noise at the two current-to-voltage convertors is filtered via 16kHz band pass filters (with 2kHz Bandwidth).

After low-pass filtering to 2kHz to smooth out the measurement signal, the sum of difference of the signals are created and fed to a dividing A/D convertor where 12-bit conversion and normalisation are obtained at the same time. The 12-bit output position signal (the position of measured surface relative to gauge probe) is then processed through the PROM section which contains linearisation data. These data then transferred via a parallel-serial converter to the Central Processing Unit (CPU).

5.4.2.3 Probe Central Processing Unit (CPU)

The serial digital signal from the gauge is received and processed in the Probe Central Processing Unit (CPU). The CPU is composed of [89] :

- i) *Data receiver board* - This board receives the serial data information from one or two gauging probes and converts them to parallel form and in a dual probe system the signals from each probe are added together. The receiver

board is the interface between the gauging probe and the microprocessor part of the central unit but the board has a digital output which is connected to averaging board.

- ii) *Averaging board* - This board reduces the data rate from the receiver board by forming the average of a number of measurements from the receiver board. The output signal is a parallel digital signal which can be used for data collection by PDP11/23 minicomputer.
- iii) *Microprocessor board* - This board treats data from one or more receiver boards, converts information from the gauge to millimetre or inches and presents the results on a numerical display. The results are compared with the set tolerances, lamp displays are activated according to the deviation from the set nominal value. The input data to the board for nominal dimension, tolerances and calibration values is normally set via thumbwheels on the central unit panel and indication for valid / invalid data condition and an analogue test output.

The serial output signal from the PPU is received in the CPU via the datareceiver board. Furthermore, signal processors are provided to convert these signals into an analogue DC voltage signal and TTL compatible signal for computer interfacing.

5.4.3 Tests for Conformance of the Optocator Output Specification

The following tests and calibration were carried out to study the suitability of the Selcom Optocator (type 2203) for geometrical data collection from a prepared joint in the pre-weld inspection station.

5.4.3.1 Output Voltage Test in Relation to Measurement Range (MR)

This test has been carried out by mounting the Optocator on to a vernier height gauge. A voltmeter was connected to CPU test analogue output point and the height gauge moved the probe from one extreme of the MR to the other. Fig 5.7 shows the relationship between gauge to work distance and output voltage. The least-square fit

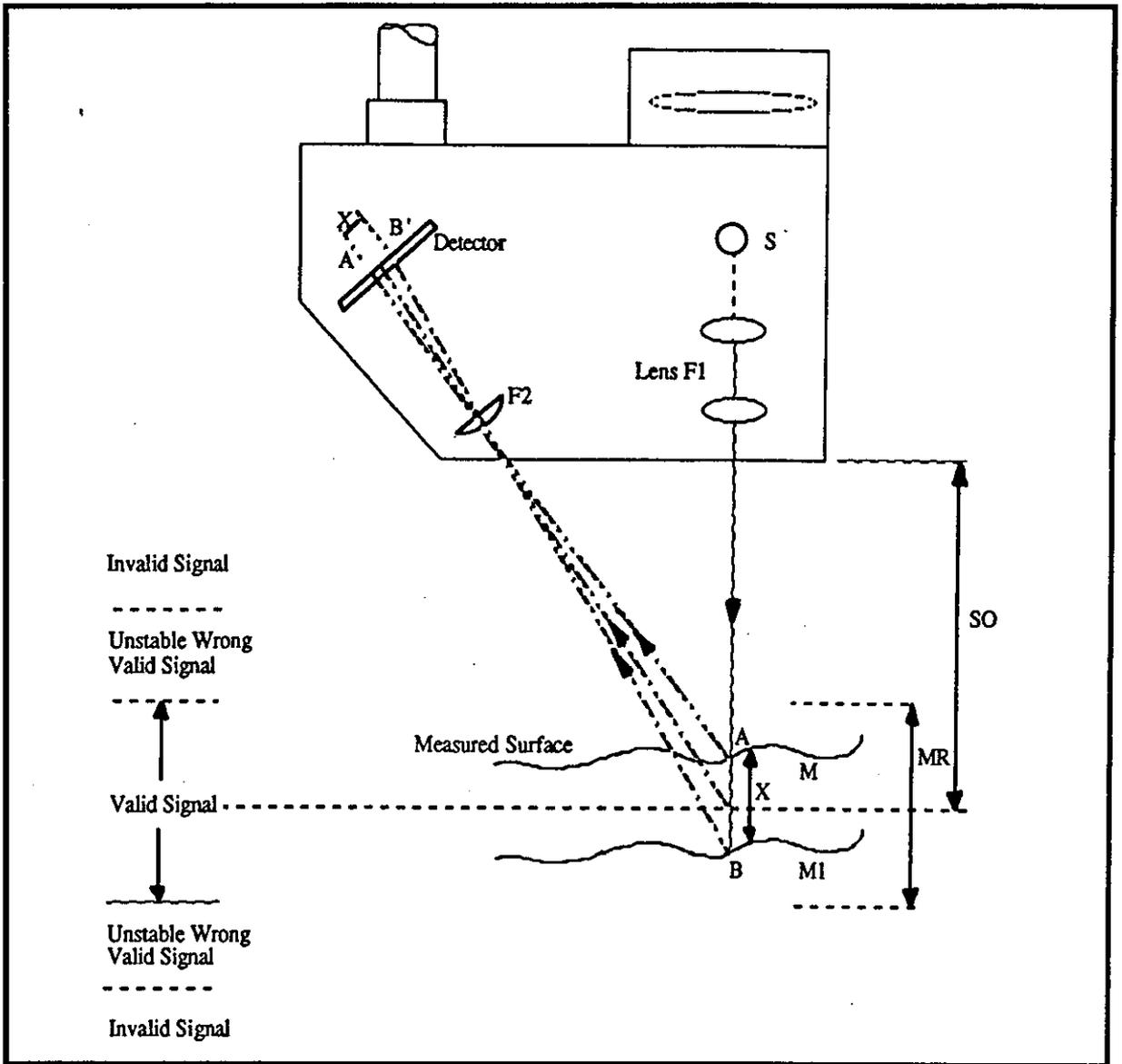


Fig (5.5) - The Optocator triangulation measurement construction.

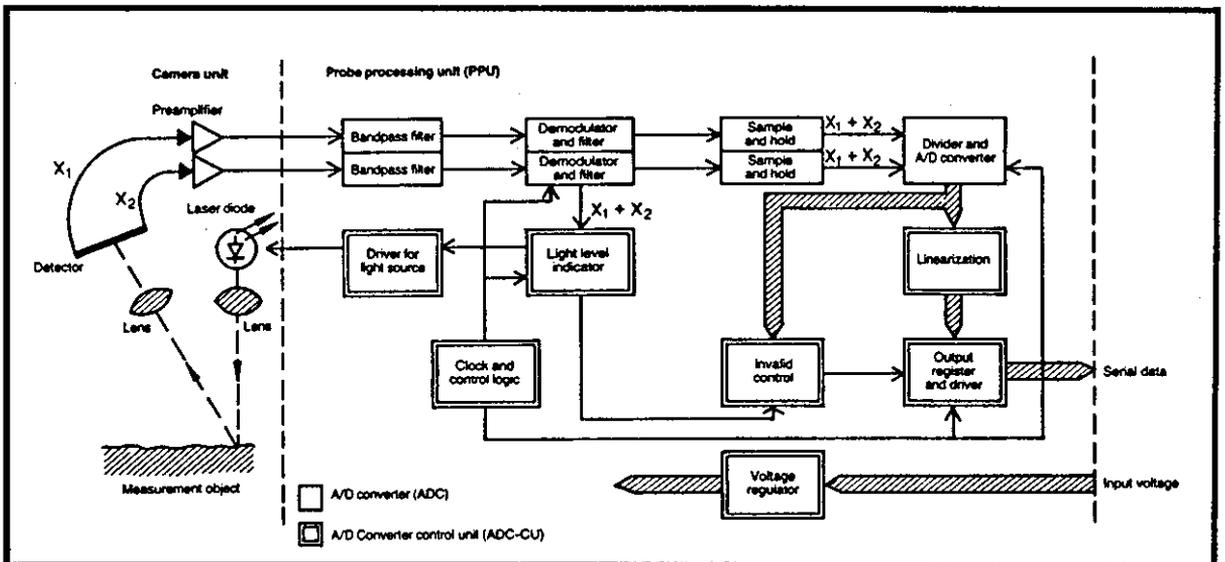


Fig (5.6) - Block diagram of Optocator PPU [169].

equation for the straight line is: $Y = 0.157X - 0.137$

5.4.3.2 Optocator Thickness Measurement Calibration

It has been observed above that the output voltage test in relation to MR was a linear relationship. A similar relationship is applicable to Optocator resolution level and MR/thickness measurement. Traversing from one end of the MR (reference base) to the other (32mm) should give an output of 0 to 4096 divisions. This condition is true while the Optocator digital output signal is in valid status. It has been found that the Optocator was only valid between 84 and 4077 divisions which corresponded to a physical distance of 32mm. The difference in levels from either end of the MR region would ensure a safe distance from the unstable region (shown in fig 5.5). This was achieved via a program SCAN using straight line equation $Y = 0.008014X - 0.675$ obtained from fig 5.8 which shows the calibration output result from the Optocator scanning.

5.4.3.3 Sources of Error in Optocator

The errors in the Optocator measurement are described by Selcom [169] and shown in fig (5.12). The errors are described as:

- i) Non-linearity - Maximum deviation from a straight line calculated by the root mean square method for all measured values (best line fit)

$$\begin{aligned} &= \pm 0.05\% \text{ of MR} \\ &= \pm 2 \text{ LSB Maximum} \\ &= \pm 0.008 \text{ mm} \end{aligned}$$

- ii) Inaccuracy - Maximum deviation between a correct line and the calculated line (best line fit)

$$\begin{aligned} &= \pm 0.05\% \text{ of MR} \\ &= \pm 2 \text{ LSB Maximum} \\ &= \pm 0.008 \text{ mm} \end{aligned}$$

- iii) Temperature Coefficient - Maximum deviation per degree C between the straight line at room temperature and the same type of line at another temperature.

$$\begin{aligned} &= 100 \text{ ppm / deg C of MR} \\ &= 0.4 \text{ LSB / deg C Max} \end{aligned}$$

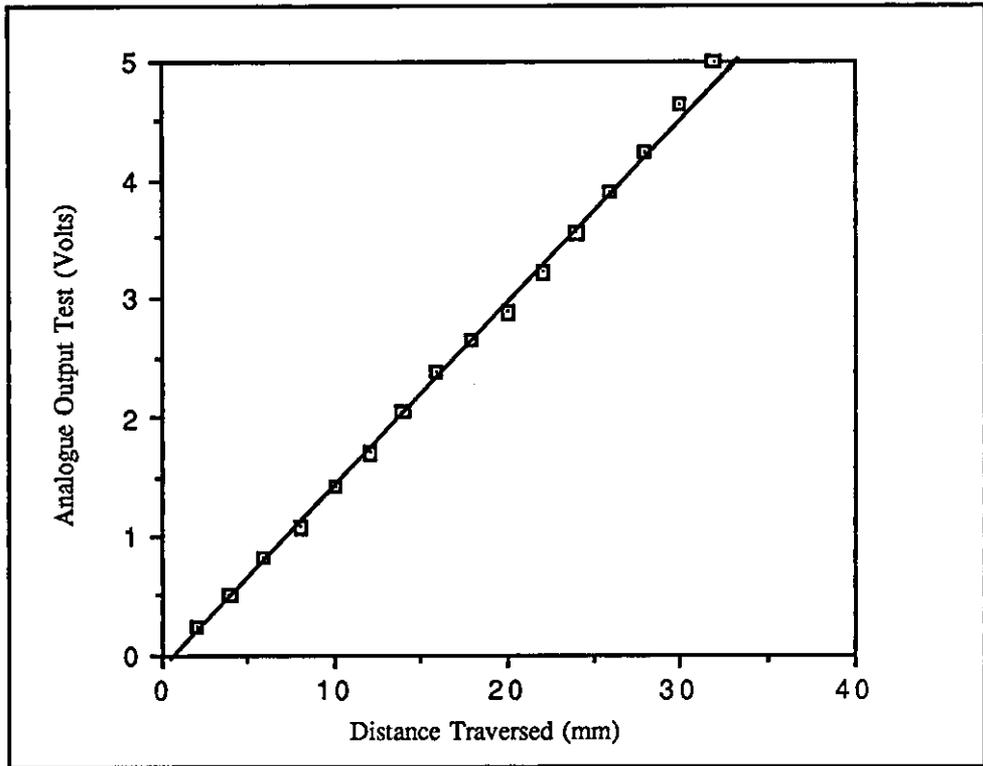


Fig (5.7) - Test output voltage in relation to M.R.

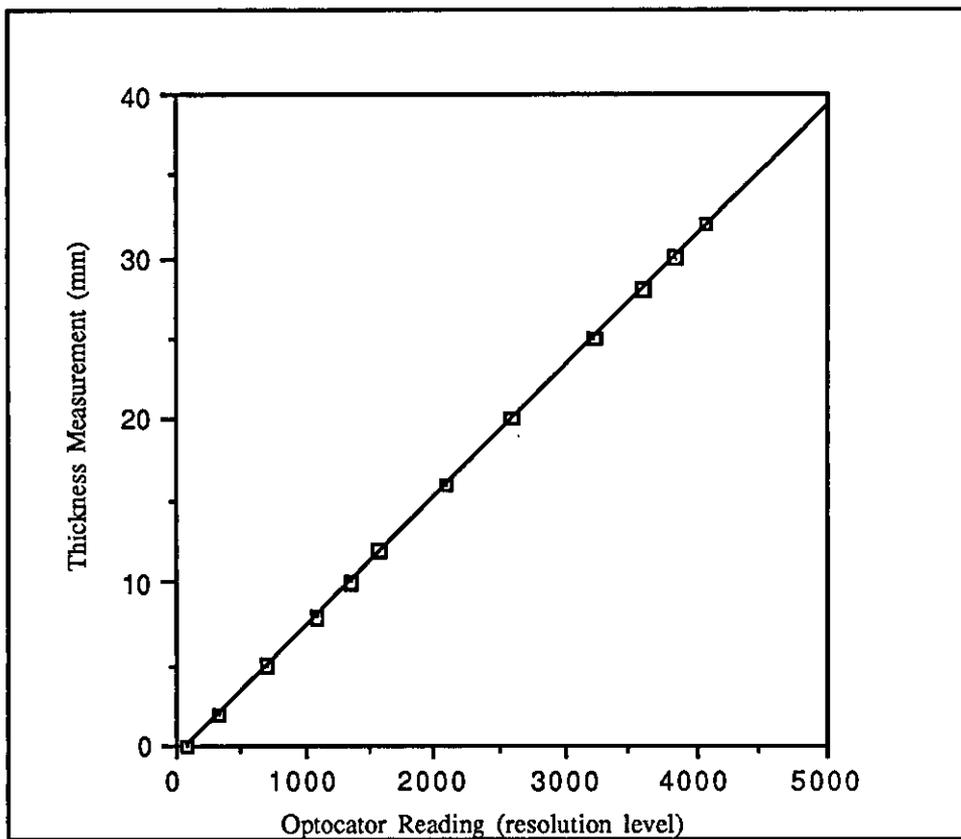


Fig (5.8) - Optocator thickness measurement calibration

= Assumed constant temperature.

iv) Noise - ± 8 LSB Maximum noise error = ± 0.0032 mm

Total error (over the total MR) = Non-linearity + Inaccuracy + Temp. Coefficient + Noise

Hence in worst case total error = $0.008 + 0.008 + 0.032 = \pm 0.048$ mm
(Neglecting temperature effects because the pre-weld inspection station sensor is remote from external heat sources and internal heat generation is insignificant).

Conditions which may also create error in the Optocator reading during data collection are as follows:

a) Invalid Signal Creation in Optocator

Further tests showed that even when the component under inspection was within the MR, there are conditions in which an invalid signal may be detected due to the photo-electronic detector and reflection of laser beam. The main causes of these invalid signals are:

- 1) Variations in Surface Reflectivity - Very black materials and shiny materials have one thing in common when it comes to Optocator measurement. They give very little light back to the probe. For a black material it is obvious that it is a bad reflector, i.e. very little of the light, that hits the surface, will bounce back, fig 5.9(b). With the shiny material we have opposite behaviour. A shiny material is a very good reflector (mirror) for the incoming light and a very high degree of the light will bounce back. The problem for the Optocator is that the more reflective (mirrorlike) the material is the more of the light will be reflected in one main direction instead of scattered, fig 5.9(a). Scattered light is the light that the Optocator uses.
- 2) "Shadowing" of the reflected light - This is caused by wrong mounting of the Optocator relative to the joint geometrical shape under inspection, fig 5.9(c) and (d), and also from rough or porous surfaces, fig 5.9(e). Tests of the Optocator output signal against a wide range of surface roughness were conducted. Fig 5.10 shows the results of these tests. The range of roughness values for which the output signal is valid was found to be 0.18

- 2.8 μm Ra. All specimen joint preparations used in trials of the pre-inspection system were manufactured to be within this acceptable range. Also in practice machine edge preparation could be expected to be within this range.

- 3) Steep surfaces of more than 60 degree - If the angle of the surface is too steep much of the scattered light is not reflected back to the detector. Fig 5.9(f) shows this effect. Further tests were conducted on plates with joint bevel angles of up to 60 to ascertain that valid signals would be obtained for the range of joint preparation to be measured at the inspection station.

b) Laser spot size and shape

The Optocator (type 2203) has a spot size of about 0.22mm in width and 1.53mm in length [169]. This depends on the location of spot size within the measurement range (MR). Such a spot size has caused a great deal of problems in edge detection. Goh [170] has also discussed in detail that the error in edge detection was principally due to the shape of the laser light spot and varied approach angle to the edges of the component. Assume that the Optocator, as positioned in fig 5.11(a), could just record a valid signal at half-way across the light spot. The amount of scattered light detected in case (b) is less than in case (a). Therefore, in case (b) the Optocator will move further forward before detecting the critical amount of light intensity hence also detecting the edge at up to 1/2 spot diameter further forward.

The three-dimensional profile of V-butt (using program 'Graph') from Optocator output fig 5.11(c) also indicates that the error in detection of edges at points B and C will result in errors in measurement of RG and RFT. These error have had to be calibrated and implemented in order to achieve desired accuracy. Shepherd [67] has discussed the same problem during the measurement of the RFT but it seems that he did not realise the effect of spot size and shape. Instead, he produced a model by dividing the range of possible RFT into levels and deciding which level is closest to the measured RFT, thus effectively giving tolerance to the measured value.

Goh [170] measured laser spot shape fig 5.13 with a scanning slot and detector combination, and the following beam sizes for Optocator (model 2010) were established:

At the bottom of MR = Approximately 1.0 x 0.5mm

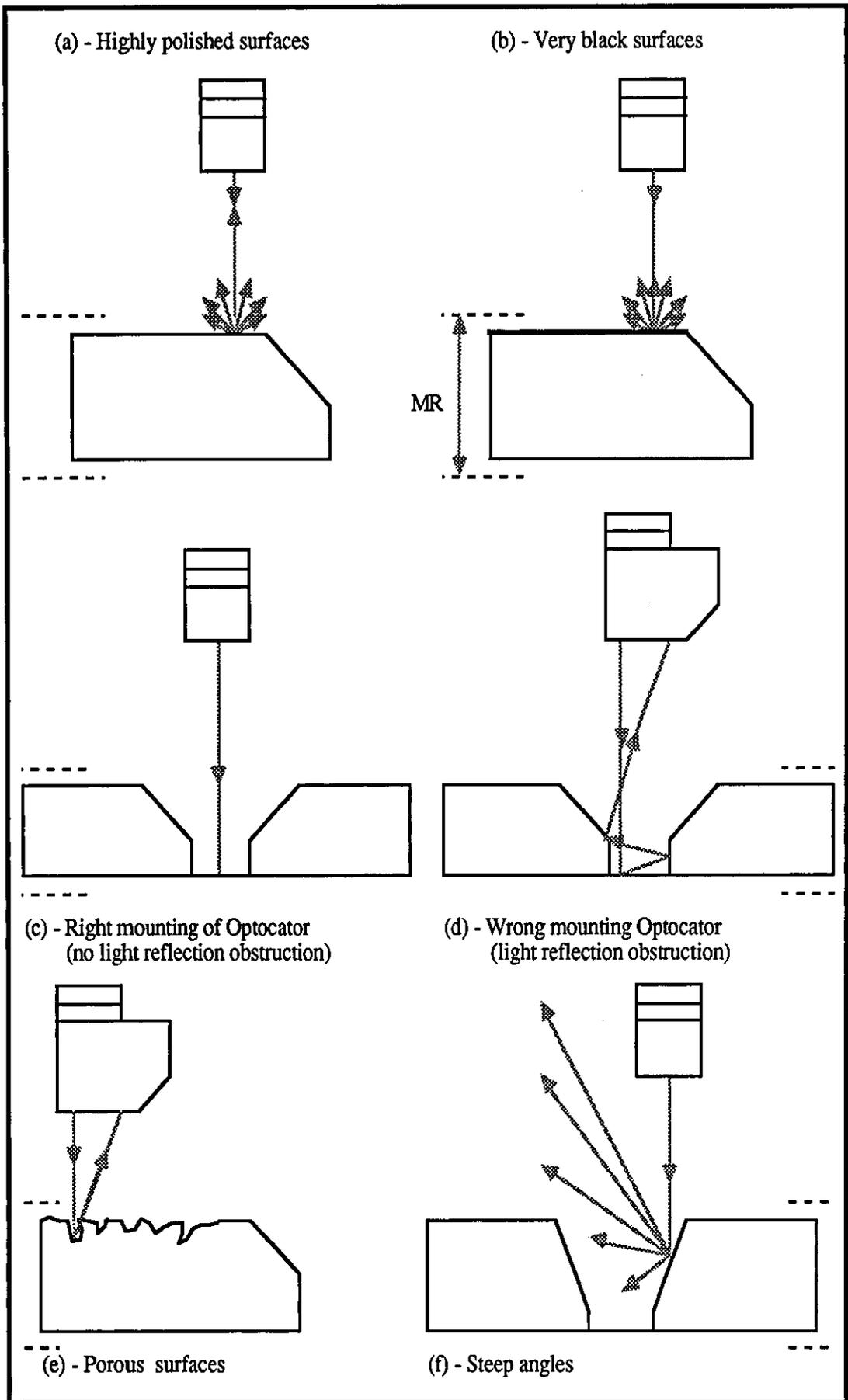


Fig (5.9) - Condition which creates invalid signal while component is within MR.

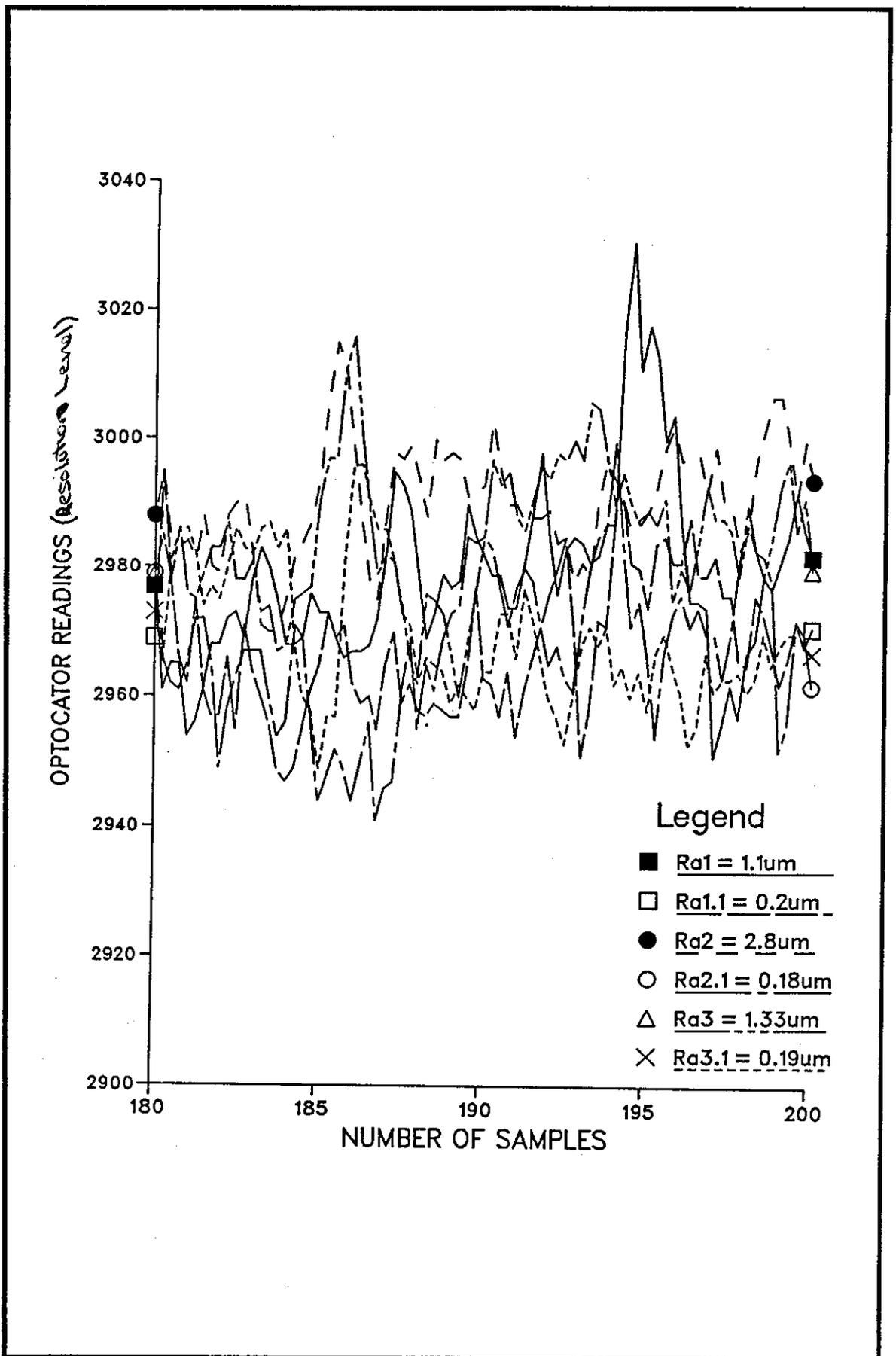


Fig (5.10) - Test of Optocator output valid signal for different surface texture (μRa).

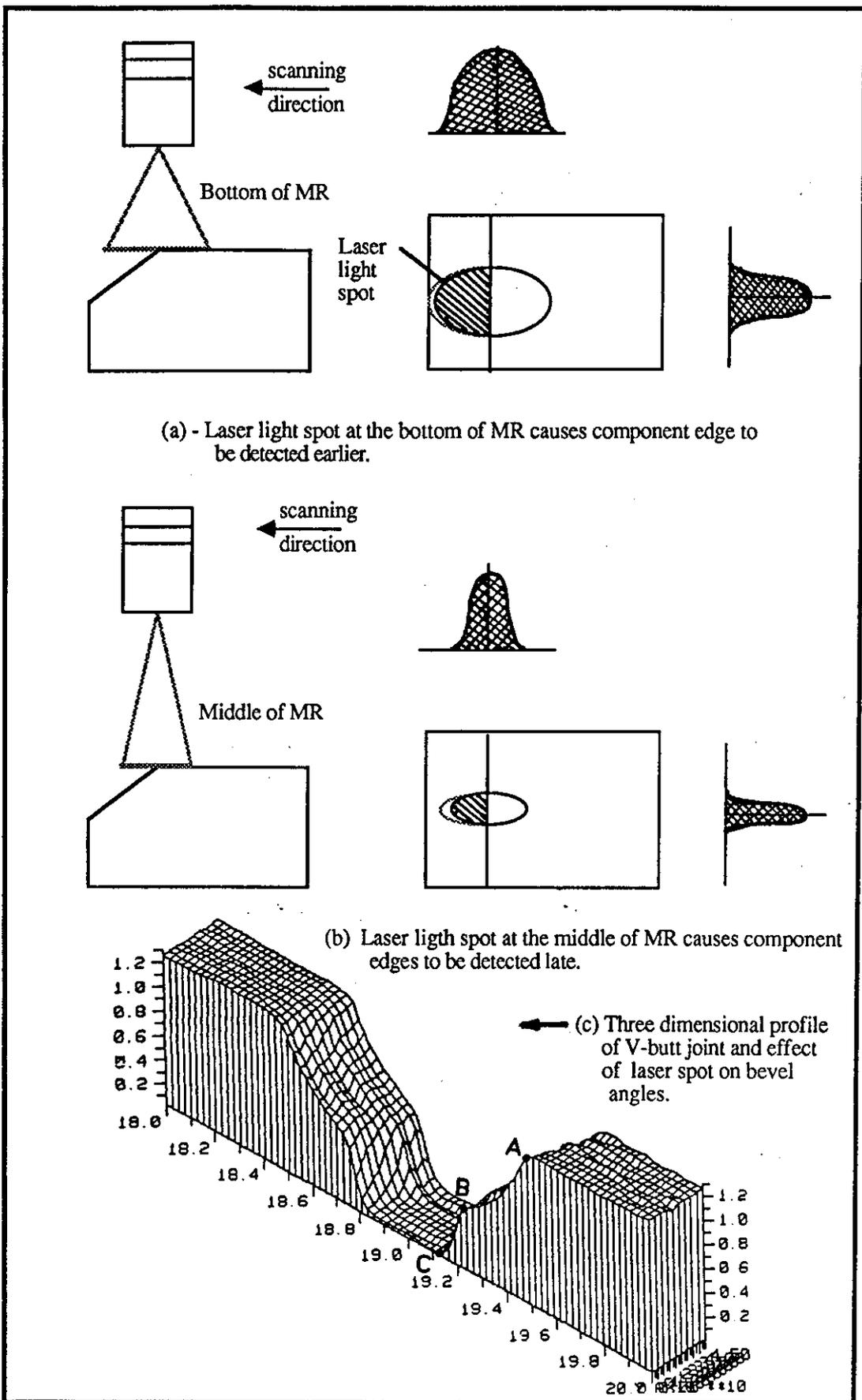


Fig (5.11) - Effect on measurement due to laser spot size relative to the edge of prepared joint during inspection.

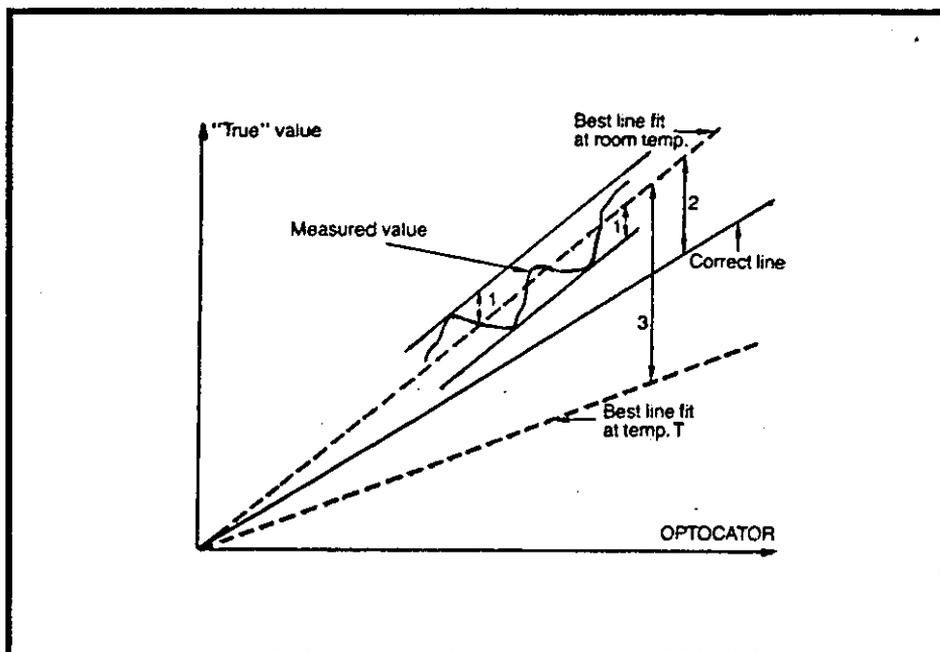


Fig (5.12) Error definition in Optocator measurement specification by Selcom [169].

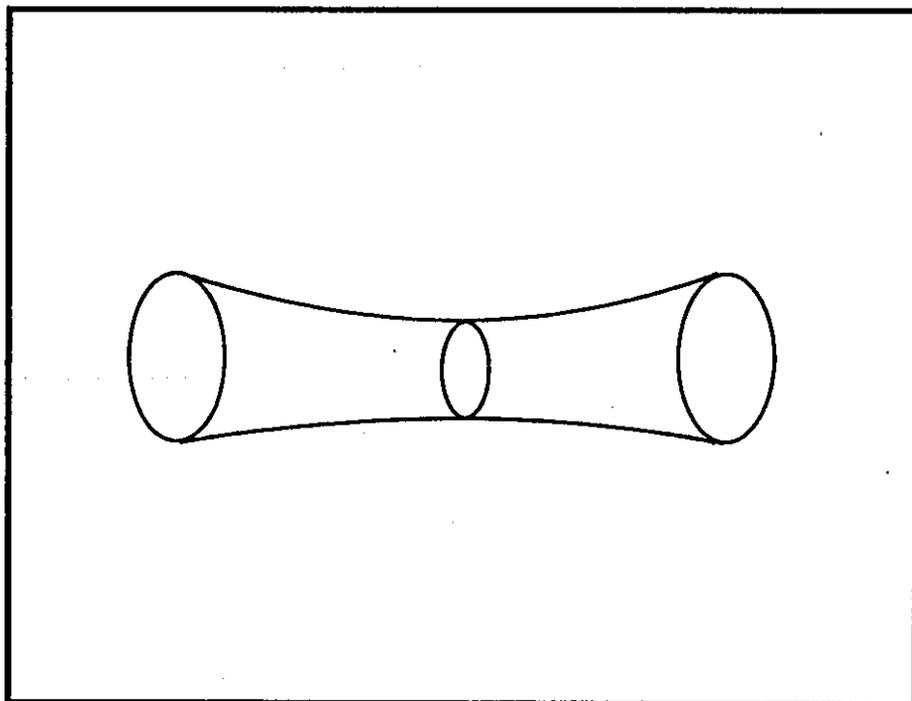


Fig (5.13) - Form of Laser propagation [170].

At the middle of MR = Approximately 0.5 x 0.1mm

At the top of MR = Approximately 1.0 x 0.5mm

5.5 Interfacing for the Pre-Weld Inspection Station

5.5.1 Integration of the Optocator with Motorised Axes

The computer system and the interconnecting hardware built around the pre-weld inspection station are all modular in design. Fig 5.14 shows the pre-weld inspection station interfacing and communication within the network. Data transfer and status registering for the Optocator read-outs and stepper motor control are governed by the 16-bits LSI 11 (PDP 11/23) minicomputer. These functions are made via a 64 I/O parallel interface card DRV11-J and programmable real-time clock K WV11-A [171]. These interface units enable the parallel line connection to TTL or DTL device to the LSI 11 bus interface.

5.5.1.1 Use of DRV11-J Interface Card

This card contains four programmable ports designated A,B,C and D. Each port contains 16 I/O lines (16 diode clamped input lines and 16 latched output). The communication between LSI 11 bus and DRV11-J are available for programmed interrupt vector addressing operations and programmed I/O operations. Work involved here in this report are programmed I/O operations.

The Optocator provides 12 parallel data bits and 2 flag bits. Both the Optocator and motorised axes data and status registering are performed respectively via B port (connector J1) and D ports (connector J2). Each port is capable of storing one 16-bits Input/Output word or two 8-bit Input/Output bytes. Therefore, in order to integrate the Optocator to the motorised axis systems, it is necessary to address the Optocator via port B, and a programmable real-time clock K WV11-A concurrently. Appendix A5 provides status register addressing and I/O signal pin connection for DRV11-J interface card.

5.5.1.2 Use of K WV11-A Interface Card

This card provides a variety of means for determining time intervals or counting events and has been used to generate interrupts to the LSI 11 processor at pre-

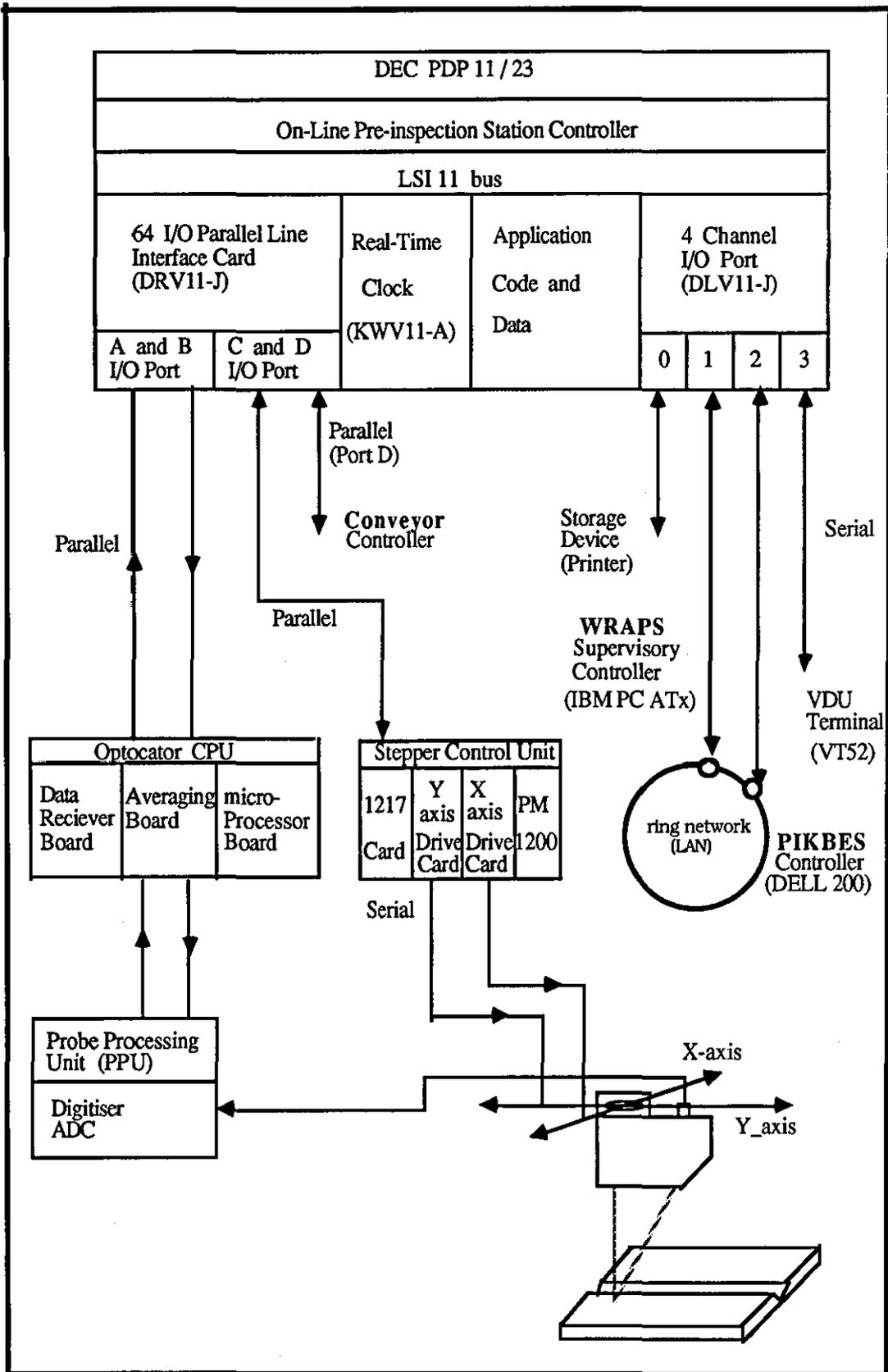


Fig (5.14) - Pre-weld inspection station interfacing and communication.

determined time intervals. All inputs and outputs are TTL compatible. The clock base frequency is divided into five selectable rates (1MHz, 100KHz, 10KHz, 100Hz) with four programmable modes (single interval, repeated interval, external event timing, and external event timing from zero base). The clock frequency of 100KHz with programmable mode 1 (repeated interval) was chosen in this report.

For a linear movement of 0.25mm, the scan axis steps through 200 steps. Using a 100KHz clock this means there will need to be a sample taken after 2000 ticks if the Optocator is being driven at a speed of 10,000 steps/sec (12.5 mm/sec).

Using mode 1, when the device reaches the end of a timing cycle, it does not stop but sets the overflow flag and status for the next timing cycle without the loss of any data.

5.5.2 Integration of the Optocator CPU with DRV11-J

As explained in section 5.4.2.3, The 12-bits output serial data information received at the Optocator CPU (Averaging board) from the probe processing unit, are then digitised by 12-bits of computer data. Hence, gives $2^{12} = 4096$ resolution levels, thus, the 12-bits of data were taken from the output of the averaging board which was connected to the external bus of CPU backpanel at terminal J11 and then to DRV11-J interface card via 64-way pin connector and 40-way connector respectively.

5.5.3 The Pre-Weld Inspection Station Communication

The pre-weld inspection station communication controls and status registering is achieved through the serial lines RS232-C [172] between the four channels serial interface card DLV11-J [171] (port 2), the knowledge based expert system (PIKBES) on DELL 200 microcomputer, DLV11-J (port 1) and WRAPS supervisory system on IBM PC ATx microcomputer. PIKBES and WRAPS are communicating via a ring network (LAN) and other peripherals. Each channel of the interface unit is equipped with a universal asynchronous receiver/transmitter and is capable of parallel/serial data transfers to devices. The character format used during data receiving/transmission are:

Baud Rate = 9600 bits/sec,
 Data bit = 8 bits,
 Stop bit = 1 bit,

Parity = odd parity.

The pre-weld inspection station communication with the flexible welding system conveyor controller for pallet and component recognition as each arrives at the inspection station encompasses the following considerations:

- i) Detection of the presence of a pallet awaiting process. This can easily be met by simple methods of condition monitoring such as detection of the presence of a queuing pallet by means of reception of 24 volts signal from the conveyor controller at the inspection station. Such a signal has at this time been simulated by means of a micro-switch which is mounted on the inspection frame. The bit-4 of DRV11-J port D connected to this switch is monitoring the status of the switch. On arrival of a pallet at the inspection station, if bit-4 is set to 1, the Optocator scanning operation will start, otherwise no operation will take place.
- ii) Identification of the pallets contents. The pallet and its contents is identified by a readable code of holes on the side of the pallet read by magnetic proximity sensors at the work station.
- iii) Determination of the joint position and orientation on the pallet. This may be achieved by further development of the sensor manipulator system such that the components position and orientation can be detected using sensor 'valid / invalid' signal and deviation of the joint from a datum line.

5.6 Software Development for the Pre-Weld Inspection Station

Two types of software were required by the inspection station. Inspection software was required for data collection by the Optocator and processing of this data by means of algorithms. Supplementary software is used to aid in the graphical and statistical analysis of results for Optocator calibration and testing, such as GINO-SURF, Tell-A-Graph and Cricket. The inspection station software for data collection and processing were written in high-level language "PASCAL" and low-level language "MACRO" (Machine Code) and was of a structured modular design. The modular structure enabled ease of other external program modules to be added to the system for further development of system. Fig 5.15 shows the hierarchical tree-structure of software modules for the pre-weld inspection station. The tree-structured modules are comprised of:

- i) The overall supervisory control program ('SUPER') - which controls the overall system operations for data collection and processing, and communication between WRAPS supervisory system, conveyor controller, PIKBES and any other additional devices.
- ii) The communication program ('COMM') - with which any message/command from the WRAPS supervisory is accepted and appropriate action taken. The message/commands are in the form of code 1, 2, ..., 9. These codes represent:

- 1 : Start the automatic scanning operation.
- 2 : Delay on scanning operation.
- : : : : :
- 9 : Emergency stop (Fatal Error Message).

If a fatal error message is received by the inspection station from either WRAPS supervisory or conveyor controller the system stops its current operation and initialise the axes and then enters a Halt and Diagnostic routine which displays diagnostic messages and stops the program. Fig 5.16 shows the pre-weld inspection close loop communication capability via ring network. Fig 5.18 provides detailed information about the communication messages/commands used in fig 5.16.

- iii) The data collection programs ('CALIB' and 'SCAN') - which initialise the motorised axes back to datum point and then starts scanning operation over the prepared joint in order to extract geometrical data. Section 5.6.1 describe the point-to-point scanning operation in more details.
- iv) The data processing program module ('AUTPAR') - which is used to carry out the feature extraction and joint recognition operation on the data collected in (iii) and provides information such as:
 - a) Joint type (square_but or v_but).
 - b) Plates thickness (T1_act and T2_act),
 - c) Gap/root gap (RG_act),
 - d) Root face thicknesses (RFT1_act and RFT2_act),
 - e) Bevel angles (BV1_act and BV2_act),
 - f) Plates angular misalignment (AM1_act and AM2_act), and

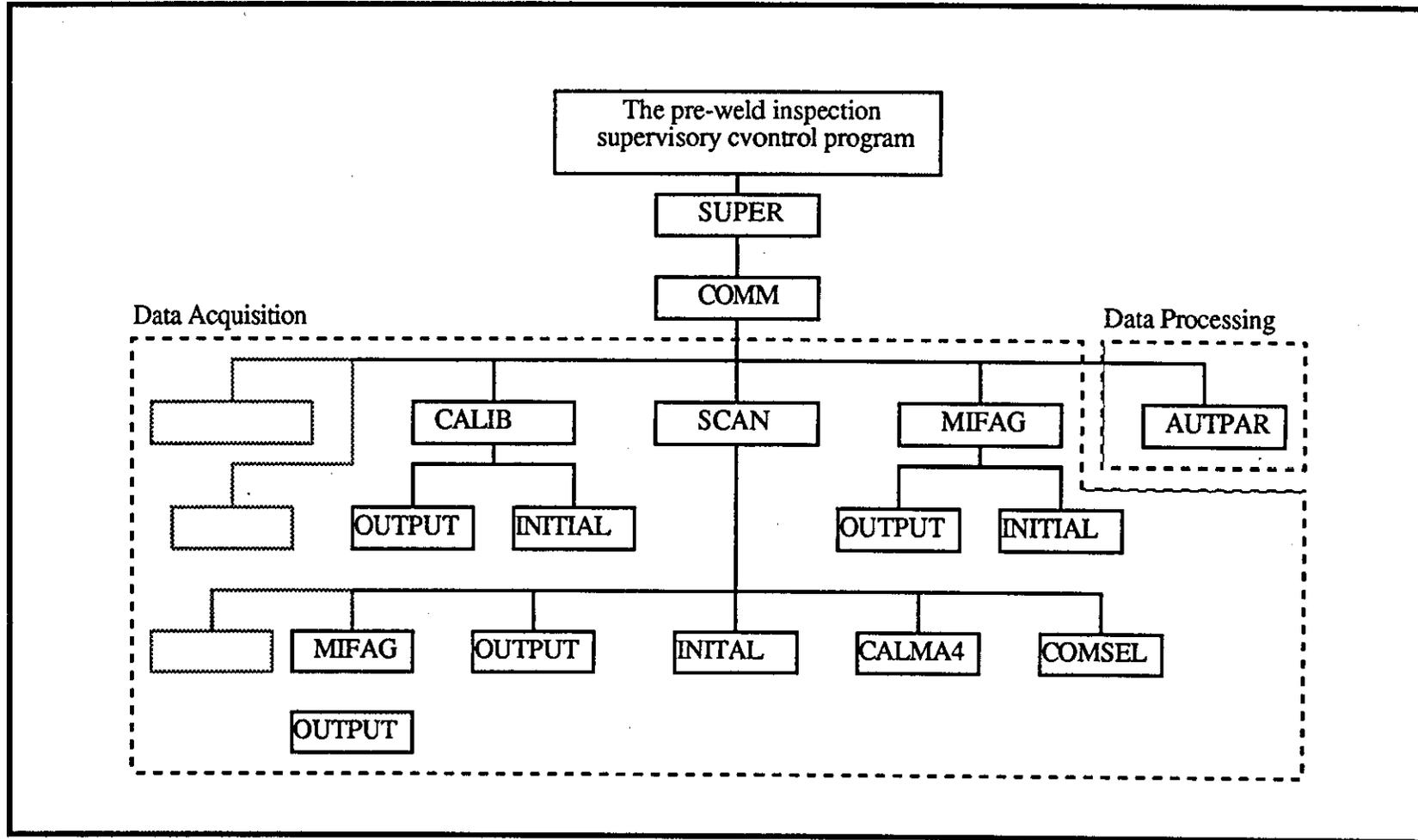


Fig (5.15) - Hierarchical tree-structure software for the pre-weld inspection station.

g) Area of the joint (A_{act}).

5.6.1 Point-to-Point Inspection

The Optocator is positioned in a "valid" condition and within the measurement range over the prepared joint at the datum point A. Fig 5.17 shows this arrangement. The scanning operation starts from point A and an Optocator measurement is taken at every 0.25mm while x-axis is moving toward the point B. This necessitates the use of real-time clock (KWV11-A) for the concurrent scanning operation between x-axis linear movement and Optocator sampling rate. 80 readings (samples) are taken for each 20mm scan across the joint and a total of 10 scans is performed for 45mm joint length, hence, 800 data samples is collected. fig 5.19 shows the Optocator data collection for one scan across the V-butt joint. The total time taken for each inspection is calculated below:

$$\begin{aligned} \text{Time taken for each sample} &= \text{steps per sample} \div \text{speed (steps/sec)} = 200 / 10000 \\ \text{to be collected} &= 0.02 \text{ sample/sec} \end{aligned}$$

x-axis scanning time

$$\begin{aligned} \text{scanning time for 80 samples} &= 0.02 \times 80 = 1.6 \text{ sec.} \\ \text{scanning time for 10 scan} &= 10 \times 1.6 = 16 \text{ sec.} \end{aligned}$$

y-axis forward movement time

$$\text{Time taken for 5mm} = 5\text{mm} \div 12.5\text{mm/sec} = 0.4 \text{ sec.}$$

y-axis movement

$$\text{scanning time for 9 movement} = 9 \times 0.4 = 3.6 \text{ sec}$$

$$\text{Total time for 45mm inspection} = 16 + 3.6 = 19.6 \text{ sec. at speed of 12.5mm/sec}$$

Time taken to weld a 45mm joint length, for example, for 2mm square-butt joint with 0.5mm gap (nominal joint) using 72 cm/min (12mm/sec) torch speed is 3.7sec whereas, time taken to weld the length of 5mm one-sided V-butt joint with 0.5mm root gap using torch speed of 11cm/min (1.83mm/sec), it takes 24.5 sec.

The comparison of time required for the inspection and data processing, and time taken to weld the prepared joint shows that the inspection time takes longer than welding process time for 2mm square-butt joint. This can be improved by better computer processing power and improvement of file handling of the software.

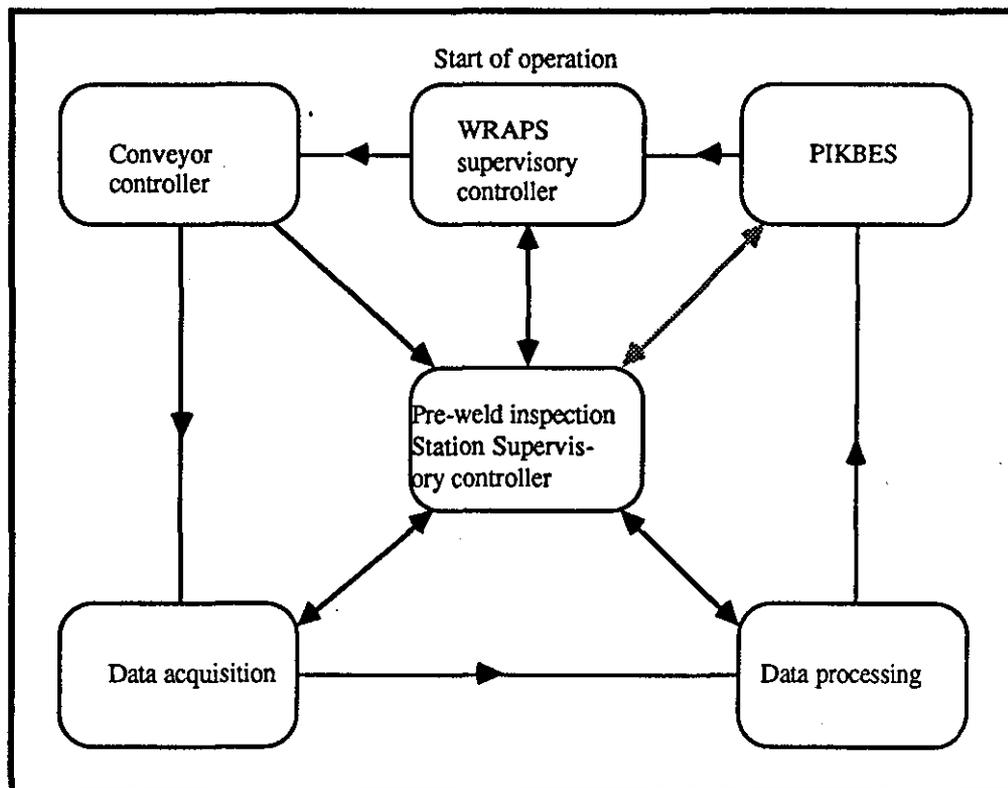


Fig (5.16) - The pre-weld inspection close loop communication capability.

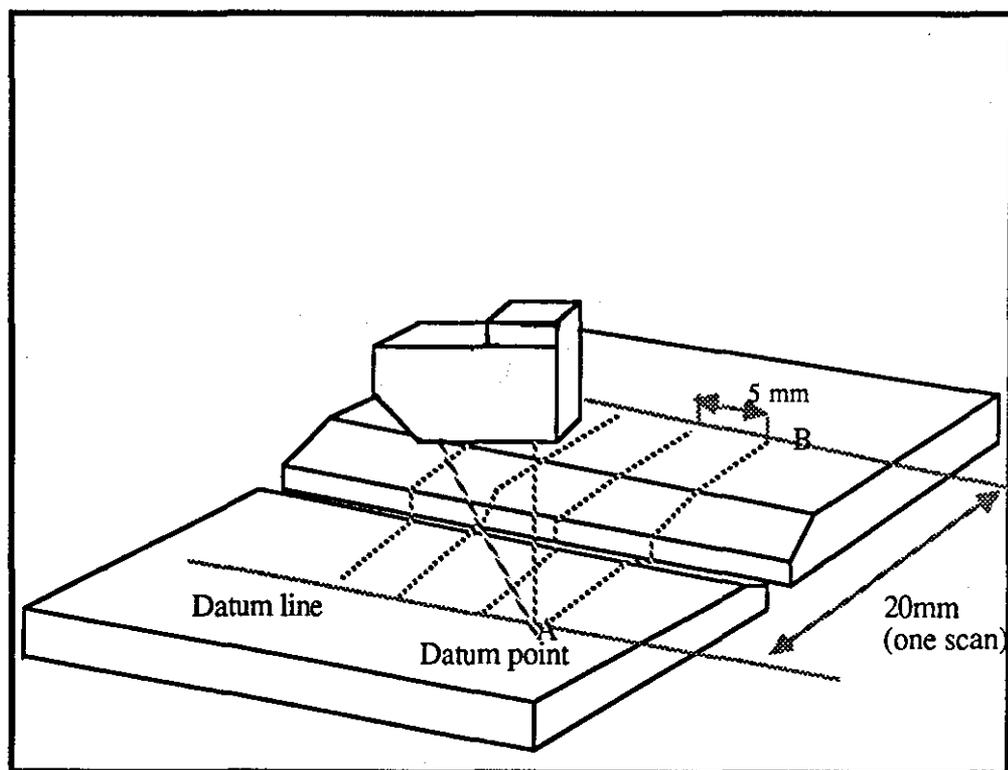


Fig (5.17) - Point-to-point inspection using laser range-finder Optocator.

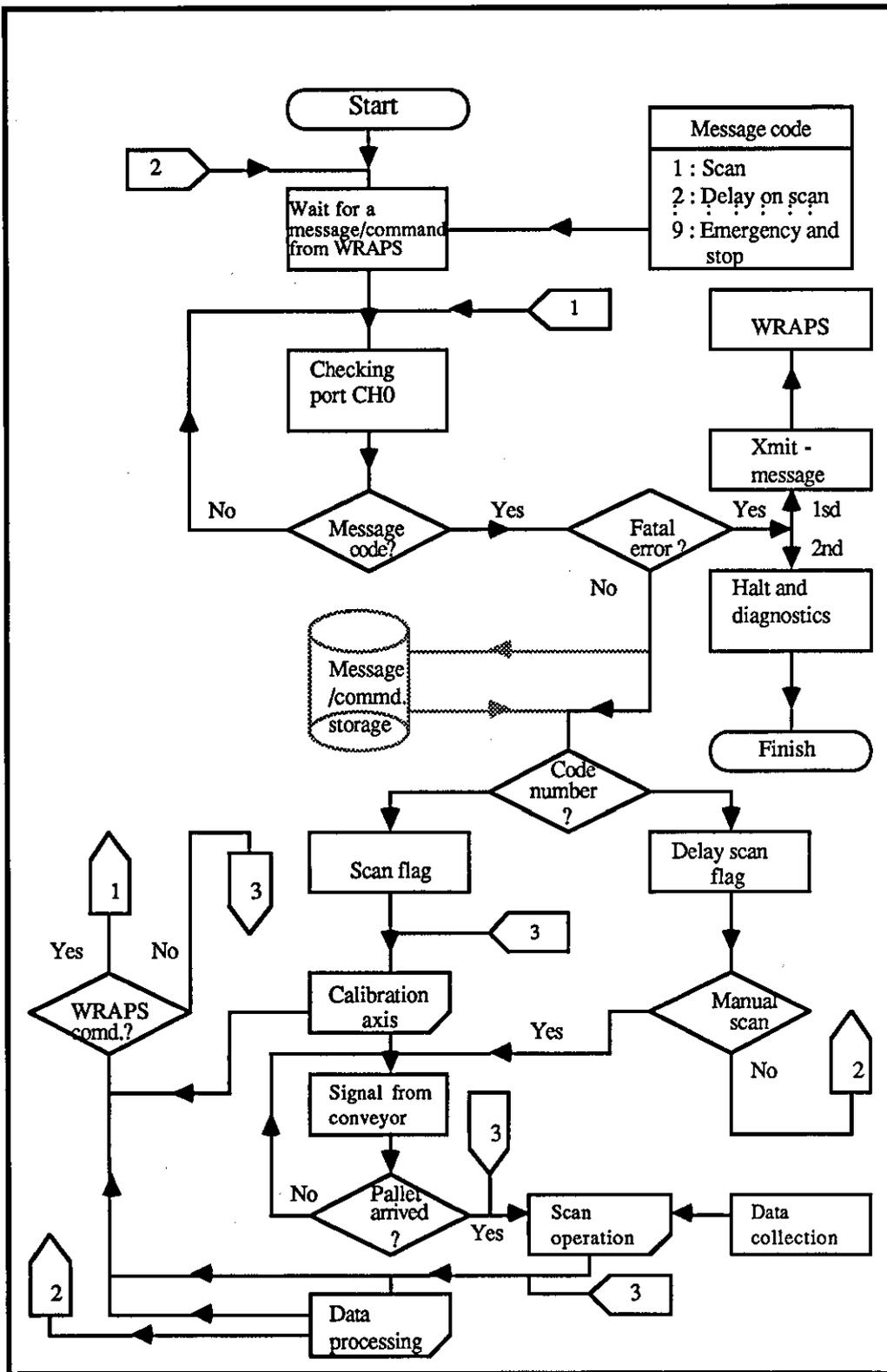


Fig (5.18) - Flow of commands/messages between WRAPS supervisory system and the pre-weld inspection station.

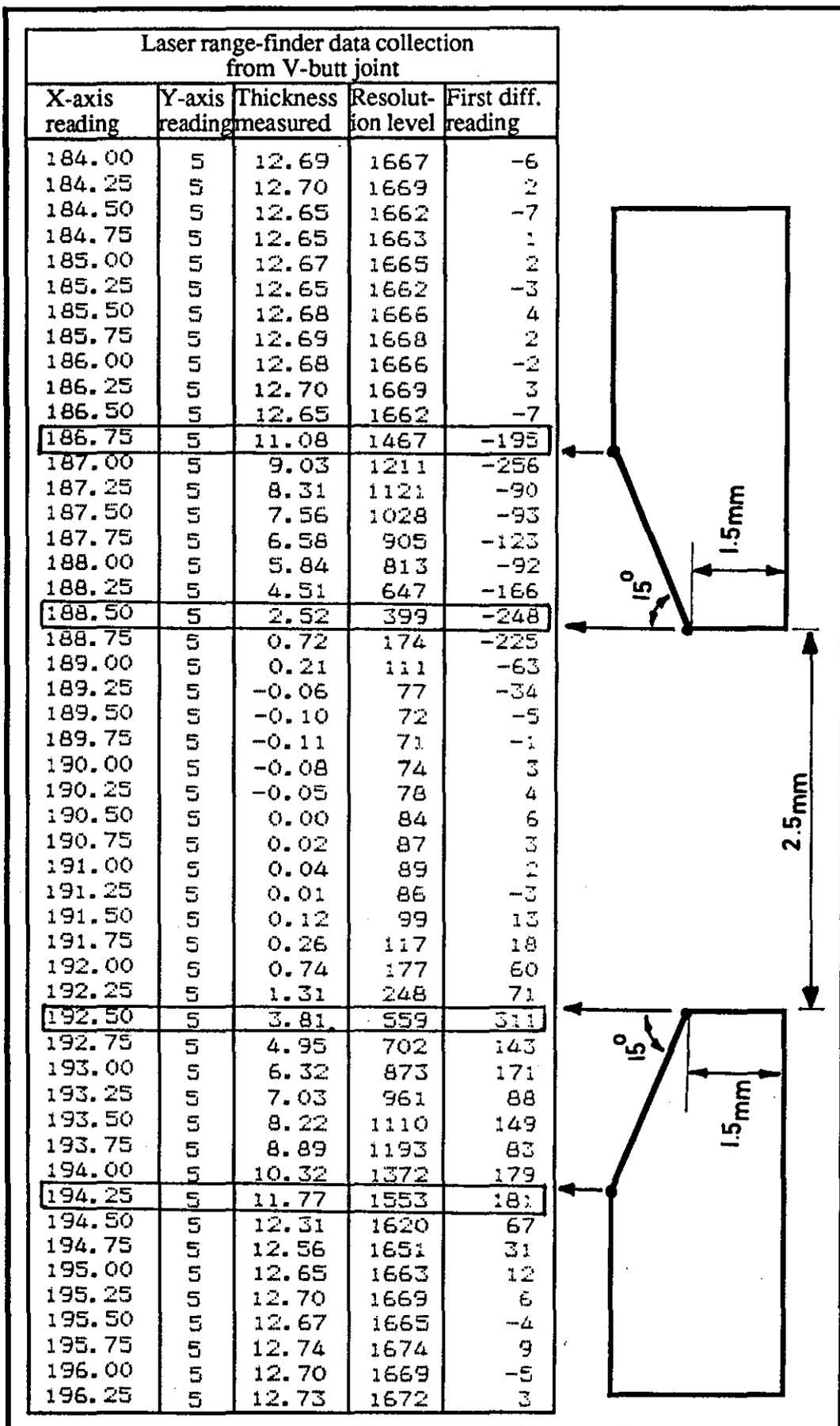


Fig (5.19) - Optocator data collection from 12.60mm V-butt joint.

5.6.2 Effect of Scanning Interval on Edge Detection

As explained in section 5.4.3.3, the laser spot size and shape created errors in the data which makes the direct measurement of the RG and particularly RFT difficult, as these depend directly on the exact detection of root face edges. It was thought that such errors would be reduced by reducing the scanning interval from 0.25mm to 0.1mm but this approach did not give a better detection of edges and also had a burden of an additional 120 data to be processed for each scan which increased the computer data processing time (i.e. 2000 data has to be processed for every 45mm scan). In fact tests showed that as the scanning interval decreased, the edge detection sensitivity decreased which made RFT measurement more difficult. Shepherd [67] has suggested the use of Ideal Observer Strategy method [173] to be used where the range of possible RFT is divided into levels which are used in process modelling. Then, a decision is made as to which level is closest to the measured RFT. Such a method required initial RFT values to be entered by operator (i.e. manual measurement from either end of the joint RFT is required). Hence, this method was not a practical way for automated welding systems. Therefore, the author suggests that a laser stripe sensor [76,77] would be more suitable when information on the detection of edges are required.

5.6.3 Feature Extraction and Joint Recognition in Pre-Weld Inspection Station

The assembled components arriving at the inspection station prior to the welding process, are inspected for any variation or misalignment along their joints and geometrical data collected. These data are then processed to extract features such as number of edges in the joint in order to recognise the type of joint. The processing algorithm is then used to measure features as explained in section 5.6(iv). The extraction of such features requires to that a data smoothing operation is performed on the raw data prior to measurements of such features. Fig 5.20, shows the hierarchical structure of data collection from the inspection station and data processing.

5.6.3.1 Smoothing

Smoothing has been used to eliminate signal noise and random large variations in the raw data. Random freak values have still been found in raw data during edge

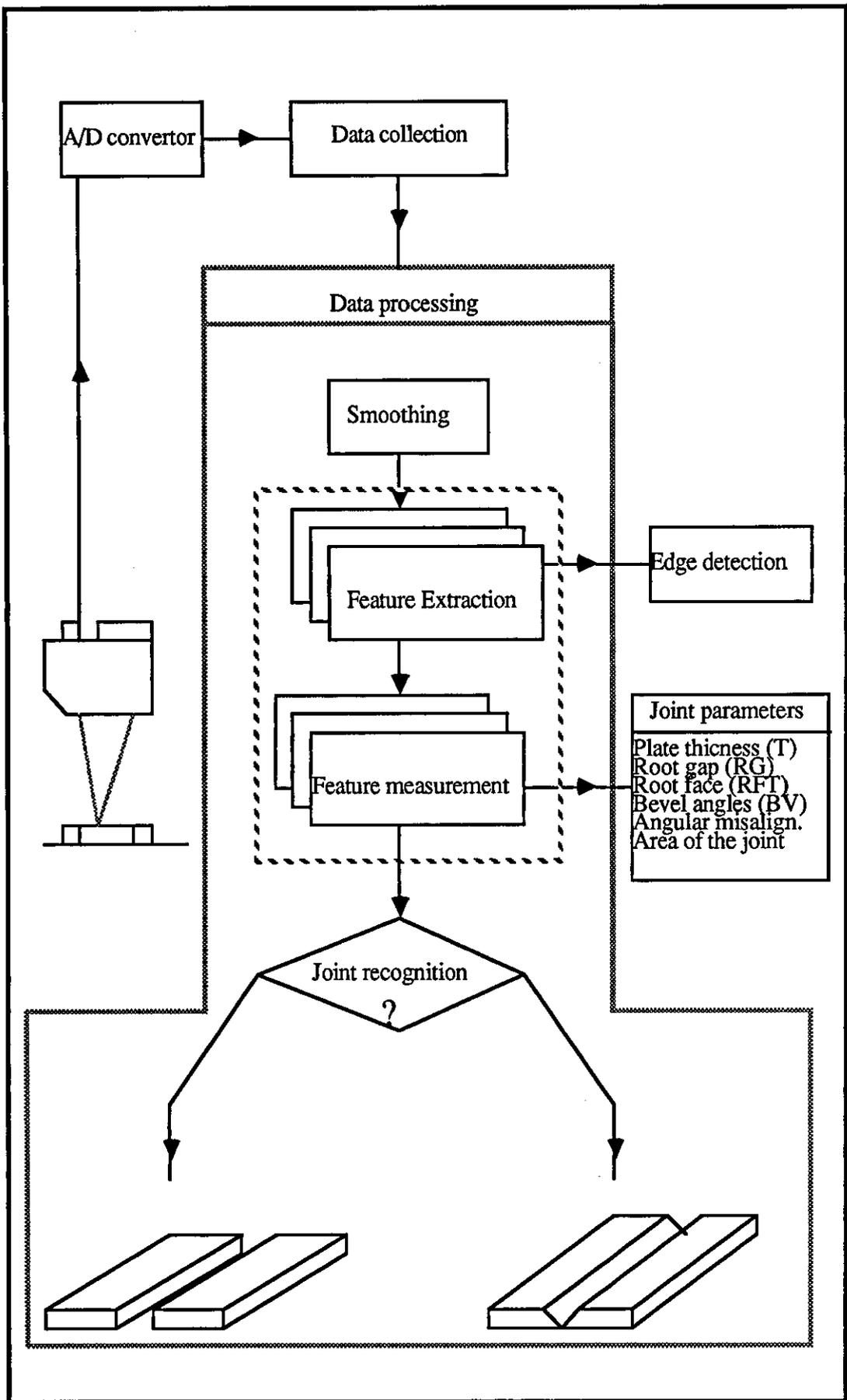


Fig (5.20) - Data collection and processing in the pre-weld inspection station.

detection which may cause misinterpretation of an edge, therefore they have been ignored. Noise suppression is also provided by performing a running average on data for thickness measurement.

5.6.3.2 Edge Detection

Edge detection involved measuring any rapid changes in section of joint structure. The simplest location technique to define the position of the joint is also to detect the edges of the joint which are normal to the plane of scan. Two methods have been tested to detect these edges:

i) Moving Line Segment Method - which consists of scanning the chain (scan points) with a moving line segment which connects the end points of a sequence of s links (number of scan points) [174]. As the line segment (whose length will vary depending on the angular variation among the chain links it spans) moves from one chain node (scan point) to the next the angular difference between successive segment positions is used to reveal edges. s values can vary from 2 to 6. The oriented line segment (vector) spanning s chain links and terminating on the node to which the link a_i is directed will be denoted by L_j . The subchain spanned by L_j is given by

$$L_j = C_{i=j-s+1} a_i \quad , \quad j = 1, 2, \dots, n$$

The x and y components of L_j are given by

$$X_j = \sum_{i=j-s+1} a_{ix}$$

$$Y_j = \sum_{i=j-s+1} a_{iy}$$

Hence, the angle of line segment are given by

$$\phi_j = \tan^{-1} Y_j / X_j$$

Fig 5.21(a) shows such moving line segment for detection of edges of joint. The test showed that although this method is quite fast and powerful, it may detect edges at a position 2-3 points before the actual edge. The author has used the same technique (with further calculation of curvature of the chain) for detection of sharp corners of an object [175].

ii) First Differential Reading Method - Where the difference between two sequential resolution level readings is taken. Sharp changes detected in the differences are indication of edges, the root gap and root face thicknesses can also be calculated from

the distance between the minimum and maximum turning points. The test of method this has showed that the edges can be detected fairly accurate and is faster than method (i). An example of first differential of data has shown in fig 5.19 and such data have been plotted for square-butt and V-butt joints in respectively fig 21(c) and fig 22(c). This method, which only involves subtraction of readings, is fast and powerful, and has been implemented in this research. This technique has also been reported by Shepherd [67] and Smati [64].

5.6.3.3 Joint Recognition

In order to recognise the type of joint and to measure the RFT at each scanning operation, a search strategy was adopted to search through the first differential reading to find:

- i) The Point-of-Inflexion (point E) - which is identified as a change of sign from negative to positive.
- ii) The Minimum-Turning-Point (point(s) C and/or D) - which is represented as a lowest point of the region (these regions are usually 3 or 4 scan points on either side of the minimum or maximum turning point).
- iii) The Maximum-Turning-Point (point(s) A and/or B) - which represented as a highest point of the region.

Fig 21(b) and (c), and fig 22(b) and (c) shows these points for 2D and first differential plot of square and V butt joints respectively. Types of joint can be recognised based on the number of minimum and maximum turning points detected for one scan operation. If the search detected two min and two max points in one scan then, the prepared joint would be recognised as a V-butt, else if the search detected one min and one max point or none then, the joint is respectively recognised as an open or close square-butt. Otherwise unknown joint type detected. The detected edges are later used to calculate the root gap (RG_act), root face thicknesses (RFT1_act and RFT2_act), and bevel angles (BV1_act and BV2_act).

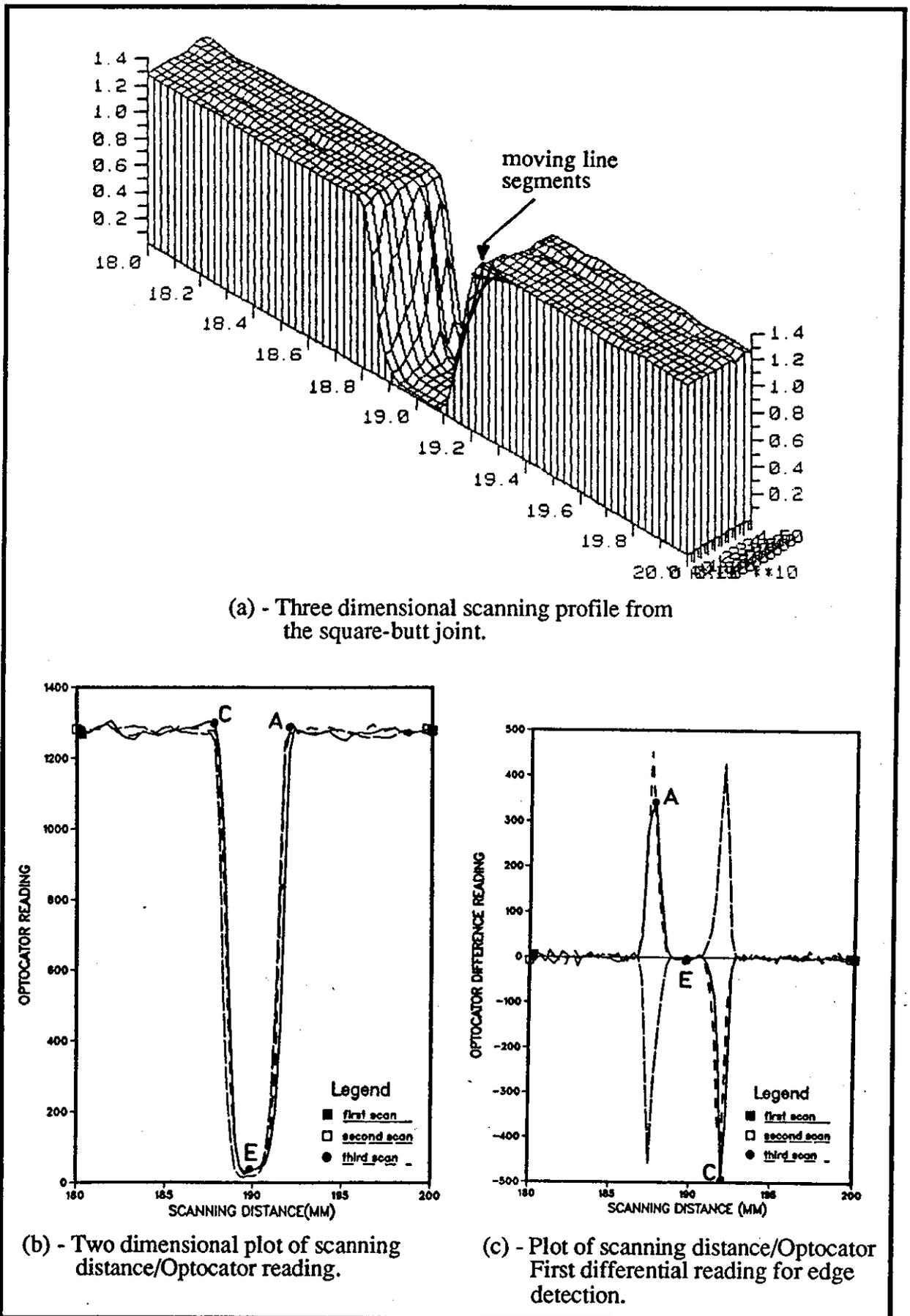
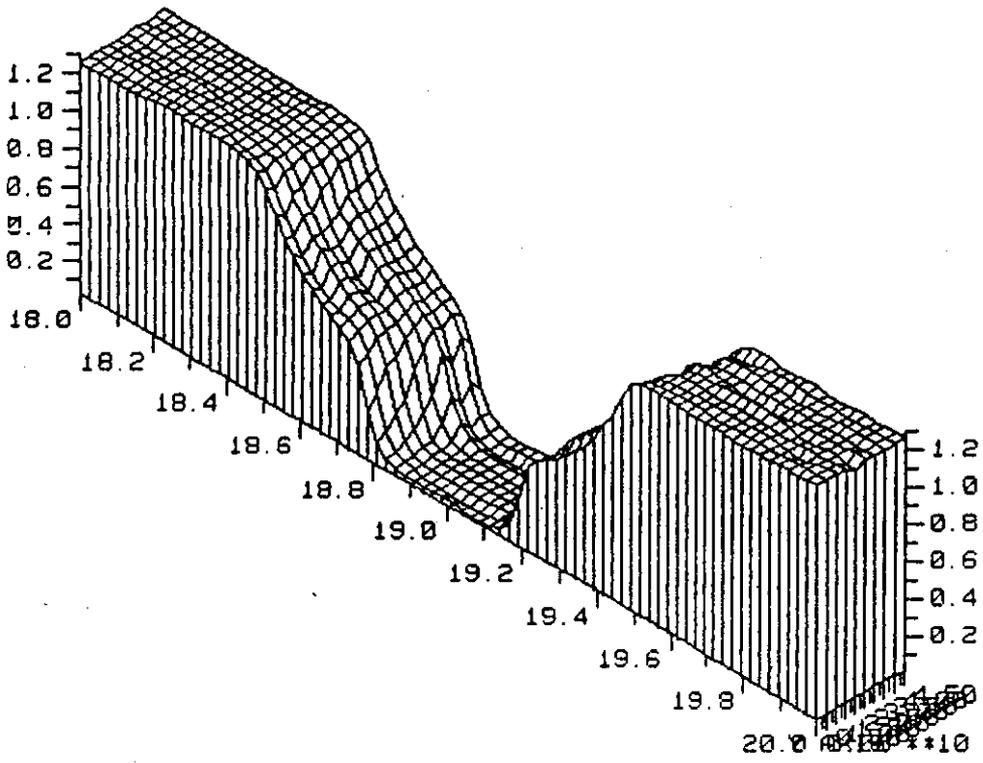
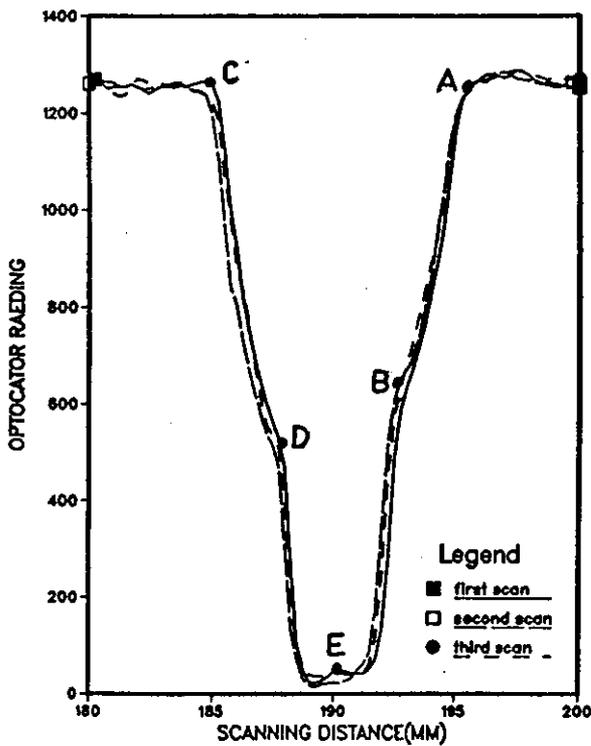


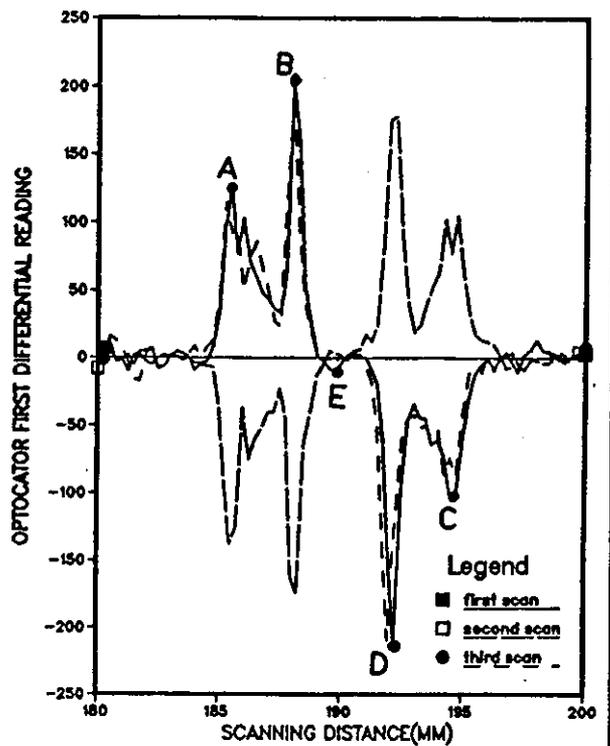
Fig (5.21) - Plot of data collected from 10mm square-butt joint with 2.54mm gap.



(a) - Three dimensional scanning profile from the V-butt joint.



(b) - Two dimensional plot of scanning distance/Optocator reading.



(c) - Plot of scanning distance/Optocator First differential reading for edge detection.

Fig (5.22) - Plot of data collected from 10mm V-butt joint with 2.54mm gap.

5.6.3.4 Calculation of Bevel Angles

Two methods were used in the calculation of V-butt joint bevel angles:

- i) To detect two edges (point A and B in fig 22(b)) of the V-butt joint of first plate and draw a straight line through the edge points and calculate the slope of lines.
- ii) To draw the 'Best' fitted straight line through the points lying between two edges (i.e. Linear Regression), where the relationship between x and y scan points is in the form $Y = aX + b$

where

$$a = \frac{n \sum X_i Y_i - \sum X_i \sum Y_i}{n \sum X_i^2 - (\sum X_i)^2}$$

and

$$b = \frac{\sum Y_i - a \sum X_i}{n}$$

Hence, the angle of fitted line can be calculated from $\phi = \tan^{-1} a$

The test result on the two methods showed that method (i) gave better results and involved less calculation than method (ii). The calculations are not effected by variations in surface roughness of the prepared bevel faces but might be effected by any damaged edges which may be generated respectively during machining or material transportation to the assembly line.

5.6.3.5 Calculation of Joint Area

The calculation of joint area is done by simple geometry and the accuracy of joint Area (A_{act}) is dependent purely on the accuracy of the Optocator data collection and processing, for determination of G/RG, RFTs, and BVs (in square and V butt joints). Such accuracy is effected by a laser spot size and shape (as discussed in section 5.4.3.3(b)).

5.6.4 Data Format Requirements by PIKBES

The processed data provided by the pre-weld inspection station controller (PDP11/23) are in form of ten blocks of information from the joint inspected. Each block of information represent one Optocator scan across the joint. The block of information (e.g. for V-butt joints) is:

- a) Joint type (square_butt or V_butt).
- b) Plates Thickness (T1_act and T2_act).
- c) Joint Gap or Root Gap (RG_act).
- d) Root Face Thicknesses (RFT1_act and RFT2_act).
- e) Bevel Angles (BV1_act and BV2_act).
- f) Plates Angular Misalignment (AM1_act and AM2_act).
- g) Area of the joint (A_act).

%

Any variation from nominal detected in the joint would be recorded. For square-butt joints (d) and (e) are not applicable.

The format of data required by the PIKBES controller is achieved by terminating each joint parameter value (attribute value) with a period ('.') and each scanned block of information with an 'end of attribute' sign ('%'). Fig 5.23 demonstrates such blocks of information from a V-butt joint together with its format.

The information collected is later transferred to PIKBES controller (DELL 200 micro-computer) via a ring communication network which then can be called as a communication file 'Fact.dat' to pass information to inspection knowledge based expert system to check for any out-of-tolerance variation in the joint so that modification on welding procedures can be carried out. Chapter 6 will discuss the data management for the PIKBES in more details.

```

Joint type = V_butt_unback.
T1_act = 12.74.
T2_act = 12.67.
RG_act = 2.75.
RFT1_act = 3.63.
RFT2_act = 3.65.
BV1_act = 16.14.
BV2_act = 13.94.
AM1_act = 1.60.
AM2_act = 2.98.
A_act = 53.5071.
%

```

```

Joint type = V_butt_unback.
T1_act = 12.82.
T2_act = 12.69.
RG_act = 2.50.
RFT1_act = 1.52.
RFT2_act = 4.00.
BV1_act = 14.02.
BV2_act = 14.31.
AM1_act = 2.75.
AM2_act = 1.15.
A_act = 52.2692.
%

```

```

Joint type = V_butt_unback.
T2_act = 12.69.
T1_act = 12.80.
RG_act = 2.25.
RFT2_act = 1.18.
RFT1_act = 3.41.
BV2_act = 14.80.
BV1_act = 15.05.
AM2_act = 0.69.
AM1_act = 0.92.
A_act = 52.7240.
%

```

```

Joint type = V_butt_unback.
T2_act = 12.71.
T1_act = 12.76.
RG_act = 2.50.
RFT2_act = 2.52.
RFT1_act = 3.81.
BV2_act = 14.80.
BV1_act = 14.49.
AM2_act = 1.15.
AM1_act = 0.92.
A_act = 50.0440.
%

```

```

Joint type = V_butt_unback.
T1_act = 12.66.
T2_act = 12.68.
RG_act = 2.25.
RFT1_act = 1.30.
RFT2_act = 3.28.
BV1_act = 15.41.
BV2_act = 13.45.
AM1_act = 2.52.
AM2_act = 0.69.
A_act = 51.1355.
%

```

```

Joint type = V_butt_unback.
T1_act = 12.79.
T2_act = 12.76.
RG_act = 2.50.
RFT1_act = 2.40.
RFT2_act = 4.37.
BV1_act = 15.26.
BV2_act = 14.69.
AM1_act = 1.60.
AM2_act = 6.39.
A_act = 51.1500.
%

```

```

Joint type = V_butt_unback.
T2_act = 12.67.
T1_act = 12.81.
RG_act = 2.50.
RFT2_act = 2.19.
RFT1_act = 3.72.
BV2_act = 14.34.
BV1_act = 14.28.
AM2_act = 0.23.
AM1_act = 2.06.
A_act = 50.4348.
%

```

```

Joint type = V_butt_unback.
T2_act = 12.66.
T1_act = 12.84.
RG_act = 2.50.
RFT2_act = 1.83.
RFT1_act = 4.22.
BV2_act = 14.28.
BV1_act = 14.78.
AM2_act = 2.29.
AM1_act = 0.92.
A_act = 51.7327.
%

```

Fig (5.23) - Shows the blocks of joint parameters information and its format.

CHAPTER 6:

**Knowledge Elicitation and
Implementation for PIKBES**

CHAPTER 6 : KNOWLEDGE ELICITATION AN IMPLEMENTATION FOR PIKBES

6.1 Introduction

This chapter starts with a background discussion of the limitation of flexible welding automation for small-batch manufacturing operations with respect to on-line quality control and the potential for the use of expert systems in compensation for variation in component joint geometry. The fitting of PIKBES into WRAPS and a flexible welding system is discussed in section 6.3, whereas section 6.4 discusses the PIKBES developmental sequence, that is, analysis of requirements, knowledge elicitation and formulation, implementation, and validation. Section 6.5 deals with the analysis requirements for PIKBES and discusses the communication, database selection and search capability of PIKBES, as well as software performance, compatibility, portability, and expansion capability. Section 6.6 discusses knowledge requirements, elicitation, and the formulation of the knowledge for PIKBES. This section discusses the problems to be solved by PIKBES, identification of source domain knowledge, the knowledge elicitation from experts, and the structuring of the knowledge into a tabular form for ease of implementation and formulation. Furthermore, it discusses 'window' and 'linear relationship' techniques which are used in order to generalise knowledge and to build the knowledge base. The implementation and validation testing of the knowledge, together with the PIKBES system's command facilities for the user, factorial designed experiments, and rule refinements, redesigns, and reformulations are discussed briefly in section 6.7 and 6.8. These are explained in more details in chapter 7.

6.2 Background

A major factor militating against the use of flexible welding automation in small-batch manufacturing operation, is the problem of establishing or selecting the best possible welding procedure for each particular joint or category of joint that might be presented to the welding station, and to provide on-line control of the procedure to take account of joint fit up variation.

Presently, the application of expert systems to this problem is virtually restricted to knowledge based selection of the best procedure from those available in a database [1], but takes no account of the eventual performance of the procedure and still

requires closer control of the assembly and fit up of the joint than would be necessary for manual welding.

Mathematical modelling approach [3,93,99] combined with the use of sensors have shown little opportunity for their generality of use. Considerable amounts of experimentation, time, and cost are involved in the development of models (or equations) which may only be applicable to a single combination of plate thicknesses, joint type, etc. This has been discussed in more detail in chapter 3 section 3.6 and 3.7.

The essential purpose of the research reported in this thesis is to apply non-mathematical model rules and heuristics in an expert system (PIKBES) in order to provide optimisation of the welding procedure applied to a joint, taking account of a possible wide range of variation in fit up.

6.3 Fitting PIKBES into a Flexible Welding System

PIKBES is a knowledge base expert system for pre-weld procedure control in an automated welding system. It is designed as a stand-alone module but with considerable interface capability and its objective is to provide a cost effective means of on-line quality control in a flexible welding cell. Fig 6.1 shows PIKBES for welding process quality control integrated into a flexible automation welding cell. The flow of components follows a sequential operation. Assembled components arrive at the inspection station and are inspected automatically for dimensions of the joint geometry using the laser range finder sensor. The measured data (Actual Joint Parameters) from the component joints are then transferred to PIKBES. PIKBES uses these parameters (e.g. joint type, plate thickness (T1_act, T2_act), gap or root gap (RG_act), etc) and compares them with nominal joint parameters (e.g. T1_nom, T2_nom, RG_nom, etc) which is provided by WRAPS supervisory system [1]. Expert decisions and conclusions are then made based on the amount of variation detected, and tolerances allowed for each joint parameter.

PIKBES works at three tolerance 'levels' which have been established from BS tolerance 'levels':

i) Tolerance 'level 1' - was initially established from BS 5135. However, these published tolerances are for manual welding and required modification, through consultation with experts to make them more appropriate to open-loop automated welding. Joints within these tolerances can be satisfactorily welded using approved

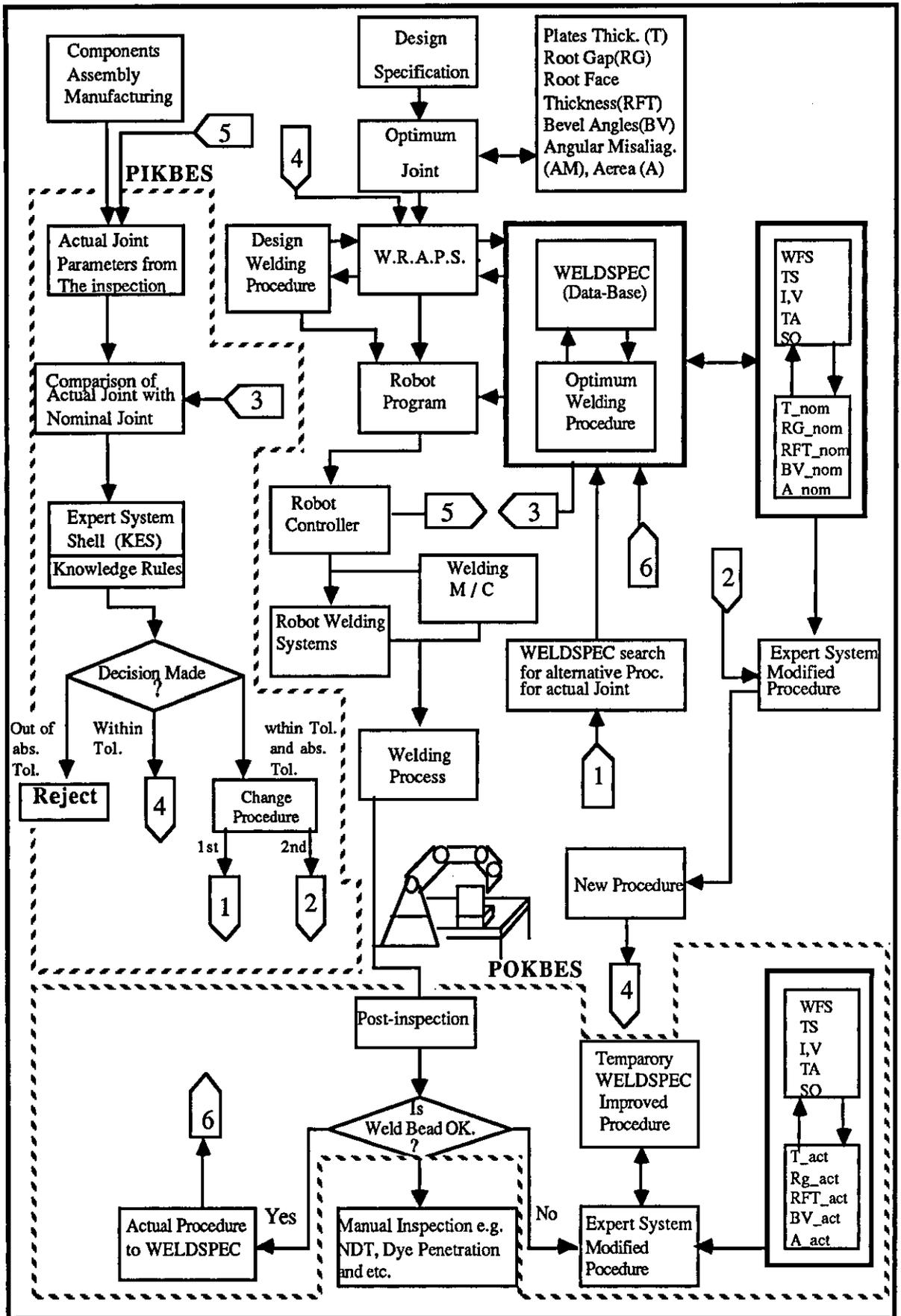


Fig (6.1) - Integration of PIKBES into a flexible automated welding cell.

nominal welding procedures. In such cases, PIKBES will command WRAPS to use the established nominal welding parameters (torch speed (TS), wire feed speed (WFS), voltage (V), etc) which will have been selected from the procedure database during off-line programming with WRAPS.

ii) Tolerance 'level 2' - is the maximum deviation from nominal joint dimensions which can be satisfactorily welded by feedforward loop automatic methods. These also have been determined by consultation with experts. In cases where actual joint dimensions exceed 'level 2', PIKBES will command WRAPS to Reject the component, and the work pallet will pass by the welding station of the flexible welding cell.

iii) Tolerance 'level 3' - is the intermediate level. Joints with dimensions in this range require the nominal welding procedure to be modified to assure satisfactory welding. The expert system (PIKBES), using expertly established rules, generates the modified welding procedure and then passes it to the WRAPS supervisory system for communication to the welding controller. The modified procedure replaces the preprogrammed procedure in the WRAPS off-line program.

In (iii), there is an alternative route which PIKBES has to follow before generating a modified procedure. PIKBES first searches the WELDSPEC database for an alternative approved procedure suitable for the actual joint dimensions measured. This is preferable to modifying the nominal procedure since any alternative procedure which is found in WELDSPEC will have approved status and there is therefore a high level of confidence in its ability to produce a satisfactory weld.

PIKBES expert decisions and conclusions are based on rules and heuristic knowledge obtained from welding domain experts and other sources of information (e.g. text book, standards, etc). The rules and heuristic knowledge are in the form of non-mathematical models which are used to modify welding parameters in such a way, that a well-filled, homogeneous and high quality weld will be the result. Hence, PIKBES is heavily reliant on two factors;

- 1) The accuracy of information from the pre-weld inspection station about actual component joint dimensions.
- 2) The accuracy of knowledge which was elicited through a dialogue and interviewing of experts in the field (e.g. The Welding Institute and LUT), rule induction from examples, and text book and published standards such as

BS 5135 [4] and 4870:part 1 [5], etc.

PIKBES also relies on information provided by the WRAPS supervisory system [1] regarding the nominal welding procedure, and from WELDSPEC database [120] for retrieval of data stored in its additional information section such as tolerances on joint absolute parameters, nominal joint area and nominal metallic area in the window. These latter terms are explained in section 6.6.1 of this chapter, whereas section 6.5.3.1 will discuss the database search and data retrieval in more detail.

6.4 PIKBES Development Sequence

Expert systems development faces similar problems to those that occur in conventional software systems. In addition, one has to cope with the question of extracting knowledge from domain experts and structuring this knowledge in a form suitable for automation.

The process of developing a functional expert system for the pre-weld inspection station (PIKBES) used systematic development in six stages. Fig 6.2 is a modification of the model used by Heng [116] and shows the stages in developing PIKBES. These are explained briefly below:

1) **Requirements Analysis** - the first step in the design of PIKBES was to analyse the requirements of the system. A complete understanding of the requirements was necessary to guide and support the design activities. To establish the understanding of requirements, the author had to:

- a) Identify the external requirements of the system (e.g. information requirements of PIKBES from the pre-weld inspection station and WRAPS supervisory system),
- b) Determine the available domain resources (e.g. experts, books, standards, etc),
- c) Characterise the end users (their familiarity with expert systems, KES and the welding domain). Normally PIKBES runs invisibly in conjunction with WRAPS but it may be desirable for the user to obtain explanation and justification of the decisions made by the system. It is assumed that a welder or welding engineer with some knowledge of the KES expert system shell will operate PIKBES, although 'help' facilities

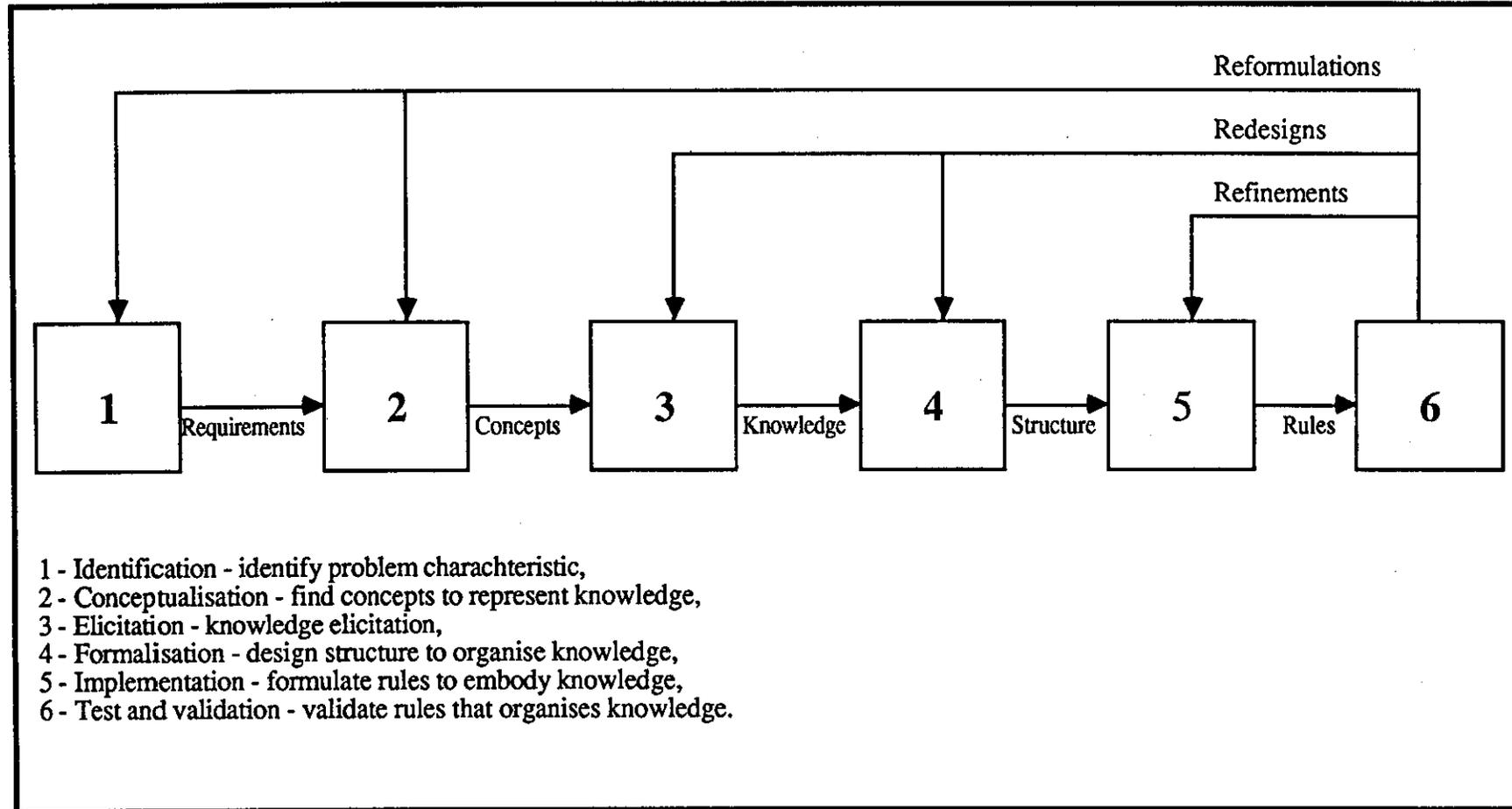


Fig (6.2) - Stages in development of PIKBES (developed from [116]).

are available.

Section 6.5 discusses the requirements of PIKBES in order to provide on-line modification of welding procedure.

2) Find a concept(s) to represent knowledge - this is accomplished by selecting KES expert system shell [116] and 'window' and 'linear relationship' techniques. These techniques are discussed in detail in section 6.6.1 and 6.6.2.

3) Elicit and formulate knowledge - this is the most crucial task in the development of PIKBES, because it determines its inferential capabilities. During this task, the author has undertaken a number of interviews and dialogues with welding domain experts both from The Welding Institute and Loughborough University in order to elicit the required knowledge. The domain experts possessed extensive knowledge of welding fields and had the ability to apply that knowledge to solve welding problems and make decisions. The main purpose of these interviews and dialogues was to find general methods and non-mathematical models to enable compensation for the deviation in joint geometry by modifying welding parameters so that satisfactory welding can be achieved. Other knowledge extracted was via welding text books, research publications, and standards. Section 6.6 discusses how such knowledge was extracted either from experts or any other resources in order to find a general solution to the joint deviation problem.

Domain knowledge consists of facts about the domain and relationships between these facts. For PIKBES, these facts were first structured in a tabular form and then built as an attribute hierarchy so that the relationship between them could be realised. This enabled ease of formulating the knowledge (facts) into a form of rules and to follow the inter-relationship between them. The KES PS expert system shell was used for formulation and implementation of the heuristic rules. Section 6.6 discusses and shows the formulation of knowledge elicited and implemented in KES shell.

4) Implement knowledge - The formulated rules are implemented using a text editor (Wordstar) and KES shell (using PS production rule inference engine) to represent the expert system. The software was produced as a set of modules, and these were tested to verify that each module meets its specification.

5) Validate knowledge - factorial designed experiments were carried out to show the validity of PIKBES knowledge. The validation involved selecting and running

different test cases to show the ability of the system to handle typical inference and end user scenarios. 'Window' and 'linear relationship' techniques were evaluated. The run-time efficiency of PIKBES during the evaluation task, together with refinements, redesign and reformulation have been carried out. Chapter 7 will discuss these in more detail and present radiographs and photographs of tested weld samples.

6.5 Analysis of PIKBES Requirements

In order to satisfy the requirements of PIKBES, The following criteria of the system have been identified:

- i) The system should have an expert system shell with good interface capability. KES expert shell was selected. The reason for its selection has already been discussed in chapter 4, section 4.4. Section 6.5.1 in this chapter discusses the communication capability of the KES shell.
- ii) PIKBES should be capable of communicating with other controllers. PIKBES is required to receive information from both the pre-weld inspection station (actual joint parameters) and WRAPS supervisory system (nominal joint parameters).
- iii) The database for welding procedure data storage/retrieval, either to be used by welding engineers in entering welding procedures manually, or accessed automatically by external programs, should be easy to use and preferably should support a graphical display. It was anticipated that the latter would be required for the future expansion of the system to provide the user with a graphical display of the joint as well as dimensional details, weld run sequence, and hardness measurement.

At present only graphical representation of nominal joints and their dimension are available in WELDSPEC database. It is possible to embed a graphical package such as HALO '88 [176], to provide other graphical displays during consultation with PIKBES.

- iv) The system should contain dynamic knowledge as well as static knowledge in its knowledge base as explained in chapter 4 section 4.3.2.2. The dynamic knowledge is held in KES expert system shell, and static knowledge in the WELDSPEC database.

- v) The system software should have high performance, compatibility with other welding cell system softwares, and portability in terms of which programs can be easily converted or transferred directly to run on a variety of computers. This is achieved by selecting 'C' language and KES shell.
- vi) The system should have future expansion capability. This is achieved by designing the system knowledge base and other software in modular forms.

6.5.1 Communication Capability of KES Shell in PIKBES

A survey carried out by the author showed that there were many expert system shells also which had external interface capability and communication with user's other application software [107,119,128], but of those in the same price bracket, the KES shell also provided three different types of inference engine. Experience with the WRAPS supervisory software had already demonstrated this shell to have a good interface capability [1]. The interface capability will play an important role where a company may wish to link its application software with an intelligent front-end, to carry out the decision making process. Some situations where external communication or exchange information is required are:

- i) Exchange information with other systems, for instance, in this research, the PIKBES communicates with WRAPS supervisory system and the pre-weld inspection station. This will be discuss in section 6.5.2.
- ii) To pass control to the operating system, telling it to execute a program. For example, in this research, this is used to execute the appropriate expert system software (for square-butt or V-butt) or to run the WELDSPEC database software.
- iii) Retrieval of existing data from a database program as an input to the expert system knowledge base. For example, here, program 'sear.c' will be executed, in order to retrieve the required data from WELDSPEC database.

KES shell can communicate with other programs, external files or the

supervisory systems through three methods; 1) read/write/message function available as a command in KES, 2) externals function, and 3) software embedding of KES shell.

1) Read/Write/Message Function

There are a number of function commands provided by KES shell which are used for example, to read or write the value of a joint or welding parameter respectively from or to a file, or the appropriately termed communication files. The format of the read/write command are:

```
read "file name",attribute or class,...,attribute or class.
write "file name",attribute or class,...,attribute or class.
(e.g. read "fact.dat",joint type,T1_act,T2_act,...,A_act.)
```

The communication files are special files which include a series of assertions. The format used by this command is:

```
attribute name = value or literal string.
(e.g. joint type = V_butt_unbacked.)
```

Attributes may have certainty factors associated with them but this feature is not necessary in PIKBES. The communication file may contain any number of assertions. It must end with the % character. Where it is required to display a message or write the message into a file in a format readable by an external database management system in order to update an existing database, a message command function can be used. Fig 6.3 shows examples of communication of information between the KES expert system shell and external application programs. PIKBES has used these function commands in order to read/write from the communication file received from the pre-weld inspection station and WRAPS supervisory system. Section 6.5.2 discusses the format of these files further.

2) External Function

The external function command in the knowledge base allows a KES expert system to call other applications, including other KES expert systems. External function can interact with the host computer's operating system to execute these applications directly. External function can receive command line parameters and can read and write communication files automatically as those discussed above. Fig 6.4

shows the use of KES expert system shell "external" function to execute other application software.

In PIKBES, external function is used to interact with the MS-DOS operating system to run the search program ('sear.c') for data retrieval from WELDSPEC database. The format used to retrieve data stored in database for square-butt joints are in the form of:

externals:

```

search_data_base:
  [program   : "sear"]
  [parameters : "RG_ABSLL","RG_ABSUL","A_nom","ouvl.dat"]
  [outputs   : RG_ABSLL,RG_ABSUL,A_nom,H_nom,W_nom,A_met]
  [outputfile : "ouvl.dat"].

```

%

The program clause 'external functions' runs the 'sear.c' program, the 'parameters' clause is used to specify the parameters passed to the external through the operating system as parameters on the command line. The 'output' clause is used to specify the attribute which has been assigned by the external program 'sear.c'. The 'outputfile' clause uses a communication file to read the attribute values to the knowledge base.

Other application of external function is when the shell has to infer a decision which is based on evaluation of a complex mathematical equation. This has been written in separate application software because of the limited mathematical capability of the shell. Therefore, the shell has to execute the external application. The output from the application software is written into a communication file which can then be read to the shell. In PIKBES, such an operation has been performed to calculate the metallic area of the joint within the window area, the calculation being performed in another expert system program.

3) Embedding the Expert System Shell

This allows conventional applications to access the expert system for solving a problem or making a decision. When embedded, a KES expert system becomes part of a single executable 'C' program that contains KES run-time functions and other applications (such as a database, graphics package, etc). Fig 6.5 shows examples of the difference between; (a) an application that is not embedded, and (b) an application that is embedded.

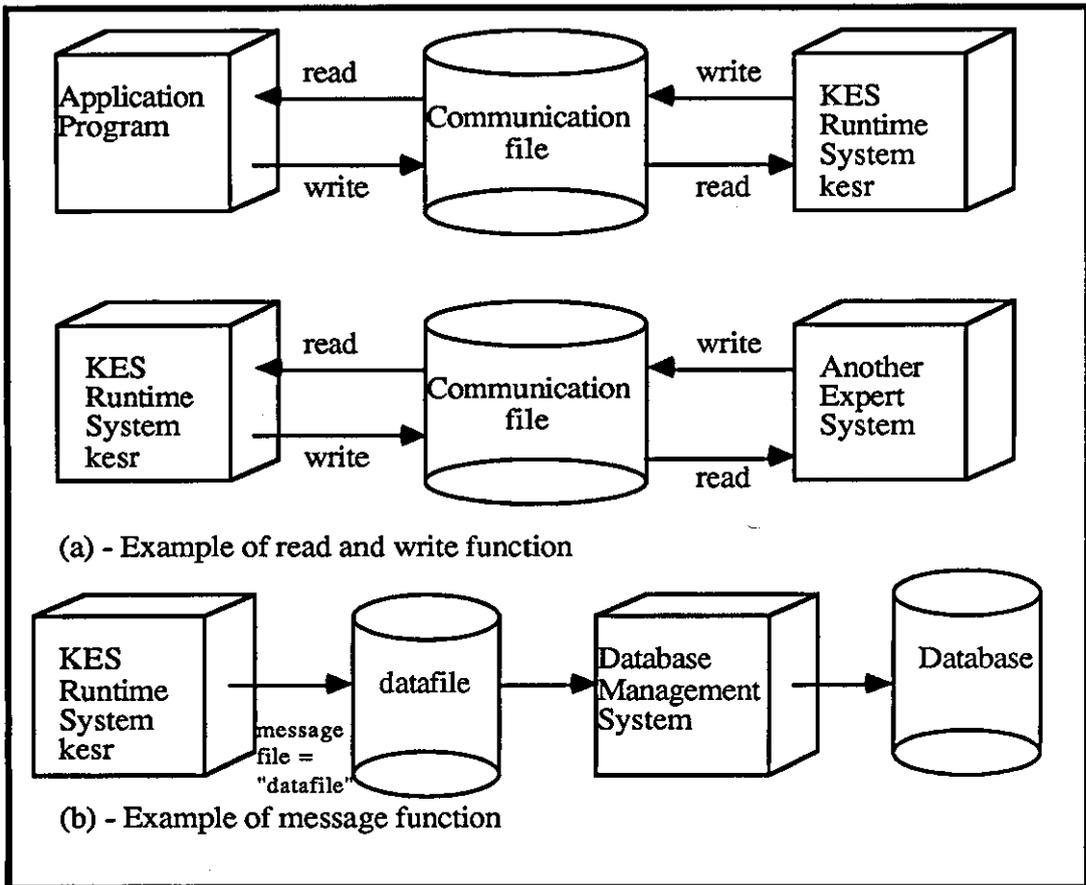


Fig (6.3) - Communication of information between the KES expert system shell and external application programs [130].

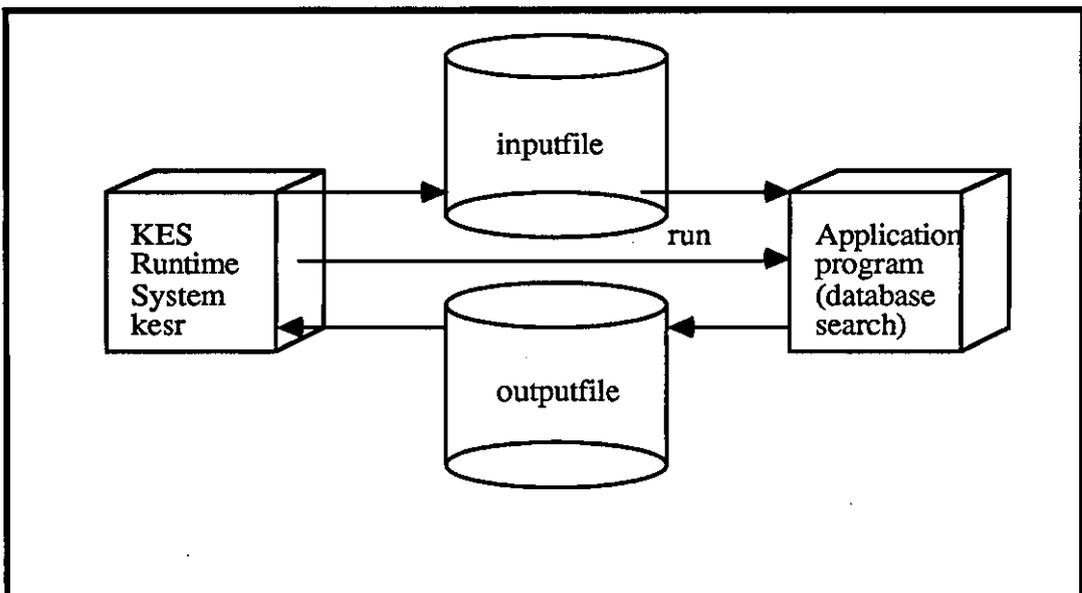


Fig (6.4) - Use of KES expert system shell "External" function to execute another program [130].

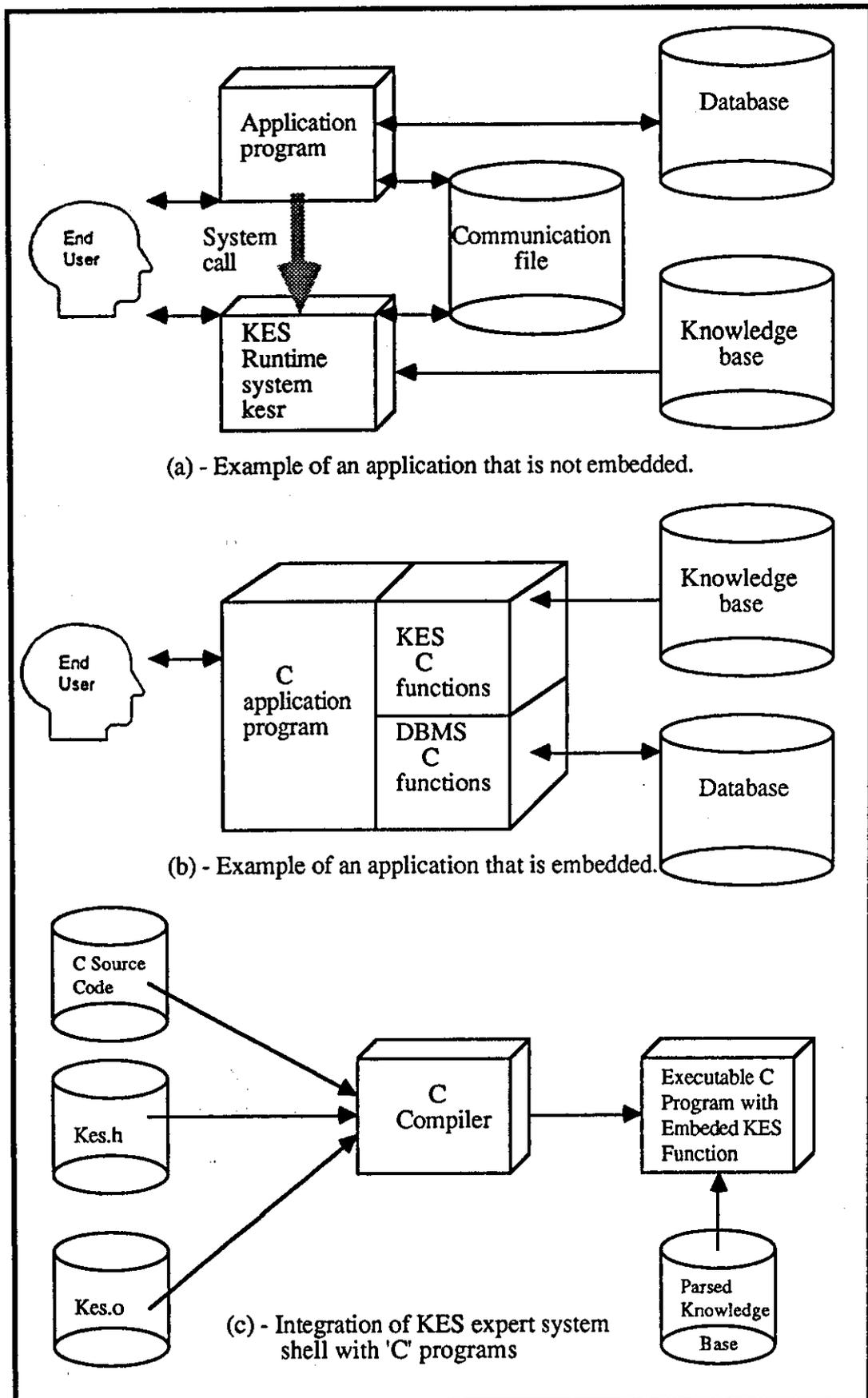


Fig (6.5) - The embedding concept used by KES expert system shell [130].

In PIKBES, the supervisory control of the system is written in 'C' language and is required to perform different operations such as selection of knowledge bases and passing control to the operating system, telling it to execute the selected knowledge, etc.

The conventional programs are normally required to be written in the same programming language as used for the development of the expert shell. For PIKBES, this is achieved by selection of 'C' language for software development and selection of KES expert system shell which is also written in the 'C' language.

The embedding is usually achieved via a well defined set of run-time functions and data types that are used in the user's application program in order to control the expert system and to send, receive, and manipulate data from a parsed KES knowledge base. Embedding a KES expert system offers several advantages over a stand-alone expert system:

- i) The embedded KES expert system operates as a module under the control of the 'C' application software. This means the user can have more control over software design and development particularly where real-time control of process or instrumentation data reading is required.
- ii) Expert system technology can be added to the application software as an "intelligent" component. This method of external interfacing is the most versatile and greatly simplifies the design of decision making programs.
- iii) The end-user interface may be modified or altered to meet the needs of different applications and circumstances.

There are three embedding levels available in KES shell. The level at which one may work depends on the needs of the application. The following guidelines provide some information about these levels:

1) Level 1

This level provides the most rudimentary functions. It provides access similar to that of the end user; the functions provide the capability to execute run-time commands. This level also includes basic functions such as loading the knowledge base, running the actions section, and executing run-time KES commands. All input and output is in the form of strings.

In PIKBES, this embedding level is used to tailor the interaction between data management software and different knowledge bases. This allows the 'C' program to communicate with the expert system programs through calls to the KES library functions. These library functions are allowed in 'C' program by including "kes.h" file. Fig 6.5 (c) shows the integration of KES expert system shell with 'C' programs. Some of the library functions are shown below:

<u>Function</u>	<u>Definition</u>	<u>Category</u>
KES_id_kb()	Loads a parsed knowledge base.	activating and
KES_run_actions()	Run the parsed knowledge base.	deactivating
KES_free_kb()	Frees a parsed knowledge base.	a KES expert
KES_id_local_language()	Loads a local language file.	system
KES_command()	Executes KES commands.	Executes KES commands

A complete description of all level 1 functions is provided in the Level 1 Reference Section of KES Manual [130].

2) Level 2

This level provides more functionality than level 1; it provides access similar to that provided by the actions section. Most KES commands are available in addition to the run-time commands.

3) Level 3

This level provides access to data that is much more specific than is accessible through level 1 or 2 functions; it provides access to all parts of the knowledge base. This level requires the user to have a great deal of experience in programming with the 'C' language.

For purpose of PIKBES, 'level 1' which is the simplest to implement provided adequate embedding facility.

6.5.2 PIKBES Communications

The communication between PIKBES and the pre-weld inspection station (with control software on PDP11/23 minicomputer) and WRAPS supervisory system will be

carried out through a ring network (LAN) by a serial line RS232-C [172]. The way in which these system communicate are:

1) Communication With the Pre-Weld Inspection Station

Arrival of a pallet at the inspection station is advised to the inspection sensor (LRD) controller by the WRAPS supervisory control software. This initiates scanning of the joint by the LRD. The LRD collects 80 sample dimensions during each scan at 0.25mm intervals during each scan. Scanning occurs at 5mm intervals along the joint. Each scan enables a block of information to be obtained regarding component joint and contains; joint type, plate thicknesses, gap or root gap, root face thicknesses, bevel angles, angular misalignment, and cross-section area for a prepared component joint(s). An example of such block of information for 5mm V-butt joint is given below:

```

Joint type = V_butt_unback.
T1_act = 5.20.           (mm)
T2_act = 5.30.           ( " )
RG_act = 1.25.          ( " )
RFT1_act = 1.25.        ( " )
RFT2_act = 1.20.        ( " )
BV1_act = 29.00.        (degree)
BV2_act = 31.00.        ( " )
AM1_act = 1.00.         ( " )
AM2_act = 1.30.         ( " )
A_act = 15.23.          (mm2)
%
```

The actual joint information data collected from the joint is saved in an ASCII communication 'fact.dat' file (in the format shown) and then transferred to PIKBES either via the ring network or directly via RS232 line. The above data format is the requirement of KES expert system shell used in PIKBES for external file communication. Fig 6.6 (b) shows the communication between PIKBES and the pre-weld inspection station via 'fact.dat' communication file.

2) Communication With WRAPS Supervisory System

PIKBES is also required to communicate with the WRAPS supervisory system for information regarding; pallet number, job number, and the nominal welding procedure which is initially chosen for the component joint during WRAPS off-line programming. The format required for example information is shown below:

Welding process = MIG_MAG mechanised.
 Root Run process = MIG_MAG mechanised.
 Joint type = V_butt_unback.
 Welding position = Flat.
 Material type = C_Mn steel.
 British_std = BS5135.
 wire dia = 1.00. (mm)
 T_nom = 5. (")
 RG_nom = 1. (")
 RFT_nom = 1. (")
 BV_nom = 30. (degree)
 pallet number = 3.
 job number = 2.
 TS_nom = 15.96. (cm/min)
 WFS_nom = 5.08. (m/min)
 V_nom = 21. (volts)
 TA_nom = 90. (degree)
 SO_nom = 15. (mm)
 %

WRAPS places this information in a communication file from where it is retrieved by PIKBES. Fig 6.6 (a) shows the communication between PIKBES and WRAPS supervisory system via 'fnom.dat' communication file. The communication and transfer of the file is performed via the ring network. This communication data file is later read by KES expert system shell together with 'fact.dat' communication file from the inspection station in order to carry out comparison and make a decision.

6.5.3 Selection of WELDSPEC Database

A survey carried out by the author showed that there were several database packages available at the time of developing PIKBES [133-136]. The WELDSPEC database package developed by The Welding Institute has been used by many researchers [135,154]. WELDSPEC is a microcomputer database for storage/retrieval of welding procedures. The information which can be stored in the database is that which is required for the Standard Welding Procedure Sheet, BS 4870:part 1, i.e. component details, welding variables, consumables and results of inspection and mechanical testing [135]. This package was selected for PIKBES and the main factors contributed in selection were:

- i) The database is "user friendly". It may be accessed by noncomputer specialists to store welding procedures. Therefore, it would be very helpful to store the information as the system provides fixed field layouts and provides pages of visual display screens.

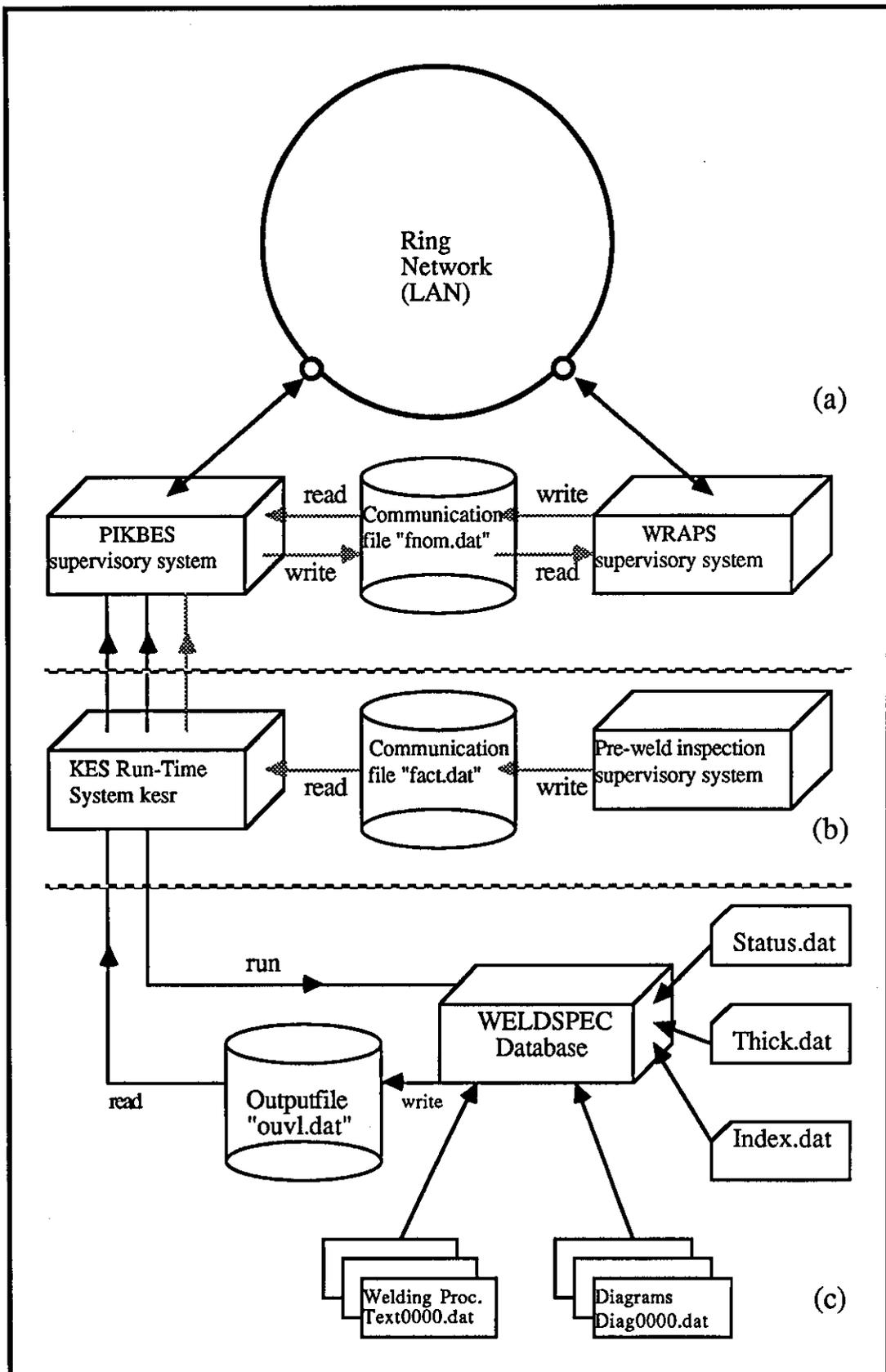
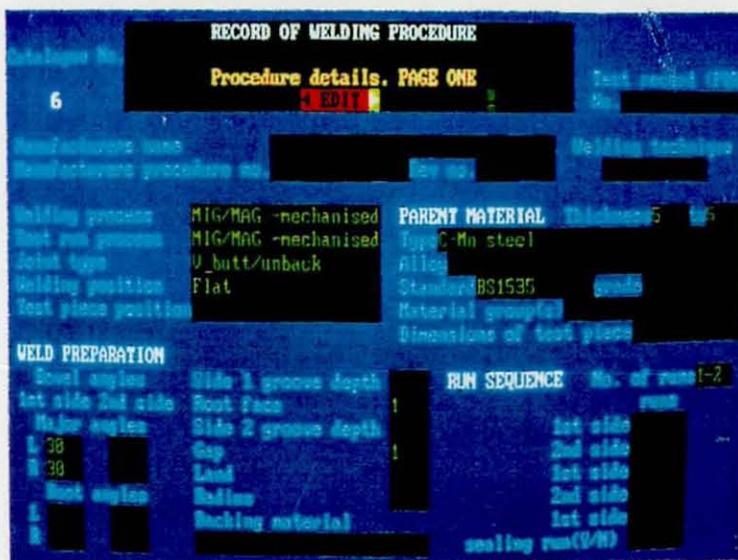


Fig (6.6) - PIKBES communication with (a) WRAPS (b) the pre-weld inspection station (c) WELDSPEC database for data collection.

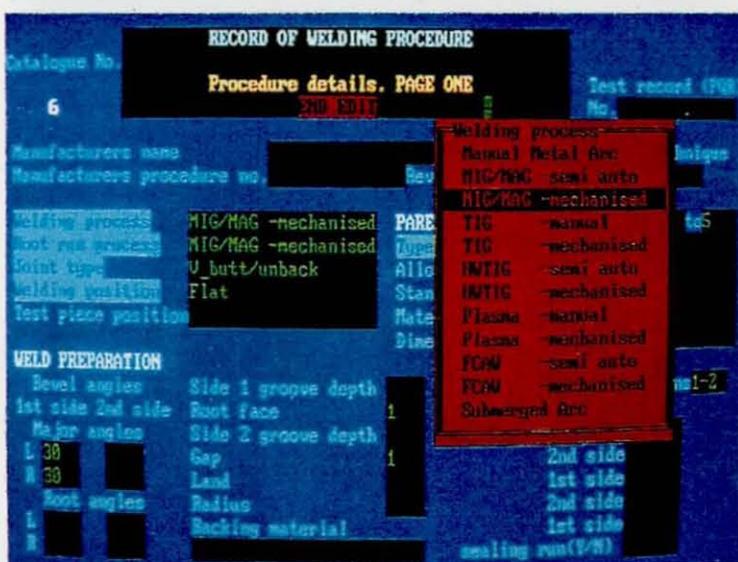
- ii) The database is extremely rapid and simple to operate. Welding procedure records can be searched by simply using a desk-top 'mouse' device. The keyboard is mainly required for entry of welding procedures data into the database.
- iii) The database display screen format is similar to that of Standard Welding Procedure Sheet, BS 4870:part 1 (as mentioned above) and is also capable of providing hard copy printout with the same format, if required by the user. This also enables the welding engineer or welder to understand how to enter the welding procedure data in the correct section.
- iv) The database contains a graphic capability. This helps the user to see the drawing of a particular joint and its dimension, running sequence of welds, or hardness measurements. Here, although only drawing of nominal joints and their details has been implemented (for PIKBES), it is thought that WELDSPEC can be a useful tool for future expansion of the system.
- v) The database is menu-driven. This approach allows the program options available at each stage to be displayed explicitly on the screen and enables the user to carry out different operations using the 'mouse'.
- vi) The database has the capability of being searched both manually (using 'mouse' device) or automatically (by an external program). The latter is used with PIKBES, a program to initiate the search having been written. Section 6.5.3.1 provide more details information about database searching methods.
- vii) Of particularly important to its application to PIKBES is that WELDSPEC provides an additional page which enables the user to incorporate data which is not included within a Standard Procedure Format. This feature has been used to file data such as tolerances on joint edge preparation, window frame size, etc.

An important feature of the software is its user friendliness. The user is taken through seven pages of visual display screens, with each page containing different fixed field layouts, as shown in fig 6.7 (a). These pages of information use menus which are overlaid on the screen by means of windows as shown in fig 6.7 (b). The

(a) - Screen display for entering data



(b) - Menu for making the operation of the software user friendly.



(c) - Typical schematic drawing.

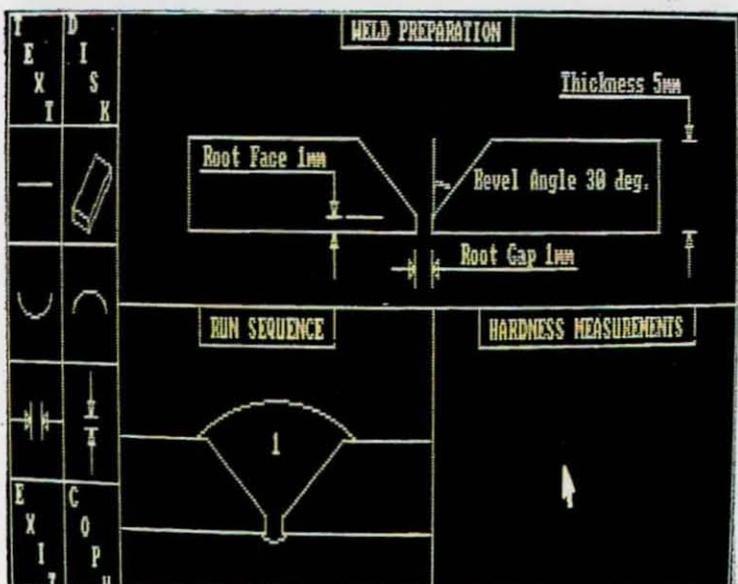


Fig (6.7) - WELDSPEC program for storing welding procedures for PIKBES.

window disappears when the choice has been made. Diagrams can be entered by use of a mouse and drawing package. A typical schematic drawing is shown in fig 6.7 (c).

6.5.3.1 WELDSPEC Database Search

In day to day welding fabrication, a batch fabricator can expect to have a wide variety of components to be welded and each component itself may contain varying types of joints. Traditionally a search for selection of the best available welding procedures for a particular welding operation would be carried out manually through files and records. This searching technique can be very time consuming. However, microcomputers together with the techniques used for such procedure selection have eased many problems.

There are a variety of search techniques available, and the technique(s) that can be adapted varies with the type of database design. Examples of these database design are; sequential organisation, random organisation, and list organisation. Also the search techniques can be sequential retrieval, binary search, direct-access, dictionary lookup, hashing, Virtual Storage Access Method (VSAM), Index Sequential Access Method (ISAM), etc. Further information about these search mechanisms and guidance for the selection of record addressing methods can be found in [178-181].

Although WELDSPEC is not essentially designed to be used by external application softwares for welding procedures data retrieval, it is possible to retrieve these data by a program using searching operation. In general, two searching methods are possible both manually or automatically;

1) Manually (using keyboard, 'mouse' and Search Options' menu). The user uses WELDSPEC'S 'SEARCH' program which allows the user to search through the stored welding procedure records to find those records which he requires. Two types of search are possible [182]:

- i) Parameter search - this applies to the six indexed search parameters of a procedure on which rapid searches can be made:
 - a) Welding process (e.g. GMAW, etc),
 - b) root run process (e.g. GMAW including root run process),
 - c) joint type (e.g. square butt, v butt, etc),
 - d) welding position (e.g. flat, etc),

- e) parent material type (e.g. C-Mn steel, etc)
- f) and thickness range (3 to 5mm, etc).

The procedure number is also asked from the user in order to carry out the searching operation. With the exception of thickness, these parameters are searched by means of the menu categories (which have been set up using the 'EDITMENU' program provided by WELDSPEC), and subsequently used to 'categorise' each record entered. Three files are accessed during this search:

STATUS.DAT - Maintains the catalogue number system.

INDEX.DAT - Index of five menu-type search parameters.

THICK.DAT - Index of the 'thickness' search parameter.

- ii) String search - Further to the six indexed search parameters described above, the user may search for up to 16 text 'strings'. The program searches for any occurrence of the entered text string in each procedure record (excluding any text used to annotate the diagram screen).

2) Automatically (using the user's own developed software). The author has developed a software to perform the searching operation and data retrieval. This was accomplished by writing a 'C' program to search for a particular record (containing stored nominal welding procedure and other additional information) held in WELDSPEC database.

The search procedure designed for PIKBES is considered efficient. It uses the index searching parameters technique and list-type organisation of the database information. Index searching technique uses index search parameters (such as mentioned above) to 'categorise' each welding procedure record in the database. List-type organisation of the database allows records to be placed anywhere within a file. This means that information to be updated can be appended to the end of the existing file, without any sorting. These techniques are the same as those used by WELDSPEC to carry out manual searching operations. Goh [1] has also used similar searching techniques to the ones mentioned here. He uses the hashing technique, which is claimed to be more suitable for the retrieval of a single record and could be arranged in a list organisation, and a variation of the list-type organisation of the database to retrieve welding procedures stored in database.

In a welding database search, to match a search to a keyword in a record, it is expected that character string comparisons will be common occurrences [1]. This is because there are descriptions, e.g. relating to the type of welding process, type of parent material, etc. When stored in a computer memory, the descriptions are usually represented by a character string. A terminating character, e.g. a '\0' in the 'C' language, is used to denote the end of a string. Character strings, if they are lengthy, can occupy a considerable amount of computer memory, and the outcome of a comparison (e.g. whether two strings are equal or not) usually takes a longer time than for instance a numerical comparison. To improve on this, the search parameters which identify a particular string (e.g. MIG_MAG mechanised) are coded as a set of numbers (e.g. 22301), and used for comparison with the available codes in 'INDEX.DAT' file. In this way, the comparison of two integer numbers is considerably quicker.

PIKBES uses this concept to carry out its searching operation. It uses Index search parameters technique similar to that used in manual search (1 - (i)). The information received from WRAPS supervisory system (see section 6.5.2 - (1)) together with two index files 'INDEX.DAT' and 'THICK.DAT' (which are generated by WELDSPEC'S 'UPDATE' program during data storage) are used to carry out two searching operations and data retrieval. Fig 6.8 shows this search operation. In the first search, plate thickness is read from the 'fnom.dat' communication file and is compared against the ones available in the 'THICK.DAT' file. If the correct match was found, the record numbers will be registered, else it give a message 'not exist'. This operation greatly reduces the number of searching operations. In the second search operation, the five parameters (welding process, root run process, joint type, welding position, and parent material type) are read from 'fnom.dat' communication file and changed to a set of coded format (e.g. 22301). Each set of codes in 'INDEX.DAT' file represents a record (which is separated by a Fun-Character) and its location in the file represents the file number (e.g. TEXT0003.DAT). These sets of codes are then compared with a formatted code from 'fnom.dat' file and the final record can be found. To retrieve any particular information (welding data procedure or any additional information), the field where that information has been stored, should be found. This can be accomplished by taking advantage of 'C' functions 'fseek()' and 'fgets()' to take the pointer to the required field and collect the information. After the information is collected it is written into 'ouvl.dat' communication file in the format required by KES expert system shell and is ready to be used in PIKBES. Fig 6.6 (c) shows the communication of WELDSPEC database with PIKBES via 'ouvl.dat' communication file. Any error occurring during file opening or other operation will be displayed to the user.

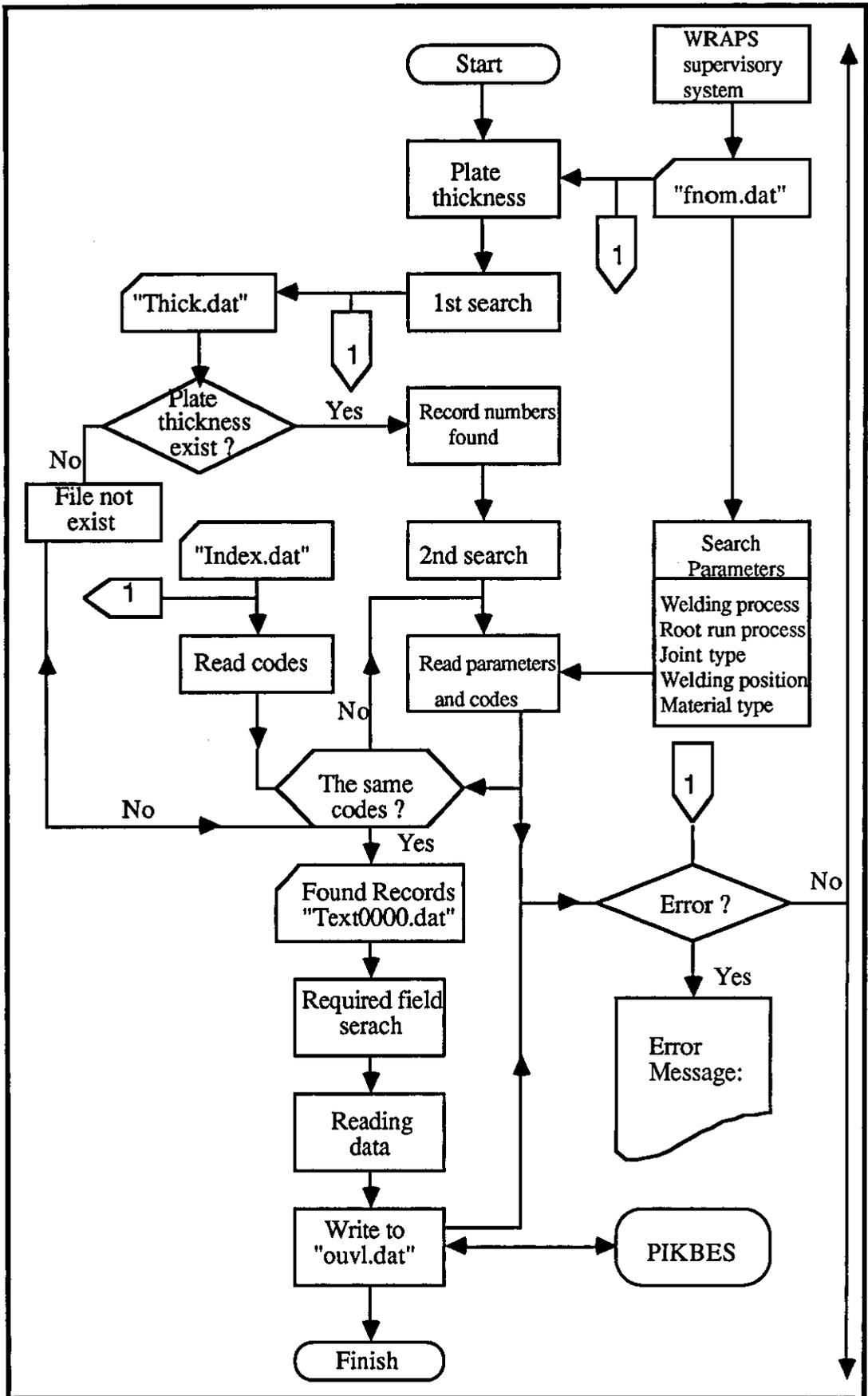


Fig (6.8) - Database search procedure.

6.5.4 Achieving High Performance, Compatibility, and Portability

The highest performance of a system is achieved when the application software works directly with a computer's built-in instruction set (e.g. assembly language). The program should work in terms of hardware and specify every operation in the machine terms, e.g. move these bits into a register and add them to the bits in that other register and so on. In PIKBES, high performance is achieved by using 'C' language and KES expert system shell for developing the system, because assembly language is difficult to readily understand, debug and edit.

'C' [183] was developed as a system programming language, designed to develop for instance, fast and efficient operating systems. 'C' is unique among programming languages in that it provides the convenience of a higher-level language such as BASIC or PASCAL, while allowing close control of hardware and peripherals, as assembly language does. Most operations that can be performed on the computer in assembly language can be accomplished in 'C'. It is also a well-structured language; its syntax makes it easy to write programs that are modular and therefore easy to understand (similar to PASCAL).

KES expert system shell is a tool kit for building expert systems. As KES is written in 'C' language and can contained parsed knowledge, this can provide the software engineer with a powerful high performance tool to build an application software with the capability of analysing the problem and dealing with uncertain data. The 'C' software of KES shell makes the system more efficient and perform faster.

Compatibility of PIKBES with other system software in the welding cell is achieved by selection of 'C' language and KES shell. WRAPS package [1] and a package developed by Abu-Bakar [32] for designing welding procedures are both written in 'C' language and use the KES expert system shell. PIKBES therefore can be readily interfaced with these.

Portable software code is code that will compile and run correctly with little or no modifications in a variety of language compilers or operating systems. Portability of PIKBES is achieved by using MS-DOS operating system and 'C' language. MS-DOS operating system is probably the most popular operating system used by Microcomputers. Some computers such as Commodore AMIGA computers support two operating systems, Amiga's own operating system, i.e. AMIGADOS [184] and MS_DOS, and some IBM compatible computers such as the DELL computer used in

this research support only MS-DOS [185] or IBM PC-DOS operating system. 'C' language has also been used to write operating systems Such as UNIX [186] and AMIGADOS [184].

6.5.5 Expansion Capability

All PIKBES softwares were designed in structured modular form. Fig 6.9 shows the hierarchy structure of PIKBES together with expansion capability of the system. The modular structure enables the ease of knowledge base expansion for different types of welding processes, joints, plate thicknesses, welding positions, material, standards, etc. To date, PIKBES rules and heuristic knowledge have been applied to the mechanised MIG/MAG welding process for flat position square-butt and one sided V-butt joints in Carbon and Carbon-Manganese Steels of up to 12mm thickness and produced to British Standards BS5135. Knowledge bases for square-butt (in 2 and 3mm plate thickness) and V-butt joints (for 4 - 12mm plate thickness) have been separated to two different modules. The information received from the pre-weld inspection station by PIKBES, is used by embedded KES expert system technique (level 1) to select the appropriate knowledge base module based on their joint type. This embedding technique provides the interaction between the 'C' programs and KES expert system. The selected knowledge base module is then accessed by the database search program module for data retrieval of nominal welding procedures or other additional information stored. Additional application requirements can be catered for by adding appropriate knowledge base modules.

6.6 Knowledge Elicitation and Formulation for PIKBES

Knowledge elicitation and formulation is the transfer of problem-solving expertise from expert knowledge sources, and the structuring of it into a computer program [116]. The knowledge sources include human experts, textbooks, technical literature, databases and other experiences. Of all these sources, the expertise of human specialists form the main target of knowledge elicitation.

To elicit knowledge for PIKBES, the author had to identify the problems which required to be solved, domain sources of knowledge, the specific information required by the expert to solve the problem, the form and content of the problem solution, and the means by which the experts gather and use information to produce

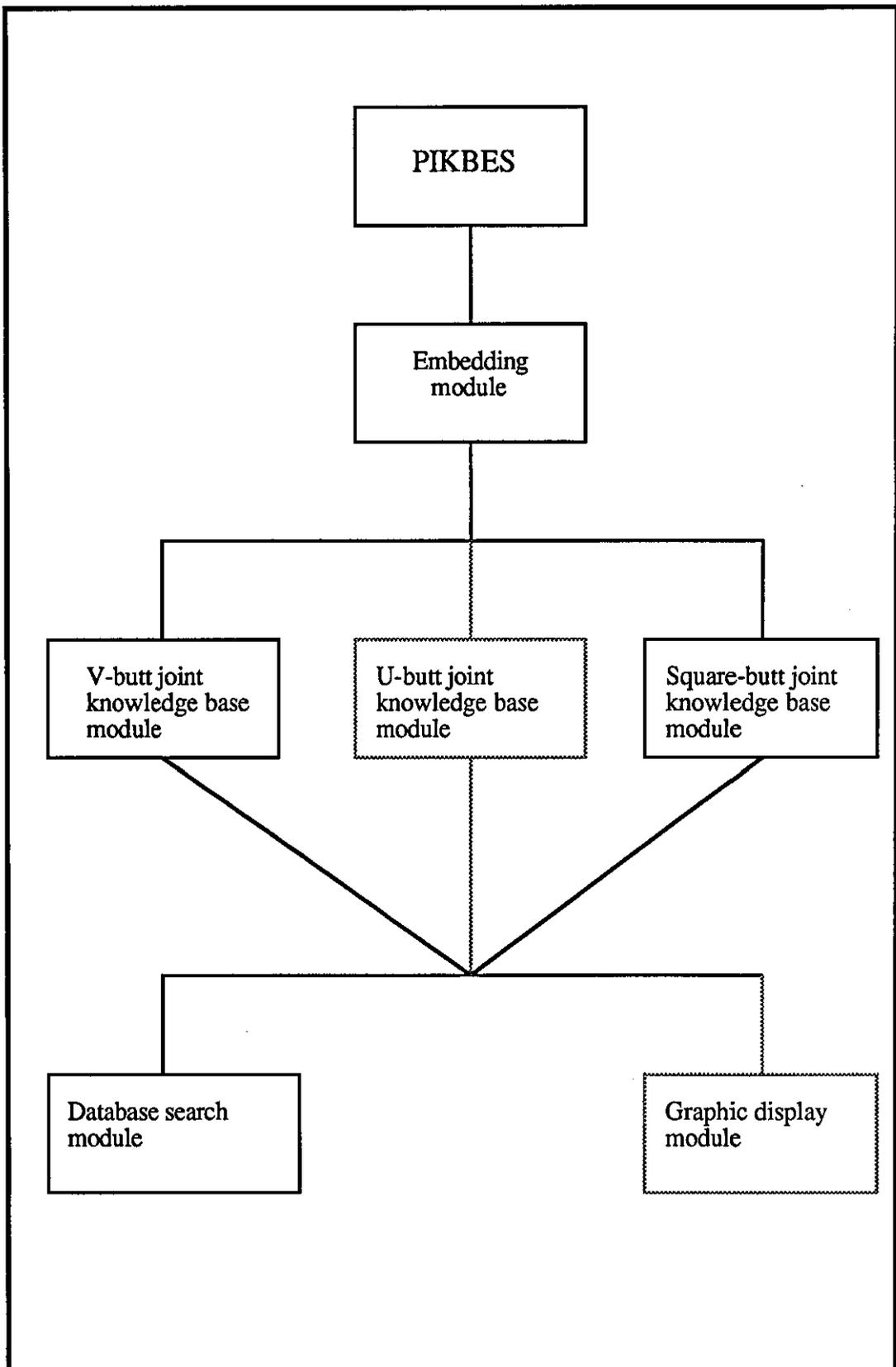


Fig (6.9) - The hierarchy structure for PIKBES.

the solution.

1) Problems Identification

Problems for PIKBES are identified as:

- i) Variation detected between actual and nominal joint geometry which is required to be compensated by some form of non-mathematical models. These variations were recognised as variation in plate thicknesses (T1,T2), gap or root gap (RG), root face thicknesses (RFT1,RFT2), bevel angles (BV1,BV2), angular misalignment in plates (AM1,AM2), and joint cross-sectional area (A). Non-mathematical models are facts, rules, and welding experts heuristic knowledge, etc. Models were to be used to modify primary welding parameters such as torch speed (TS), wire feed speed (WFS), voltage (V), etc.
- ii) Finding a technique to generalise the heuristics knowledge in the knowledge base. Two techniques are used; 'window' and 'linear relationship' techniques. Sections 6.6.1 and 6.6.2 discuss these techniques.
- iii) Finding a concept to represent the knowledge. Domain knowledge consists of facts about the domain and relationships between these facts [130]. In PIKBES, KES expert system shell uses these facts and represents them as attributes. Attributes represent some piece of welding knowledge. The attribute section of the knowledge base contains these pieces of knowledge.

2) Domain Sources of Knowledge

Domain sources of knowledge for PIKBES were identified as:

- i) Textbooks on arc welding [183,192,187], publications [93-105], Standards [4-7,189], and the author's own experience of arc welding which was acquired during experimental test exercises.
- ii) Domain experts - domain experts are distinguished from layman and general practitioners in a technical subject by their task-specific knowledge, acquired from formal training, subsequent readings, interactions with professional peers, research and especially experience of handling many hundreds of cases in the course of their career [116].

Domain experts consulted were from Loughborough University and The Welding Institute, U.K. All experts possessed extensive knowledge of welding fields and had the ability to apply that knowledge to solve problems and make decisions.

After all problems and sources of knowledge were identified, a set of nominal welding procedures (for different plate thicknesses) were selected from those available in 'Standard Data for Arc Welding' [189]. The tolerances on nominal joint parameters (T_{nom},RG_{nom},RFT_{nom},etc) were set using BS5135 [4]. The selected welding procedures were as follows:

- Welding process : mechanised GMAW (MIG/MAG).
- Joint type : open or closed square-butt (2 and 3mm plate thickness) and V-butt (4 -12mm plate thickness) single-sided unbacked, permanent backed, and temporary backed.
- Material type : Carbon and Carbon Manganese Steel (C-Mn) to BS 4360.
- Joint position : Flat.
- Wire diameter : 1mm.
- Consumed gas : Ar/20% Co₂ or Co₂.

The above information together with nominal joint parameters and their tolerances were structured in a table which is shown in a table 6.1. The tolerances were initially established (on nominal joint parameters) from BS5135 which is for the manual welding process, but it was recommended by welding experts that for automatic or mechanised welding processes, closer limits were necessary. Therefore, after consultation, the tolerance limits were adjusted for use as PIKBES tolerance 'level 1'.

To elicit further knowledge regarding absolute tolerance limits, 'level 2', and a technique to generalise welding experts heuristic knowledge, the author has carried out a number of interviews and dialogues with welding experts. 'Level 2' tolerances are such that if any parameters of the joint are detected to be outside this 'level', the component should be rejected. The results of consultation with welding experts regarding this 'level' are also shown in table 6.1. Intermediate tolerance limits (tolerance 'level 3') is where the joint parameters are greater than 'level 1' but less than or equal to 'level 2'. At this 'level', non-mathematical expert models were necessary to modify welding parameters to compensate for joint geometry changes.

During knowledge elicitation, the author described problems to the welding domain experts who were then invited to describe the methods by which they would solve the problem and explain any particular difficulties to be overcome. Initially in specifying the problem for solution, the author adopted a strategy similar to the

Plate Thickness (mm)	Joint Type	Nominal Specification			BS 5135 Modified Tolerances on Nominal Joints						Expertly Established Absolute Limits on Joint Parameters (unbacked joint)						Area of Nominal Joint (mm)	WFS of Nominal Joint (m/min)	TS of Nominal Joint (cm/min)
		RG (mm)	RFT (mm)	BV (deg)	RG (mm)		RFT (mm)		BV (deg)		RG (mm)		RFT (mm)		BV (deg)				
					LL	UL	LL	UL	LL	UL	LL	UL	LL	UL	LL	UL			
2	S-butt	0.5	-	-	0	1	-	-	-	-	0	1.55	-	-	-	-	1	5.1	69
3	S-butt	1	-	-	0.5	1.5	-	-	-	-	0	1.55	-	-	-	-	3	7.8	57
4	S-butt	1	1	30	0.5	1.5	0.5	1.5	27.5	32.5	0	1.55	0	1.75	25	35	9.196	5.08	20
5	V-butt	1	1	30	0.5	1.5	0.5	1.5	27.5	32.5	0	1.75	0	1.75	25	35	14.23	5.08	15.96
6	V-butt	1	1	30	0.5	1.5	0.5	1.5	27.5	32.5	0	1.75	0	1.75	25	35	20.43	5.08	12.03
8	V-butt	1	1	30	0.5	1.5	0.5	1.5	27.5	32.5	1	2.50	0	2.5	25	35	36.29	1st Run 5.08	1st Run 7.5
10	V-butt	1.5	1.5	30	1	2	1	2	22.5	27.5	1	2.50	0.5	2.5	20	30	48.69	1st Run 8.66	1st Run 10.26
12	V-butt	1.5	1.5	30	1	2	1	2	22.5	27.5	1	2.50	0.5	2.5	20	30	69.41	1st Run 8.66	1st Run 32.36

Table (6.1) - Shows a typical knowledge elicited from Standard Data [189], BS 5135 [4], and welding domain experts and structured in a tabular form which is then used in PIKBES.

'one-variable-at-a-time' method of analysis. However, this results in an enormous number of possible situations, which would have been a time consuming and costly exercise, as well as producing an unacceptably large number of rules. This approach emphasised the need to classify the expert knowledge to enable logical generalised solutions to be developed. This table shows a typical example of the pseudo-coded format of elicited knowledge obtained from the welding experts which is structured in a tabular form.

The most important control factor in selecting particular heuristic knowledge for a particular joint geometry deviation problem, was recognised as the increase or decrease in joint area compared to the nominal joint area, that is the difference between A_{act} and A_{nom} . For example, experts suggested that for plate thicknesses of up to 5mm (this can be either square or V-butt joint type), if the actual gap or root gap is greater than the nominal gap or root gap upper limit tolerance and below or equal to the absolute gap or root gap, and if the joint area increases by less than 100% then the torch speed (TS) has to reduce to give the same deposited area or joint fill. The amount of reduction in torch speed is the ratio (X) of actual joint area over nominal joint area. Sections below gives a sample of knowledge elicited (as shown in table 6.2) and which have been formulated using KES expert system shell;

Text section

```
{Reference_1:" ",
  "RULE_18: If the plates thickness less than or equal to",
  "5mm and the actual joint area decreases by 40% or more.",
  "(X <= 0.6 ) of nominal area then :",
  " ",
  " * Torch Speed has to decrease by (1-X)*TS_nom",
  " * Wire Feed Speed has to increase by 10%",

{Reference_2:" ",
  "RULE_19: If the plates thickness less than or equal to",
  "5mm and the actual joint area decreases by less than 40%.",
  "(X<1 and X>0.6) of the nominal joint area then :",
  " ",
  " * Torch Speed has to decrease by (1-X)*TS_nom. ",
  " * Wire Feed Speed has to be kept the same."}
```

Plate Thickness (mm)	Joint Type	Nominal Specification Joints							
		RG (mm)	RFT (mm)	BV (mm)					
2	S-butt	0.5	-	-	If increase in joint area <= 100% Then reduce travel speed to to give the same deposited and keep wire feed speed same as nominal	/	If increase in joint area > 100% or > 50% and Gap/ Root Gap <= 2 mm Then apply Weaving with a weave amplitude of wire dia. + 1/2 gap/root gap. Nominal WFS and Voltage and adjust travel speed along the joint to give required effective welding speed for required deposited area.	For plate thicknesses of up to and including 4mm. If increase in joint area >100% or > 50% but gap > 2mm Then reduce the travel speed by 60% of nominal travel speed.	
3	S-butt	1	-	-					
4	V-butt	1	1	30					
5	V-butt	1	1	30					
6	V-butt	1	1	30					
8	V-butt	1	1	30					
10	V-butt	1.5	1.5	30					
12	V-butt	1.5	1.5	30					
-With back abs. limit RFT = 0. -Abs. low lim. for gap in all = 0. -Within the tolerances use std. welding					Min Travel Speed = 60% of nominal then increase WFS by the remaining percentage amount. The opposite of this is acceptable for Maximum Travel Speed	/	If increase in A<=50% Then reduce TS to give the same deposited area and keep WFS constant (same as nom.) This is for all thicknesses. Max weave amplitude (WA)= 2 x wire_dia. and Weave frequency = may be found in experiments with relation to WA and TS.	Then increase effective speed to nominal speed and increase WFS to give required deposition rate Max WFS = 2 x nominal WFS.	Beyond this point reduce again effective traverse speed.

Table (6.2) - Shows a typical example of pseudo-coded format of elicited knowledge from the welding experts.

Rule Section

```

RULE_18:  if  T1_act le 5 and T2_act le 5    and
            RG_act lt RG_LOLIM              and
            RG_act ge RG_ABSLL              and
            X le 0.6
            then
            result          = mod_wld_proc.
            torch_motion    = linear.
            TS               = (1 - X)*TS_nom.
            WFS              = 1.1 * WFS_nom.
            display attach Reference_1 of kb.
            endif.

RULE_19:  if  T1_act le 5 and T2_act le 5    and
            RG_act lt RG_LOLIM              and
            RG_act ge RG_ABSLL              and
            X gt 0.6                        and
            X lt 1
            then
            result          = mod_wld_proc.
            torch_motion    = linear.
            TS               = (1 - X)*TS_nom.
            WFS              = WFS_nom.
            display attach Reference_2 of kb.
            endif.

```

In Rule_18, originally WFS was kept the same as the WFS nominal based on the expert advise but the experiment tests showed that the lack of penetration resulted. Empirical tests showed that a 10% increase in WFS was required to achieve full penetration in plates thicknesses of less than or equal 5mm. The above rules were prototype rules used in the development of PIKBES. Test case results from the rules showed a technique was also required to control the heat input and material deposition rate to the joint (i.e. joint area). These are discussed later in section 6.6.1.1 and 6.6.1.2. Two technique were adopted; 'window' and 'linear relationship' techniques. These techniques are discussed below in section 6.6.1 and 6.6.2.

6.6.1 'Window' Technique

After further discussion with experts, the 'window' technique was developed. This technique was based on extensive expert experience and some intuitive judgments. The purpose of using the 'window' technique is to control penetration and fusion at the root of the joint. The metallic cross-sectional area of the joint within a defined window is calculated for both nominal and actual joint dimensions. Considering a unit length of joint the actual welding parameters are adjusted to maintain the specific welding energy per unit volume of metal for the actual case equal

to that of the nominal condition.

When using the window technique, the actual joint condition can vary from minimum, through nominal to maximum metallic area condition. Fig 6.10 shows the application of 'window' technique to one-sided V-butt joint and the extremities of joint geometry change that can occur.

For V-butt joints, the size of window (h and w) is calculated for the nominal joint by calculating the area of joint inside the window (A1) so that the area (A1) becomes equal to the area of the joint outside the window (A2). Appendix A6 provides general formula for 'window' size calculation (for nominal joint). When dealing with square-butt, the technique uses the window height and width equal to the plate thickness. This window is then used with the actual joint condition. Two extreme condition can happen:

1) A joint with minimum metallic area in the window. The joint has maximum RG (RG absolute upper limit), minimum RFTs (RFT absolute lower limit), and maximum BVs (BV absolute upper limit). Fig 6.10(b) shows this condition. In this case, the welding experts recommended that; as the metallic area is reduced there is a danger of getting burn-through, therefore, the specific energy (P) must be reduced and/or welding speed must be increased, and also torch weaving must be applied. Recommendation regarding weave amplitude and frequency were obtained by consultation with experts and this knowledge is included in tables of factorial experiment tests (chapter 7, section 7.3.2) and in appendix A8. A general rule for weave amplitude was recommended as equal to root gap size plus two electrode wire diameter. Weave frequency is primarily dependent on torch speed and wire feed speed. Recommendation for weave amplitude and frequency were tested experimentally prior to their implementation to PIKBES.

2) A joint with maximum metallic area in the window. The joint has zero RG (RG absolute lower limit), maximum RFTs (RFT absolute upper limit), minimum BVs (BV absolute lower limits). Fig 6.10(c) shows this condition. This is the opposite condition to (1). In this case, the welding experts recommended that; as the metallic area increases, there is a problem of lack of penetration at the joint, therefore, the specific energy (P) must be increased and/or welding speed must be decreased. There is then of course the problem of excess weld metal being deposited.

There are four different cases which effect calculation of metallic cross-sectional area in the window for a particular joint. The selection of each particular case

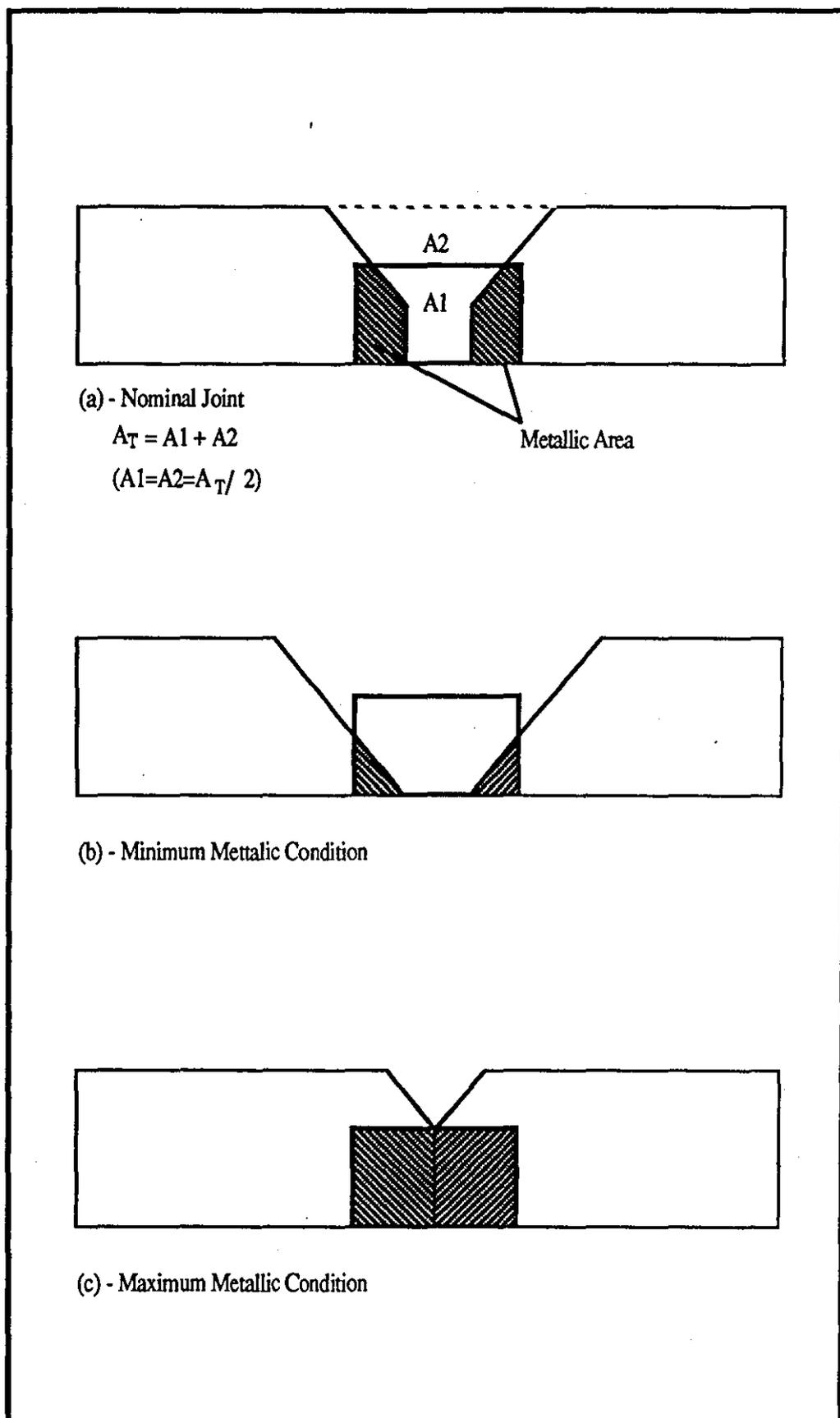


Fig (6.10) - Shows the application of 'window' technique to one-sided V-butt joint and the extremity of joint geometry changes that may occur.

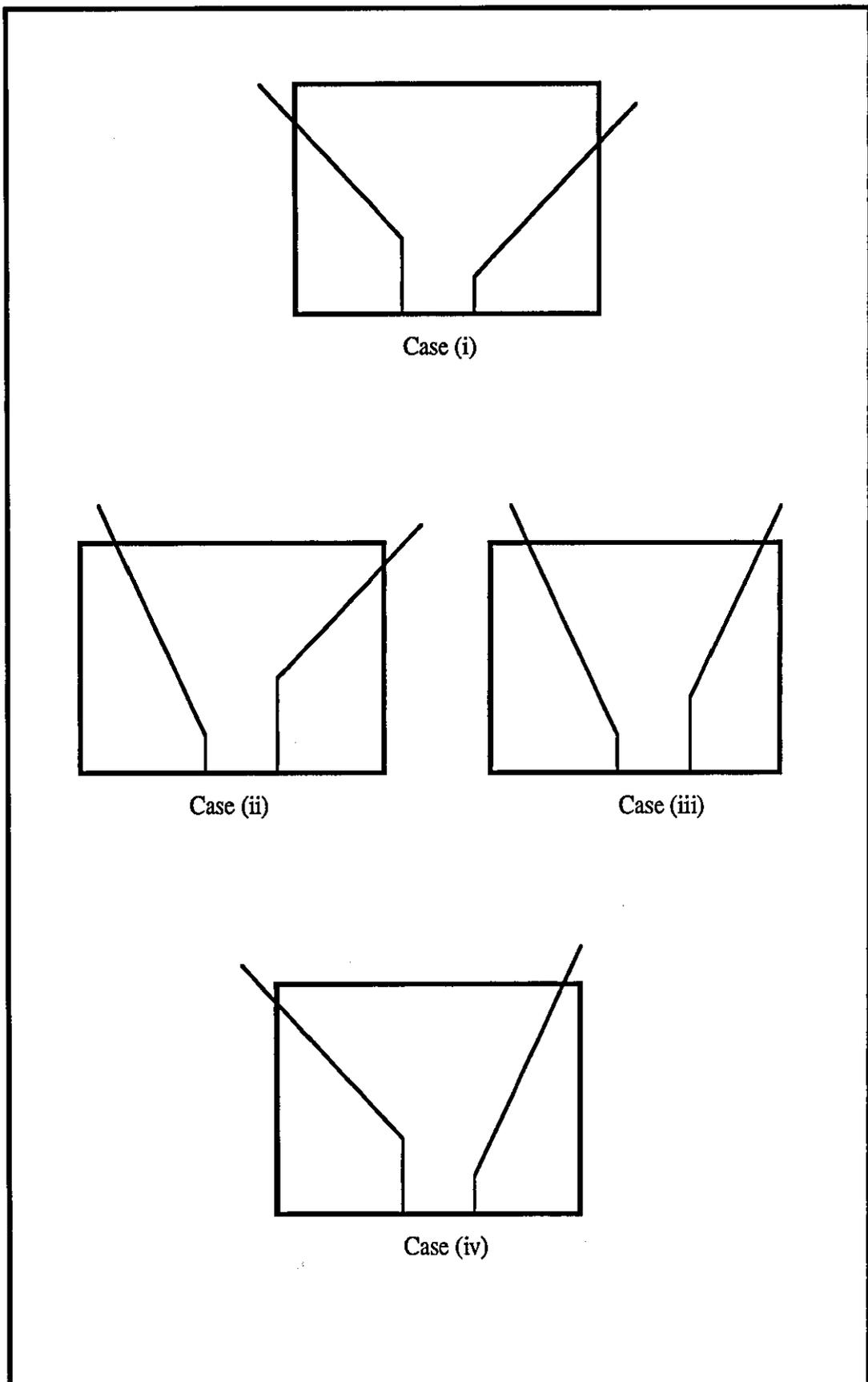


Fig (6.11) - Shows variation in joint geometry which will effect on calculation of metallic area of the joint within the window.

depends on the intersection of bevel angle line and window side walls. Fig 6.11 shows these different joint geometry cases which will effect the calculation of metallic area of the joint within the window. Appendix A7 provides general formula and program of the metallic area calculation for different joint geometry changes. The metallic area calculation for each half of joint will be performed separately and because of the possible combination of events that can happen in a joint.

Although the calculation of metallic area can be written in a 'C' program or any other language, KES expert system shell is used to do this calculation. KES shell has enough mathematical calculation capability as well as ease of reading/writing information respectively from/to a communication file. The dimension of the 'window' and the metallic area in the 'window' for the nominal joint are obtained from WELDSPEC (ouvl.dat file). Actual joint dimensions (from the pre-weld inspection station) are obtained from the 'fact.dat' communication file. A program (calc2.kb) written in the KES shell then applies the window to the actual joint and calculates the actual metal area in the 'window'.

6.6.1.1 Adoption of Heat Input

It is required to adaptively change the material deposition rate and heat input (energy per unit metal) when the joint geometry changes. To maintain a reliable and stable welding process such changes can be made only if a number of conditions are fulfilled. This can be accomplished by changing weld parameters such as wire feed speed (WFS), torch speed (TS) or voltage (V), etc. The specific energy (heat input) per unit volume of metal of the joint can be shown as:

$$P = \frac{V \times I}{TS \times A}$$

$$P = \text{Joules/mm}^3$$

P = specific energy

V = voltage

I = wire feed speed

TS = torch speed

A = Area in joint

To achieve full penetration in joints, it is assumed that specific energy per unit metal volume in the window on the actual joint must be equal to that on the nominal

joint (i.e. $P_{act} = P_{nom}$). Therefore:

$$P_{act} = \frac{V_{act} \times I_{act}}{A_{metact} \times TS_{act}} \quad (1)$$

$$P_{nom} = \frac{V_{nom} \times I_{nom}}{A_{metnom} \times TS_{nom}} \quad (2)$$

From (1) and (2), $P_{act} = P_{nom}$ and they are constant, $V_{act} = V_{nom}$ and $I_{act} = I_{nom}$, hence

$$TS_{act} = \frac{A_{metnom} \times TS_{nom}}{A_{metact}}$$

Where

- P_{act} = specific energy (heat input) for the actual joint
- P_{nom} = specific energy for the nominal joint
- V_{act} = voltage for the actual joint
- V_{nom} = voltage for the nominal joint
- I_{act} = current (wire feed speed) for the actual joint
- I_{nom} = current (wire feed speed) for the nominal joint
- A_{metact} = metallic cross-sectional area of the actual joint
- A_{metnom} = metallic cross-sectional area of the nominal joint
- TS_{act} = torch speed for the actual joint
- TS_{nom} = torch speed for the nominal joint

The influence of parameters I_{act} and V_{act} are discussed later in section 6.6.1.2 and 6.6.2. With the help of welding experts rules were developed to understand the logic behind the above concept. A number of test cases (problems) have been tested to see how welding expert solve them using the 'window' technique. The author noted the welding expert heuristic knowledge and derived the following pseudo-code rules:

- rule 1.** If the actual gap/root gap less than or equal nominal gap/root gap and if the actual metallic area of the joint greater than the nominal metallic area of the joint then reduce torch speed (TS) to keep nominal specific energy constant.
- rule 2.** If the actual gap/root gap less than or equal nominal gap/root gap and if the actual metallic area of the joint less than the nominal metallic area of the joint

then increase torch speed (TS) to keep nominal specific energy constant.

- For both above rules welding experts suggested that; torch speed should not decrease/increase by less/more than 40% of nominal torch speed (i.e. $TS_{min} = 0.6 TS_{nom}$ or $TS_{max} = 1.4TS_{nom}$). Wire feed speed (WFS) should be kept the same as wire feed speed nominal.

rule 3&4. If the change in area would result in torch speed requiring more than a 40% decrease/increase, change in torch speed is constrained to 40% and the further required change in specific heat input is achieved by changing WFS.

The above facts and heuristic rules were accepted to work on all different joint types. The author used the above pseudo-code type of rules and translated them into Production-Rule form acceptable to KES PS expert system shell. This is shown below:

Attribute section

```
T_act      : real [default : (A_nom * TS_nom)/A_metnom].
             { question : "What is the torch speed value for the actual joint ?" }
             { explain  : "This is a real value attribute which calculates the",
                           "torch speed value for the actual joint using; ",
                           " TS_act = (A_metnom * TS_nom)/A_metact"}.

TS_min     : real [default : 0.6*TS_nom].
             { question : "What is the torch speed minimum value ?" }
             { explain  : "This is a minimum value that torch speed can be",
                           "reduced. That is 40% less than the nominal torch",
                           "speed"}.

TS_max     : real [default : 1.4*TS_nom].
             { question : "What is the torch speed maximum value ?" }
             { explain  : "This is a maximum value that torch speed can be",
                           "increased. That is 40% more than the nominal torch",
                           "speed"}.

```

Externals section

\ This section run external program 'sear.c' in order to select appropriate
 \ welding procedure record and retrieve required data.

```
externals:search_data_base:
  [program: "sear"]
  [parameters:"RG_ABSLL","RG_ABSUL","A_nom","ouv1.dat"]
  [outputs : RG_ABSLL,RG_ABSUL,A_nom,H_nom,W_nom,
             A_met,RFT_ABSLL,RFT_ABSUL,BV_ABSLL,BV_ABSUL]
  [outputfile: "ouv1.dat"].

```

Rule section

```

RULE_1:  if RG_act le RG_LOLIM and
          A_metact gt A_metnom
          then
            TS      = TS_act.
            WFS     = WFS_nom.
            Voltage = V_nom.
          endif.

RULE_2:  if RG_act le RG_LOLIM and
          A_metact lt A_metnom
          then
            TS      = TS_act.
            WFS     = WFS_nom.
            Voltage = V_nom.
          endif.

RULE_3:  if TS le TS_min
          then
            TS      = TS_min.
            WFS     = ((1+X)-0.4)*WFS_nom.
          endif.

RULE_4:  if TS le TS_max
          then
            TS      = TS_max.
            WFS     = ((2-X)+0.4)*WFS_nom.
          endif.

```

X is the ratio of joint area ($A_{act} + A_{nom}$) as described previously. However, adoption of heat input control is also performed concurrently with metal deposition rate control in order to avoid excess weld bead height or undercut.

6.6.1.2 Adoption of Metal Deposition Rate

Further discussion with experts regarding material deposition rate was undertaken. Deposition rate is the volume of metal deposited in a given unit of time (usually expressed as mm^3/min). Deposition rate for a given electrode wire size is greatly affected by welding current, and also by voltage and wire extension. Increasing current, other factors being equal, increases penetration and dilution, as well as deposition rate. As a practical matter, because of the useful current ranges and effect of current density, the smaller diameter bare metal welding wires deposit faster than larger diameters. Voltage or wire speed should be adjusted to obtain a stable arc with minimum spatter. Excessive voltages increase loss of carbon and other elements through vaporisation. Travel speed should be such as to provide the deposit size desired, avoiding excessive molten pool time [191].

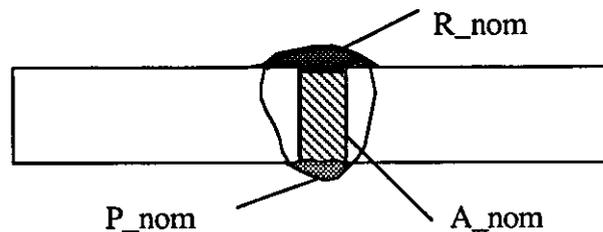
Hence, required deposit cross-sectional area (D_{nom}) for a nominal joint was accepted as a function of wire feed speed (WFS), torch speed (TS), and wire area (Wire_Area). It can be shown as:

$$D_{nom} = f(WFS, TS, Wire_Area)$$

$$D_{nom} = \frac{WFS \times Wire_Area}{TS}$$

The metal deposited in a joint is assumed to be divided into three distinct areas as shown in the figure below for square-butt.

(Nominal Joint)



$$D_{nom} = R_{nom} + A_{nom} + P_{nom}$$

From expert advise

$$P_{nom} = 0.1 \times D_{nom}$$

$$R_{nom} = D_{nom} - A_{nom} - 0.1 \times D_{nom} = 0.9 \times D_{nom} - A_{nom}$$

Where

D_{nom} = nominal deposited area

R_{nom} = metal deposited at weld top bead

A_{nom} = metal deposited in joint gap

P_{nom} = metal deposited at weld under bead

Hence, to control penetration and weld bead shape, the above assumptions are formed into the following pseudo-codes:

- If actual area become greater than nominal area ($A_{act} > A_{nom}$)

rule 1. If the difference between the areas ($A_{act} - A_{nom}$) is less than 90% of deposited top weld bead metal ($0.9 \times R_{nom}$) then nominal welding procedure has to be used which will be provided by WRAPS (minimum 0.1 R_{nom} excess fill).

rule 2. If the difference between the areas ($A_{act} - A_{nom}$) become greater than 90% of deposited to weld bead metal ($0.9 \times R_{nom}$) then nominal welding procedure provided by WRAPS has to be used and torch should perform weaving motion. The weave amplitude will be:

$$\text{Weave amplitude} = \text{Gap} + 2 \times \text{wire diameter.}$$

rule 3. Weave Frequency (WF) has been determined empirically for the specific welding robot and are shown in chapter 7 table 7.4, 7.6, 7.8 and also in appendix A8. WF are selected from knowledge base for particular combination of thickness and joint type.

The above expert pseudo-codes are then formulated and implemented in the format required by KES expert system shell. This is shown below:

Attribute section

D_nom : real [default: (WFS_nom*wire area)/TS_nom].
 P_nom : real [default: 0.1*D_nom].
 A_nom : real. \This will be receive from WRAPS supervisory system.
 R_nom : real [default: (0.9*D_nom) - A_nom].
 Weave_amp : real.
 Weave_fre : int.
 diff_area : real [default: A_act - A_nom].
 wire dia : real.
 RG_act : real.

Rule section

RULE_1: If $A_{act} > A_{nom}$ and
 $diff_area < (0.9 \times R_{nom})$
then
 result = WRAPS. \Nominal welding procedure provided by
endif. \WRAPS should be used.

RULE_2: If $A_{act} > A_{nom}$ and
 $diff_area > (0.9 \times R_{nom})$
then
 result = WRAPS.
 $Weave_amp = RG_act + 2 \times \text{wire dia.}$
endif.

RULE_3: if Joint type = square_butt_unback and
 $T1_act = 2$ and $T2_act = 2$
then
 $Weave_fre = 18.$
endif.

Similar rules are applied when A_{act} is less than A_{nom} . The 'window' techniques, although shown to be a useful tool and to provide generality in solving the problem of joint deviation, has been found to have only limited success in their application for PIKBES. The test results of this technique are shown in chapter 7. It is clear that more control over the expert knowledge is required. This can be accomplished by separating knowledge in modular form for different joint types, and controlling each block of knowledge in each module more precisely.

6.6.2 'Linear Relationship' Technique

The 'linear relationship' uses area ratio of joints (i.e. actual joint area + nominal joint area (X)) as a function to control welding parameters (such as torch speed, wire feed speed, etc.). Hence, deviation in the joint geometry can be compensated by modify welding procedure. This technique also takes advantage of the modular structure of PIKBES and selects knowledge concerned with different joint types rather than considering knowledge for all different joint types (as used in above 'window' technique). Selected knowledge is then narrowed down further by choosing knowledge concerned only with one or a few plate thickness(s). For example, RULE_20 below shows knowledge concern with one-sided V-butt joints for 5mm plate thicknesses when the root gap is in 'intermediate level' (i.e. the actual root gap greater than root gap lower limit and less than or equal root gap absolute upper limit). This uses the same knowledge when the root gap is in 'intermediate level' for 6mm plate thickness. The comparison of the actual with nominal joint parameters is carried out to find out which tolerance level applied to a particular parameter. After the search is carried out, the area ratio (X) is checked to find out the percentage increase or decrease in the joint area which is caused by changes in joint geometry. The area ratio (X) is then used in the conclusion section of the rules to modify welding parameters. The modification of welding parameters are performed by a percentage increase /decrease factor of joint area ratio, or simple linear relationship(s) between percentage decrease/increase in joint areas and percentage decrease/increase in torch speed and/or wire feed speed. Examples of these rules are shown in RULE_20 below and RULE_55 in section 6.6.2(2):

```

RULE_20:  if  T1_act gt 4.5 and T2_act gt 4.5  and
            T1_act le 6.5 and T1_act le 6.5  and
            RFT1_act ge RFT_LOLIM             and
            RFT1_act le RFT_UPLIM            and
            RFT2_act ge RFT_LOLIM             and
            RFT2_act le RFT_UPLIM            and
            RG_act lt RG_LOLIM                and
            RG_act ge RG_ABSLL               and
            X le 0.40
            then
                Rule_num      = 20.
                result         = mod_wld_proc.
                torch_motion   = linear.
                run_num        = run_no1.
                TS              = X*TS_nom.
                WFS             = 1.20*WFS_nom.
                Voltage         = V_nom.
                Torch_Angle     = TA_nom-20.
                Stand_Off       = stand off1.
            endif.

```

{explanation:"RULE_20: For the plate thickness 5 and 6mm. If the Actual Root",
 "Gap (RG) is less than Root Gap Lower Limit (RG_LOLIM) but",
 "greater than Root Gap Absolute Lower Limit (RG_ABSLL), and the",
 "Root Face Thicknesses are within the tolerance, Actual joint ",
 "area decreases by maximum 60% (X) of the Nominal joint area.",
 """,
 " * Torch Speed (TS) has to decrease by the ratio of the actual",
 " joint area / nominal joint area (X).",
 " * Wire Feed Speed (WFS) has to increase by 20%.",
 " * Torch Angle (TA) has to change from 90 to 70 deg from ",
 " horizontal (drag angle)."}.

Knowledge regarding welding variables and their relationships are the most important part of controlling any welding process and achieving full penetration, and acceptable weld bead geometry and weld mechanical strength. Therefore, for PIKBES, welding variables are divided into three classifications. These are: primary adjustable variables, secondary adjustable variables, and preselected or distinct level variables [192]. This classification is reviewed here in order to understand the effect of each variable on penetration, weld bead geometry, etc. and are used during development of PIKBES.

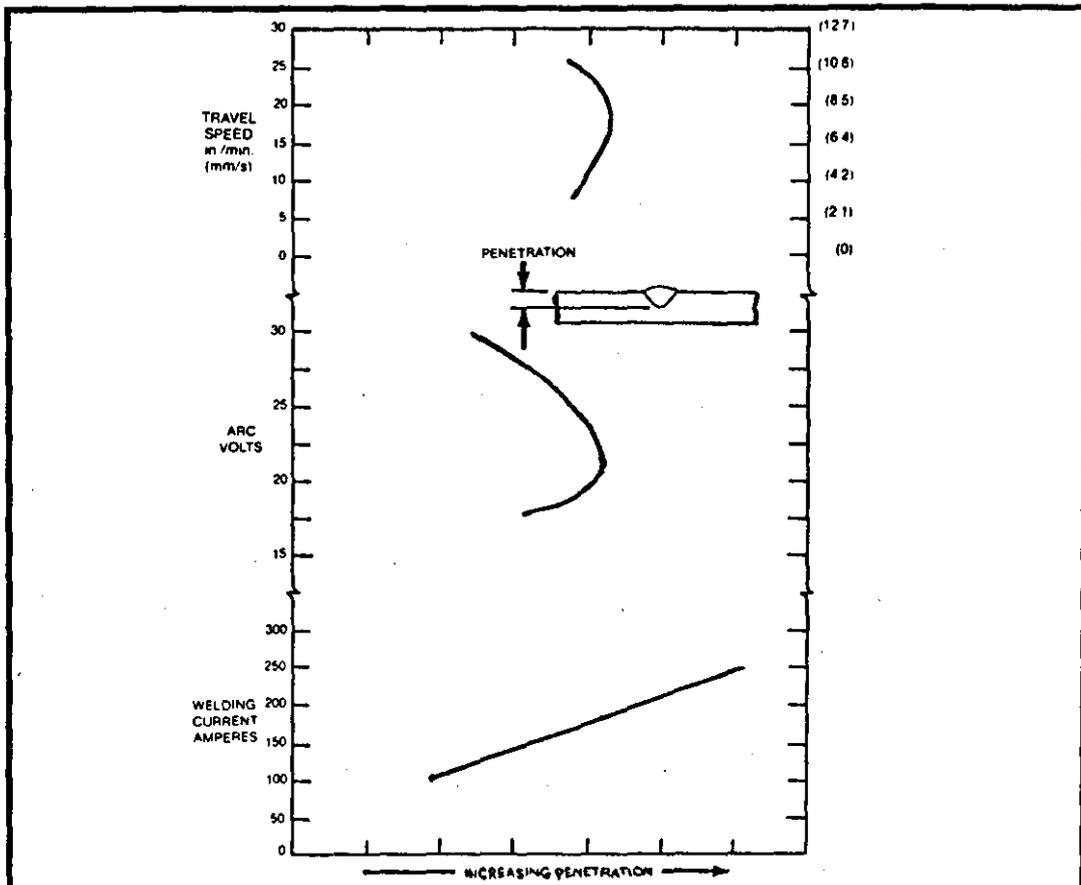
1) Primary Adjustable Variables

The primary adjustable variables are those mostly used to change the characteristics of the weld. These are: the travel speed (TS), the wire feed speed (WFS) or welding current, and the arc voltage (V). These primary variables control the formation of the weld by influencing the depth of penetration, the bead width, and the

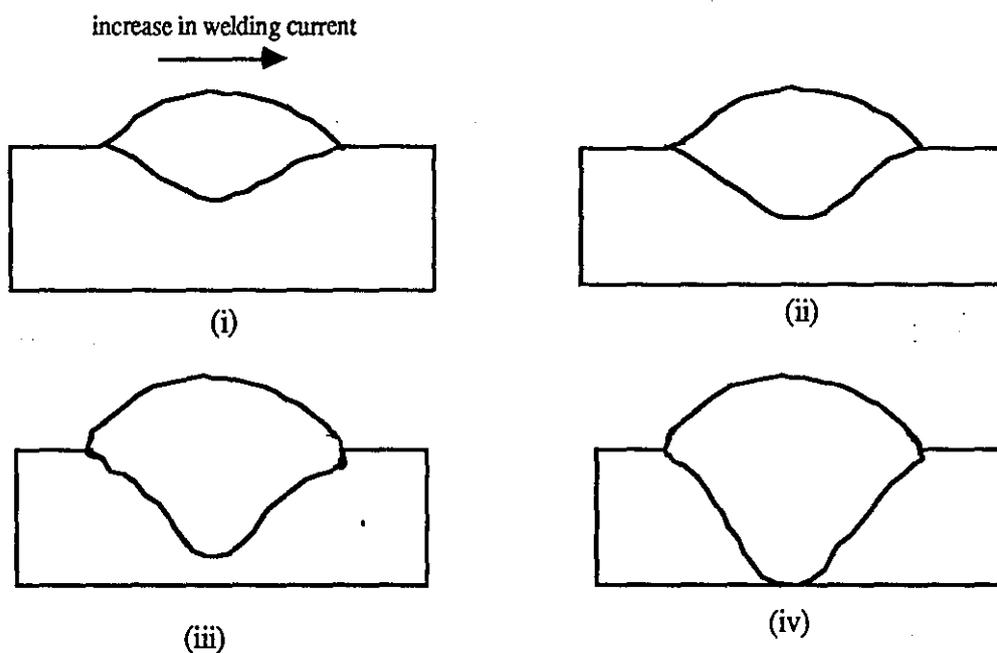
bead height (or reinforcement). They also effect deposition rate, arc stability, spatter level, etc. Each of the variables has a distinct effect on the three weld characteristics. Fig 6.12(a) shows the effects of these three variables on weld penetration. These curves are based on gas metal arc welding and are used in PIKBES to understand the effect of these variables on weld penetration. The depth of penetration increases as the current level increases. The welding current (WFS) and weld penetration relationship is a linear and is the most effective controlling factor on this weld characteristic. Fig 6.12(b) shows the weld cross section of welds when welding current increases (from (i) to (iv)). The relationship between travel speed and weld penetration is not a linear relationship. Penetration is maximum at a certain travel speed. Increasing or decreasing the travel speed from this point will reduce the amount of penetration. When the travel speed is decreased, the amount of filler metal deposited per unit length increases which creates a large, shallow weld puddle. Travel speed should not be used as the major control, since, for economical reasons, it is usually desired to weld at the maximum speed possible. The relationship of penetration and arc voltage also is not linear. The penetration will increase up to an optimum voltage level and then begin to decrease as shown in 6.12(a). Raising or lowering arc voltage from this level reduces penetration. Thus, a long arc or short arc will decrease penetration. A higher voltage is often used to bridge a gap because of the decreased penetration obtained. An excessively high arc voltage causes excessive spatter, porosity, and undercutting. A decrease in the arc length produces a narrower weld bead with a greater convexity and down to the optimum voltage level deeper penetration. For a given welding current there is a certain voltage that will provide the smoothest welding arc. It is for this reason that arc voltage is not recommended as a control for penetration.

In PIKBES, the above knowledge is used to compensate for variation in the joint geometry (RG,RFT,BV) and achieve sound weld bead shape and full weld penetration. That is by modifying two main welding parameters such as torch speed (TS) and wire feed speed (WFS) and at the same time considering the joint area ratio (X) as a control factor in increasing/decreasing TS and WFS parameters. To achieve this X was catagorised into bands and expert advise taken on the values of TS and WFS appropriate to the end points of each band. These conditions at the end points have been empirically tested to assure their correctness. It is then assumed, on the basis of expert advise that the relationships X and WFS, and X and TS are linear between the end points.

An example of the implementation of this methodology for plate thickness 6mm is described as follows: **I**f the the actual root gap is less than Root Gap Lower Limit (RG_LOLIM) but greater than Root Gap Absolute Lower Limit (RG_ABSLL), and



(a) Weld penetration related to primary variables



(b) Weld penetration vs increase in welding current

Fig (6.12) - Shows the relationship between primary variables and weld penetration, and the effect of welding current on weld penetration [193].

the Root Face Thicknesses (RFT) are within the nominal tolerance, and actual area is within a 30% decrease ($X=0.7$) and a 10% increase ($X=1.1$) of the nominal joint area **THEN** torch speed (TS) has to decrease to a maximum of 30% and wire feed speed (WFS) has to increase by maximum of 16% as joint area ratio decreases or increases. The modification of welding parameters is carried out by linear relationship between the joint area ratio (X) and welding parameters TS and WFS. Fig 6.13 and 6.14 show the plots of the X and TS, and WFS and X relationships for 6mm V-butt joint when RG and/or RFT deviate at intermediate levels. RULE_26 in below shows an example of these linear relationships and the knowledge which is elicited, formulated, and implemented for PIKBES:

```

RULE_26:  if  T1_act gt 5.5 and T2_act gt 5.5    and
            T1_act le 6.5 and T2_act le 6.5    and
            RG_act lt RG_LOLIM                 and
            RG_act ge RG_ABSLL                 and
            RFT1_act ge RFT_LOLIM             and
            RFT1_act le RFT_UPLIM            and
            RFT2_act ge RFT_LOLIM             and
            RFT2_act le RFT_UPLIM            and
            X gt 0.7                           and
            X lt 1.1
    then
        Rule_num      = 26.
        result        = mod_wld_proc.
        torch_motion  = linear.
        run_num       = run_no1.
        TS            = (0.77*X+0.18)*TS_nom.
        WFS           = (-0.52*X+1.56)*WFS_nom.
        Voltage       = V_nom.
        Torch_Angle   = TA_nom-20.
        Stand_Off     = stand off1.
    endif

```

{**explanation:**"RULE_26: For the plate thickness 6+_0.5mm. If the Actual Root",
 "Gap (RG) is less than Root Gap Lower Limit (RG_LOLIM) but",
 "greater than Root Gap Absolute Lower Limit (RG_ABSLL), and the",
 "Root Face Thicknesses are within tolerance, and the Actual joint",
 "area decreases by up to 30% of the Nominal joint area i.e. Root ",
 "GAP = 0:-",
 " ",
 " * Torch Speed (TS) has to decrease gradually up to maximum of",
 " 30% as the joint area ratio (X) decreases/increases.",
 " * Wire Feed Speed (WFS) has to increase gradually up to ",
 " maximum of 16% as the joint area ratio (X) decreases/increases.",
 " * Torch Angle (TA) has to change from 90 to 70 deg from ",
 " horizontal (drag angle)."}.

However, similar relationships for other plate thicknesses can be plotted using TS, WFS, and joint area ratio (X) data which is given in tables of factorial experiment design tests in chapter 7 section 7.3.2 and appendix A8.

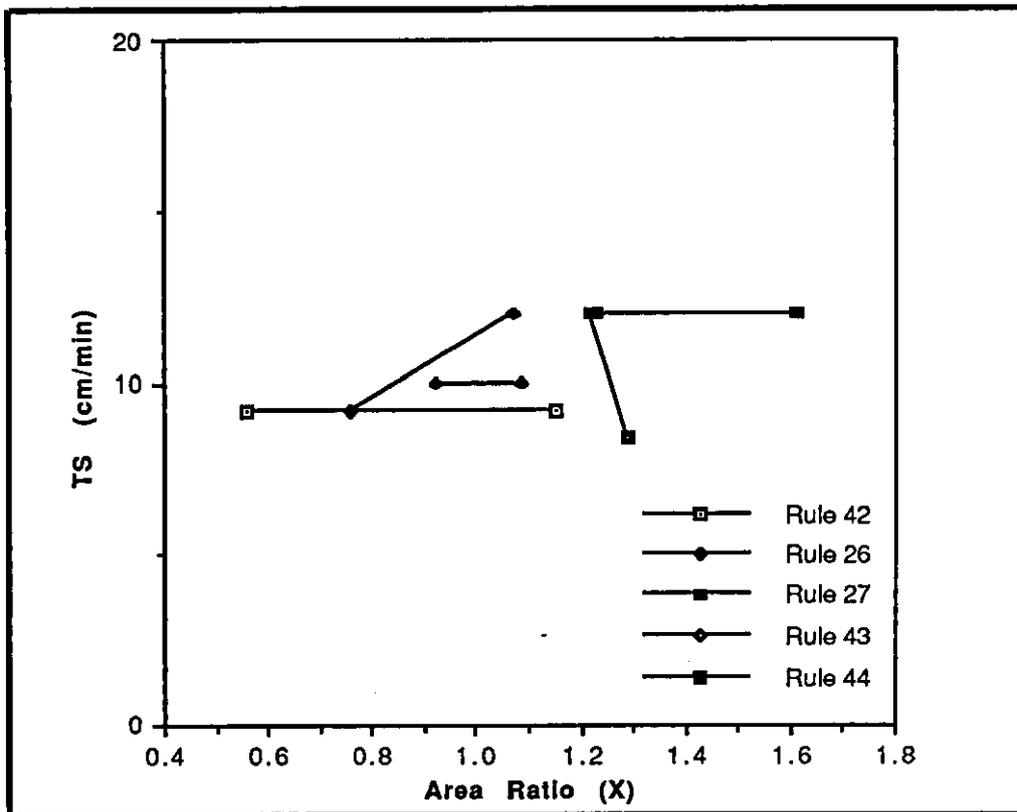


Fig (6.13) - Shows plot of changes in torch speed (TS) vs joint area ratio (x) for variation of root gap and root face thicknesses in 6mm V-butt joint.

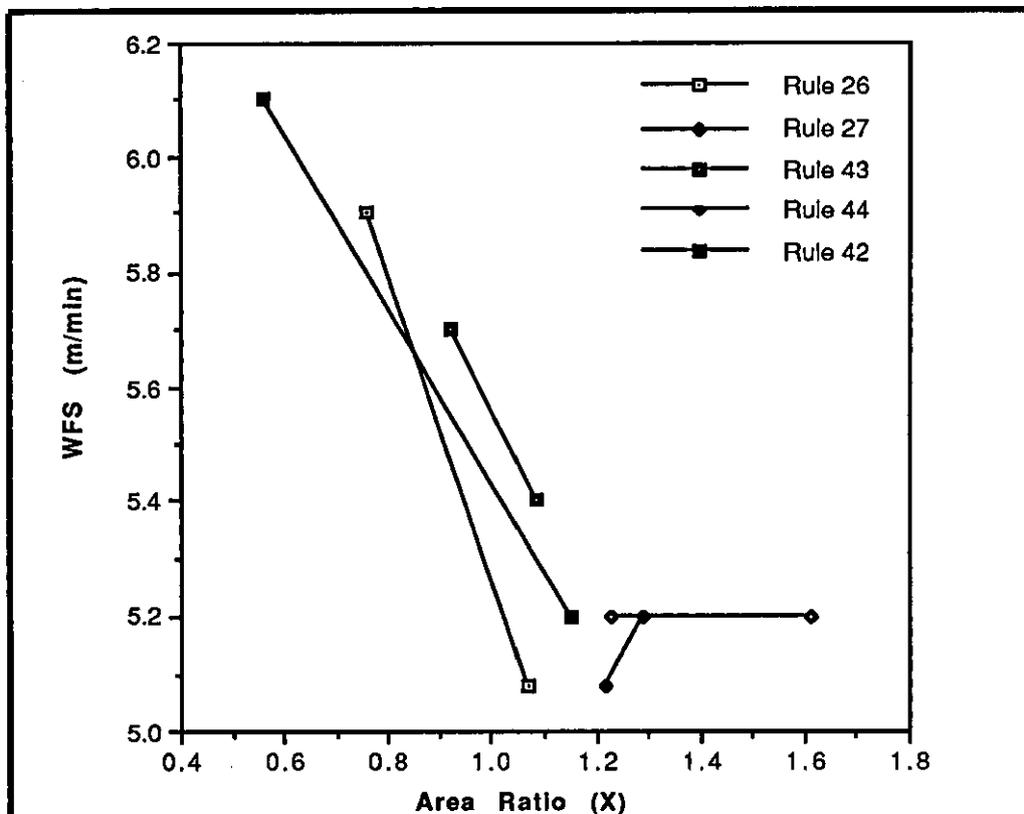


Fig (6.14) - Shows Plot of changes in wire feed speed (WFS) vs joint area ratio (x) for variation of root gap and root face thicknesses in 6mm V-butt joint.

In above rule, the linear relationships between X, TS and WFS are developed by limited experimentation and by recourse to knowledge elicited from the domain experts and published knowledge regarding the effect of primary variables on weld penetration. In the experiments, TS and WFS are respectively set at 8.65cm/min and 6.07m/min with area ratio $X=0.7$. The same procedure was carried out for $X=1.1$ and appropriate TS and WFS was selected (i.e. TS = 12.35cm/min and WFS = 5.016) and the joint was tested. The equation of linear relationship was then built using above X, TS, WFS.

$$\begin{array}{ll} \text{TS} = 9.26X + 2.165 & \text{where} \quad \text{TS} = (0.77X + 0.18)12.03 \\ \text{WFS} = -2.64X + 7.92 & \text{WFS} = (-0.52X + 1.56)5.08 \end{array}$$

Similar procedures were carried to develop these relationships for other thicknesses.

The weld bead width relationship to the primary variables is shown in fig 6.15(a). Bead width is an important characteristic of a weld, particularly where using automatic equipment to fill a weld groove or to produce a specific geometry of a weld. The arc voltage variable, or arc length, is almost a linear relationship with weld bead width. As the arc voltage is increased bead width increases. This can be explained by considering the welding arc. The welding arc has a point-to-plane relationship and is thus conical in shape with the apex of the cone at the end of the electrode and the base at the surface of the weld. This is shown by fig 6.15(b) and explains the relationship between a longer arc with higher voltage and the bead width. This shows the arc voltage at different arc lengths and how the arc spread out and makes a wider bead. This relationship is also shown by fig 6.15(c) which shows the cross-section of welds made at different arc voltages. Since increasing the arc voltage makes the bead wider, the reinforcement height is reduced because the same volume of weld metal is involved. Conversely, reducing the arc voltage makes the bead narrower and increases the height of the reinforcement. Travel speed is the second choice for changing bead width, since it has a relatively straight line relationship. The welding current has also a relatively straight line relationship. The weld bead reinforcement or height related to the three primary variables is shown by the curve of fig 6.16(a).

In PIKBES, the arc voltage is invariably kept the same as nominal as this primary variable did not have such large effect on weld penetration as welding current (WFS) and torch speed (TS) have. However, after further consultation with experts, it is also realised that increase in the arc voltage has to be carried in a 'step change', for example, if we are using the 17 volts for 6mm plate thickness (the nominal voltage for

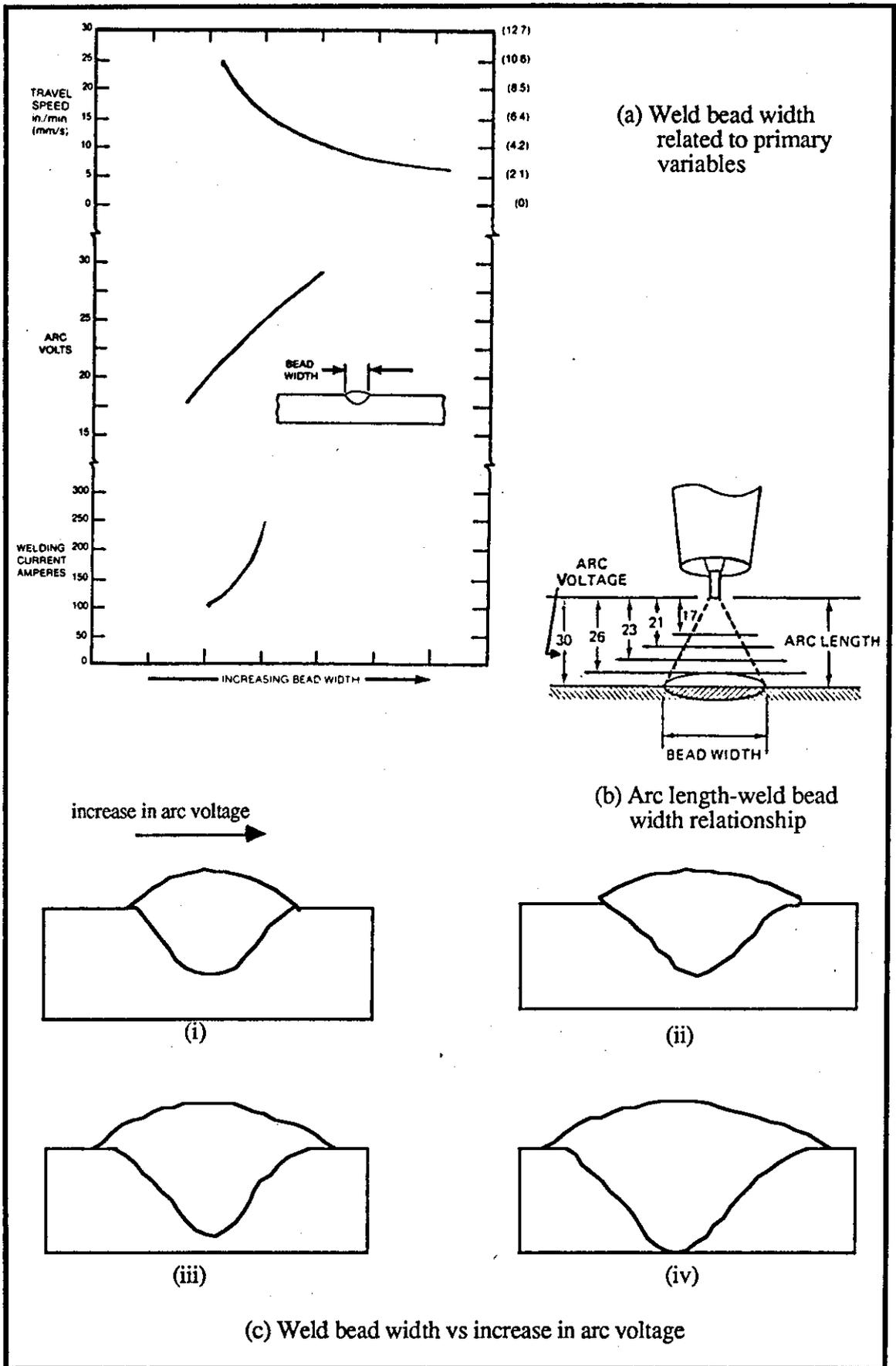
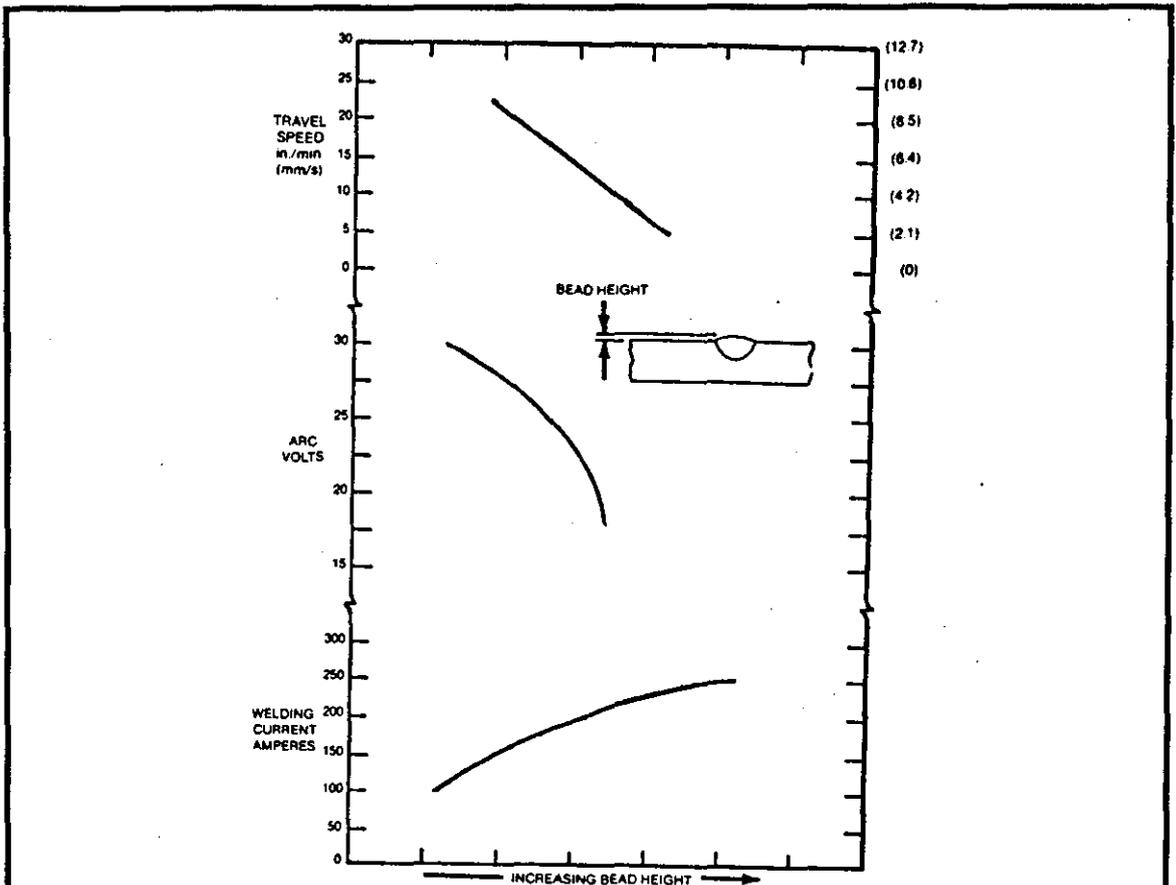
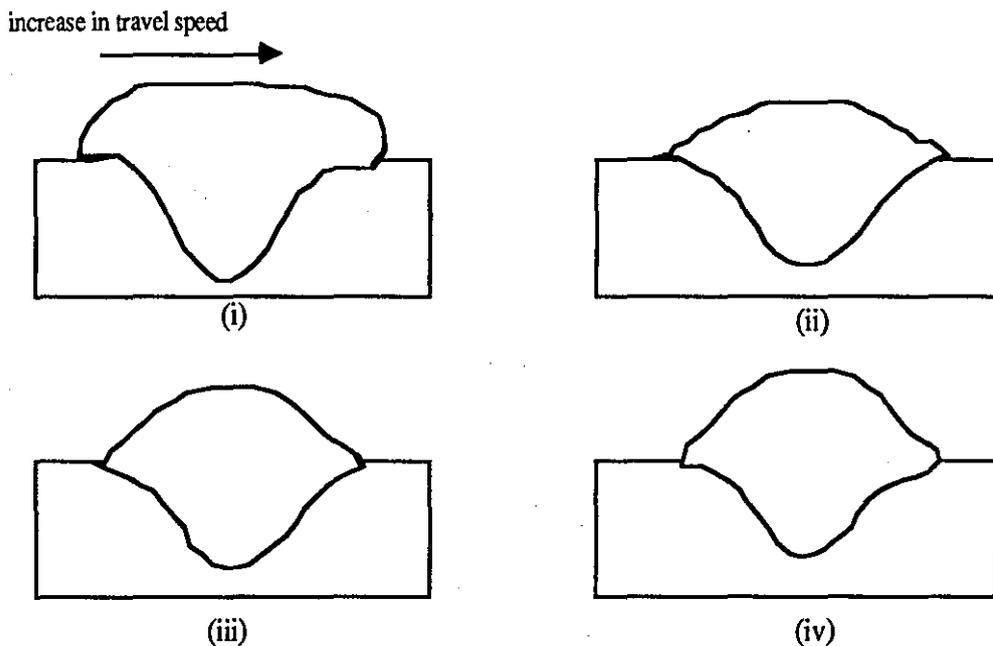


Fig (6.15) - Shows the relationship between primary variables and weld bead width, and the effects of arc voltage on weld bead width [19].



(a) Weld bead reinforcement related to primary variables



(b) Weld bead height vs increase in travel speed

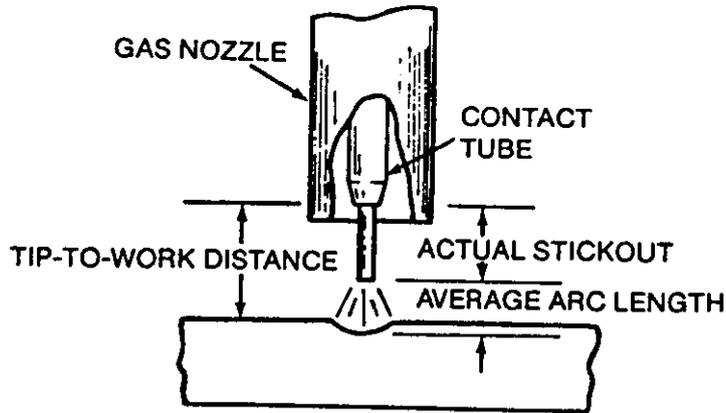
Fig (6.16) - Shows the relationship between primary variables and weld bead height and the effect of travel speed on weld bead [19].

6mm plate thickness is 17-21 volts) and increase in voltage is only effective when voltage changes above to 21 volts.

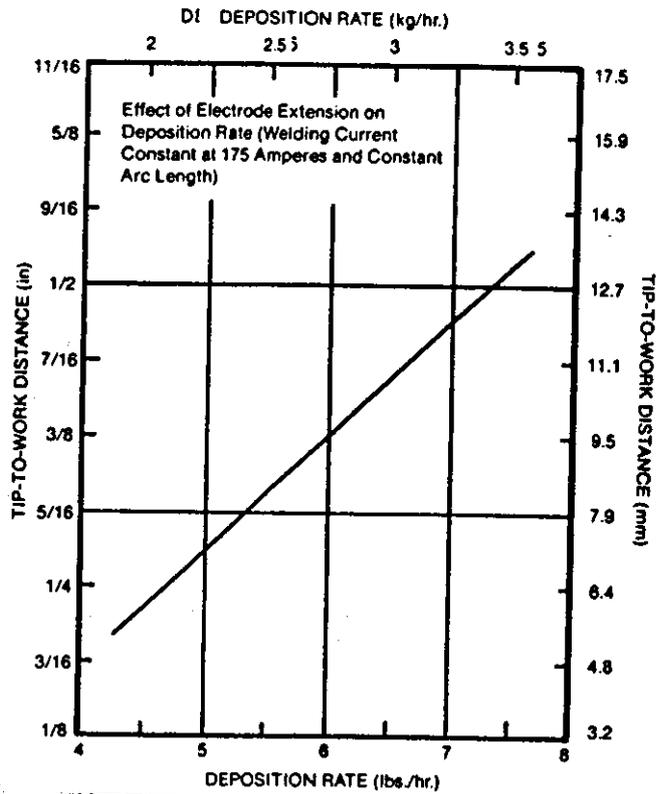
The weld height is most effectively controlled by travel speed because of a straight line relationship. This is based on the mass of weld metal deposited. Fig 6.16(b), shows the cross-section of gas metal arc welds made at different speeds. At the lower travel speeds the weld is large in mass whereas at the high travel speed it is smaller in mass. This relationship is very easily determined by relating the cross-sectional area of the welding electrode times the wire feed speed to the cross-sectional area of the weld times the travel speed. As more electrode is fed into the arc based on higher welding current, a greater mass of metal is deposited. However, as the speed of travel is increased this mass of metal will be spread out over longer length. It is possible to establish an exact weld size (mathematically) based on this relationship. The relationships shown relate penetration, bead width, and reinforcement to welding current, arc voltage, and travel speed. These relationships can only be varied within limits, since there is a relatively fixed relationship between arc voltage and welding current within the stable operating range. This relationship changes for different processes, shielding gas atmospheres, and electrode sizes. All of these relationships are relative. Different values would be used for different processes. The shape of the curves and the changes in weld bead characteristics would be the same.

2) Secondary Adjustable Variables

The secondary adjustable variables include the stickout and torch or electrode angle. These variables do change the weld characteristics because they influence one of the primary variables. When using a mechanised welding system, welding current is controlled by the electrode wire feed speed. Therefore, penetration is directly influenced by wire feed speed when all other conditions are the same. The wire feed speed - current relationship can be changed by changing polarity, shielding media, electrode wire size, and the stickout. Stickout is shown by fig 6.17(a). Increasing stickout increases deposition rate only if the wire feed speed is increased sufficiently to maintain the current at a constant value. This is shown by fig 6.17(b). The relationship between stickout and welding current is also shown by fig 6.18(a). Increasing the stickout will reduce the welding current in the arc by almost 100 amperes when the wire feed speed rate is not changed. This reduces penetration by a proportional amount. Stickout exerts an influence on penetration through its effect on welding current as shown by fig 6.18(b). Stickout is thus a control during the welding operation. It influences the welding current. As the electrode extension or stickout increases, the circuit resistance increases and the welding current decreases. The

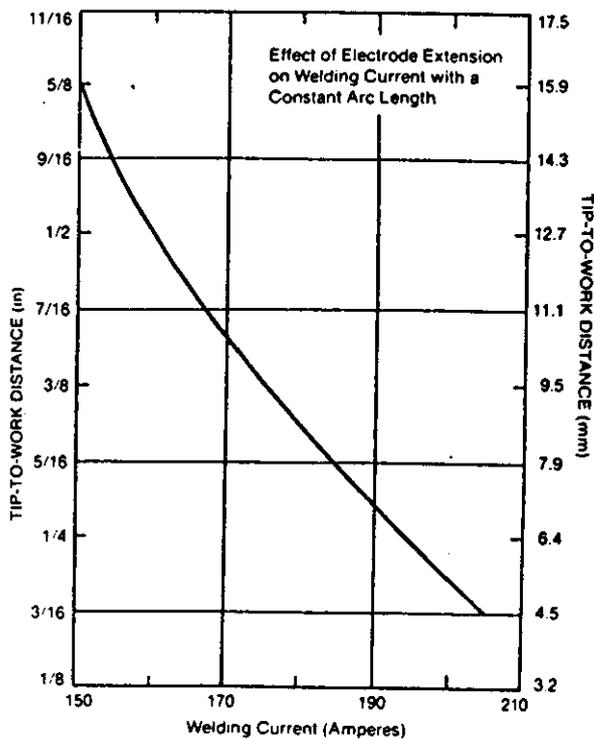


(a) Stickout (or electrode extension) and Tip-to-work-distance.

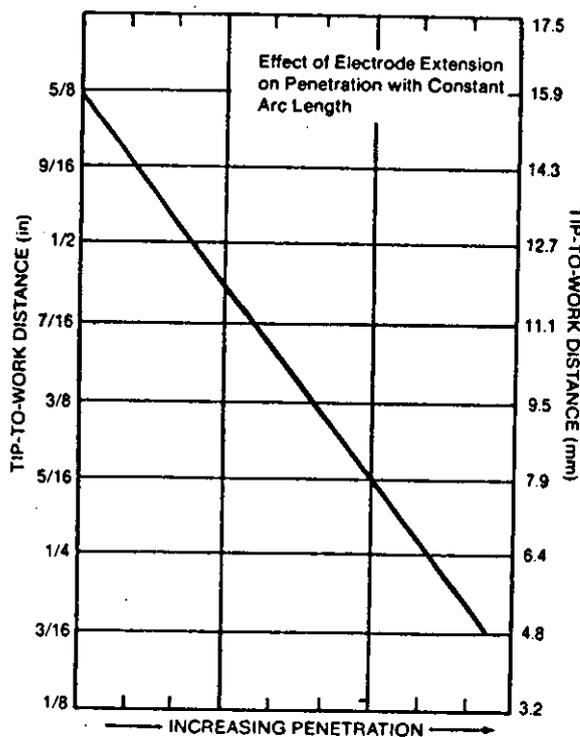


(b) Tip-to-work-distance vs deposition rate.

Fig (6.17) - Shows the relationship between torch tip-to-work-distance and prepared plates, and deposition rate [192].



(a) Tip-to-work-distance vs welding current.



(b) Tip-to-work-distance vs penetration.

Fig (6.18) - Shows The effect of secondary adjustable tip-to-work-distance vs welding current and penetration [192].

output voltage of the power source remains constant; therefore, more voltage drop across the extension and thus less voltage occurs across the arc. The decrease of both voltage and current will reduce the penetration of the arc. Conversely, as the stickout (electrode extension) decreases, the preheating effect is reduced and the welding power source furnishes more current. This increase in welding current provides a proportionate increase in penetration.

In PIKBES, the wire stickout is varied between 15 to 25mm depending on joint types and thickness. This factor together with the distance from the plate surface (in square-butt joints) or top of root face thickness (in V-butt joints) to the tip of the wire is considered as stand-off (SO) in PIKBES. This is shown as tip-to-work distance in fig 6.17(b). The stand-off distance will effect weld penetration. As the stand-off distance increases so the size of the underbead decreases. The maximum penetration into the base plate also decreases. This can be explained by the reduction in welding current due to the increased resistance of the extended electrode (as mentioned above). For square and V_butt joints, this distance is control by a heuristic rule as shown below:

Constants Section

```
torch surf : 10.
const1     : 0.5.
```

Attribute Section

```
T1_act      : real.
T2_act      : real.
T_AVR       : real    [default: (T1_act + T2_act)/2].
stand off1  : real    [default: ((T_AVR - RFT_AVR)+ torch surf) + const1].
stand off2  : real    [default: (stand off1 - (T_AVR/2))].
```

Rule Section

```
RULE_55:  if T1_act gt 10.5 and T2_act gt 10.5           and
            T1_act le 13.0 and T2_act le 13.0           and
            RFT1_act gt RFT_UPLIM and RFT1_act le RFT_ABSUL and
            RFT2_act gt RFT_UPLIM and RFT2_act le RFT_ABSUL and
            X gt 0.75                                   and
            X le 0.9
            then
            Rule_num      = 55.           Voltage      = V_nom.
            result        = mod_wld_proc. Voltage2     = V_nom2.
            torch_motion  = linear.       Voltage3     = V_nom2.
            torch_motion2 = linear.       Torch_Angle  = TA_nom-20.
            run_num       = run_no14.     Torch_Angle2 = TA_nom.
            TS = (-4.89*X+5.76)*TS_nom.   Torch_Angle3 = TA_nom.
            TS2           = TS_nom2.      Stand_Off    = stand off1.
            TS3           = TS_nom2.      Stand_Off2   = stand off2.
```

```

WFS = (-3.37*X+4)*WFS_nom.Stand_Off3 = stand off2.
WFS2 = WFS_nom2.
WFS3 = WFS_nom2.
endif

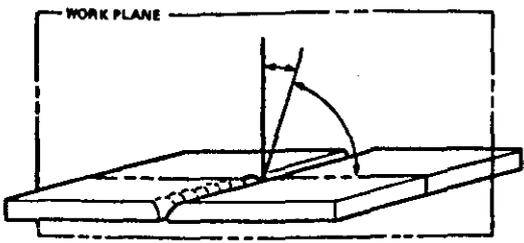
```

{**explanation:**"RULE_55: For the plate thickness 12+_0.5mm. If the Root Face",
 "Thicknesses are greater than RFT Upper Limit (RFT_UPLIM) but",
 "less than or equal RFT ABSolute Upper Limit (RFT_ABSUL), and",
 "the Actual joint area decreases by more than 10% of the",
 "Nominal joint area :",
 " "
 " * Torch Speed (TS) has to increase over the range of X up to",
 " maximum of 79% of TS_nom as the area ratio (X) decreases.",
 " * Wire Feed Speed (WFS) has to increase over the range of X up to",
 " maximum of 27% of WFS_nom as the area ratio (X) decreases.",
 " * Torch Angle (TA) has to be change from 90 degrees to.",
 " 70 degrees (from horizontal (Lead)).").

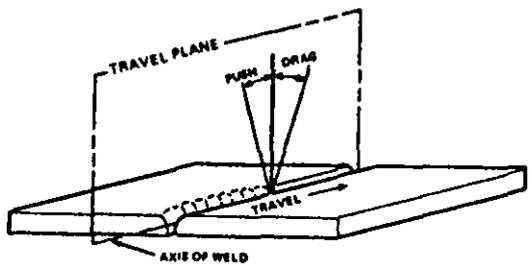
Similar procedures as described for the development of RULE_26 (page 189) was carried out to develop the linear relationships for Ts and WFS in the above rule. The rule calculates the stand-off as the difference between average plate thicknesses and average root face thicknesses, and the preset value of wire from the head of torch to the surface (10mm) and the length of wire between nozzle and head of torch (0.5mm).

Another secondary adjustable variable is the electrode or nozzle travel angle, which has an appreciable effect on penetration. Two angles are required to define the position of an electrode or welding gun nozzle: (1) the travel angle and (2) the work angle. The work angle is the angle that the electrode or the centreline of the welding gun makes with the referenced plane or surface of the base metal in a plane perpendicular to the axis of the weld. Fig 6.19(a) shows the work angle for a V-groove weld. The travel angle is the angle that the electrode, or the centreline of the welding gun, makes with a reference line perpendicular to the axis of the weld in the plane of the weld axis, fig 6.19(b). The travel angle is further described as either a drag angle (it is also known as backhand welding, lead or pull angle) or a push angle (it is also known as forehand welding or lag angle). Fig 6.19(b) also shows the drag and push travel angles. It is found that maximum penetration is obtained when a drag angle of 15-20 degree is used. If the gun travel angle is changed from this optimum condition penetration decreases.

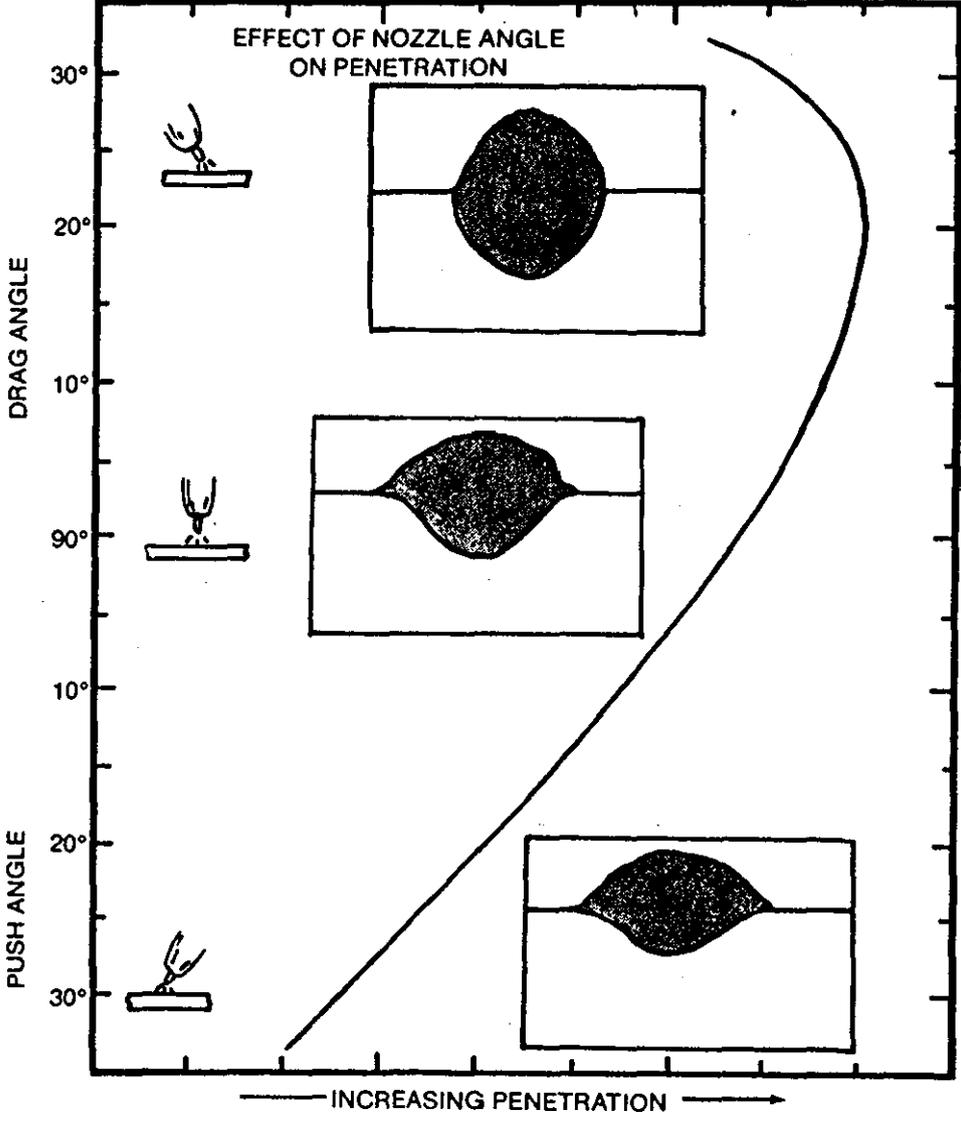
In PIKBES, the same logic was used when root gap or root face thickness of the actual joint were at the 'intermediate tolerance level'. As it can be seen from the above rule (RULE_55) if the actual joint area is decreased by less than 15% of nominal joint area, although the torch speed and wire feed speed are respectively increased up



(a) Work angle - V-butt joint



(b) Travel angle - V-butt joint



(c) Travel angle vs penetration

Fig (6.19) - Effect of secondary travel angle on weld penetration [19a].

to maximum 79% and 27%, torch angle (Torch_Angle) is change from 90 degree vertical to 70 degree drag angle from horizontal. This allows more penetration through the root faces.

From a drag angle of 15 degree to a push angle of 30 degree the relationship between penetration and travel angle is almost a linear. Therefore, good control of penetration can be obtained in this range. The gun travel angle variable can also be used to change bead height and width, since the gun travel angle does affect bead contour. A drag travel angle tends to produce a high, narrow bead. As the drag angle is reduced, the bead height decreases and width increases. As the gun travel angle decreases from 90 degree vertical to a maximum 70 degree drag angle from the surface of plates, the penetration increases but it is not recommended that a drag angle of greater than 25 degree be used (65 degree from surface of plates). This relationship is shown by fig 6.19(c) the push travel angle is used for high travel speeds and good bead finish. These angles vary slightly with different processes and procedures.

3) Distinct Level Variables

The polarity of welding is the next important variable after selection of the welding process. In general direct current electrode positive DCEP (reverse polarity) produces greater penetration than electrode negative DCEN (straight polarity) in GMAW process. Alternating current, which is used with the submerged arc welding, produces penetration between that produced by electrode positive and electrode negative. The penetration increases as the polarity changes from DCEN to AC, and to DCEP.

The other variable is electrode size. A Smaller size of electrode tends to produced deeper penetration. This is related to the geometry of the arc and the point-to-plane relationship. The higher the current density on the electrode wire, the deeper the penetration. Larger diameter electrodes produce wider beads and less penetration, as shown by fig 6.20(a). In gas metal arc welding, the use of CO₂ gas shielding provides deeper penetration. The shielding gas relationship to penetration is shown by fig 6.20(b). Also, in gas metal arc welding the type of shielding gas affects the weld bead shape and penetration pattern. Argon has a characteristic deep centre or pointed penetration, while CO₂ provides a wider pattern. The Co₂-Argon mixture is between these. The shielding gas relationship to weld bead shape is shown by fig 6.20(c).

By fully understanding these relationship of the variables and their effect on

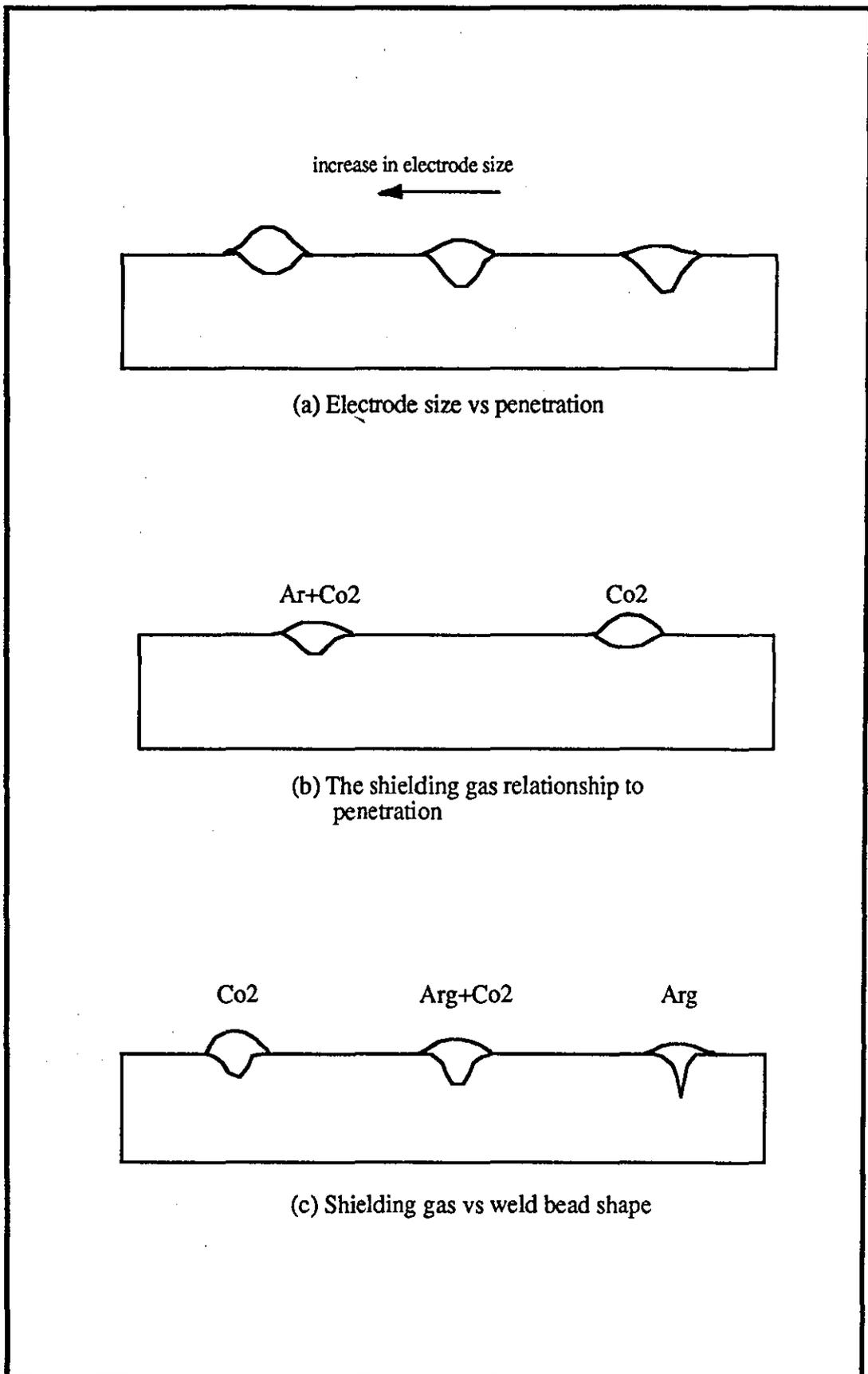


Fig (6.20) - Shows the effect of distinct level variables [193].

weld characteristics together with other knowledge regarding the 'window' technique, PIKBES is developed to compensate for variation in joint geometry. Joint geometry variation was recognised as: gap or root gap (0 - 1.75mm), root face thickness (0 - 1.75mm), bevel angles (25 - 35 degree) for plate thickness of 2 - 6mm and for square and one-sided V-butt joints; root gap (0.5 - 2.5mm), root face thickness (0 - 2.5mm), and bevel angles (25 - 35 degree) for plate thickness of 8mm one-sided V-butt joint; root gap (1 - 2.5mm), root face thickness (0.5 - 2.5mm), bevel angles (20 - 30) for plate thicknesses of 10mm and 12mm one-sided V_butt joint.

The linear relationship technique has been found to be a successful technique in spite of its reduced generality. The knowledge base can be built very quickly. This technique mainly uses primary and secondary adjustable variables, experts heuristic knowledge, and author's own understanding of the effect of each welding variables during test case welding exercise.

6.7 Knowledge Implementation for PIKBES

The software is produced for PIKBES as a set of modules. Fig 6.9 has already shown this set of modules for square and V-butt joints. Each module was tested for number of different cases to verify that each module meets its requirement. During knowledge implementation, the knowledge base for each module was formulated in a way that can minimise and reduce the complexity of the knowledge. Further implementation of knowledge was to produce facilities to help the user to understand the course of action to a particular problem. Tests of interaction between the users and PIKBES has been carried out to understand the users need to ask questions from the system. Facilities such as 'explain', rule 'display', 'explanation' to explain the course of action, etc is provided in PIKBES to help the user during consultation with the system. Chapter 7 provides run session samples of PIKBES and user consultation with the system.

6.8 Knowledge Validation of PIKBES

Evaluation is an integral part of the development cycle for any software system. PIKBES was evaluated to determine how well it provides solutions to the joint deviation problems it was designed to solve. PIKBES was evaluated:

- i) During development of its prototypes,

ii) After completion,

As the evaluation process uncovered discrepancies within PIKBES or in the techniques used to generalise the rule and heuristic knowledge, refinement, redesign, and reformulation of rules and heuristic knowledge was performed to correct the rules and heuristic knowledge.

A factorial experiment design has been carried out. This experiment was required to evaluate 'linear relationships' technique used for modification of TS, WFS, V, TA, SO. One/two joint variables, G/RG and RFT at five levels and five welding variables at different magnitudes are considered in the factorial design for 2 to 12mm square-butt and V-butt joints. Five levels tested were nominal parameters, parameters at lower and upper tolerance limits which were established by British Standard (BS5135) and are known here as tolerance 'Level 1', parameters at lower and upper absolute limits which are expertly established tolerances and are known here as tolerance 'Level 2'. A further experiment was performed to modify the expertly established tolerance levels in order to prevent burn-through or lack of penetration problems. Chapter 7 discusses these experiments in more details.

Further validation of PIKBES is performed by using test cases. Test cases have been used to evaluate PIKBES problem solving, the user interaction capability, its speed in solving a problem, and actually welding joint samples. This consisted of sets of data submitted to the PIKBES and measuring each specific aspect of its performance. Chapter 7 discusses these test cases further together with run session samples, and radiographs and photographs from weld cross-section of welds which is generated from test cases.

CHAPTER 7:

Validation of PIKBES

CHAPTER 7 : VALIDATION OF PIKBES

7.1 Introduction

This chapter first discusses the background to the practical evaluation of PIKBES and considers two different tests of the system (section 7.2). The design of factorial experiments and selection of variables and levels are discussed in section 7.3. Section 7.4, 7.5, and 7.6 briefly discuss plate edge and weld tests preparation, and the quality assessment techniques used for experimental tests. The welding experiments on the two PIKBES modelling techniques namely 'window' and 'linear relationship' techniques are discussed respectively in section 7.7 and 7.8. These sections present weld cross-section macro-graphs of experiment test cases for 2mm and 3mm square-butt joints and 4mm to 12mm V-butt joints. The radiographs of some of the test cases are also presented in these sections. Furthermore, the interaction capability between PIKBES and end-user is discussed in section 7.9.

7.2 Background

Evaluation is an integral part of the development cycle for any software system. PIKBES is evaluated by selecting and running test cases using factorial experiment designed to give appropriate treatment combinations of joint variables and their levels. These tests show the ability of PIKBES to provide on-line feedforward control of welding procedures.

PIKBES has been evaluated; 1) during development of its prototypes, and 2) prior to the system being released to the user. It should also be evaluated during the early stages of implementation. During test evaluation, if the evaluation process uncovered any significant discrepancy within the knowledge base, the evaluation process was repeated after making suitable corrections in the knowledge base. This iterative process of evaluation has resulted in sound knowledge base contents and valid decisions made by PIKBES.

Two specific tests were carried out for PIKBES; 1) practical welding tests of modified welding procedures for different techniques using treatment combination test cases, and 2) example test cases have been performed to observe the interaction between the end-user and PIKBES. A sample is given in section 7.9.

7.3 Experimental Design

The experiments were designed with a view to test, develop, and refine the non-mathematical models of PIKBES and to correlate the independently uncontrollable joint parameters i.e. root gap (RG), root face thickness (RFT), bevel angles (BV), etc., and the controllable welding parameters, i.e. torch speed (TS), wire feed speed (WFS), arc voltage (Voltage), torch angle (TA), and stand off (SO) with respect to weld bead quality parameters i.e. penetration (P), weld bead width (BW), weld bead height (BH), width of penetration (WPe), under bead width (UBW), under bead height (UBH). Fig 7.1 shows the controllable and uncontrollable variables whereas fig 7.2 shows the weld bead geometry parameters considered during quality control of welded joint for square and V-butt joints for different plate thicknesses.

The GMAW process was used for butt welds in Carbon and Carbon Manganese (C-Mn) steel plate of eight thicknesses. Most joints required use only one weld run. Where two or more weld runs were required, the experiment concentrated on only the first weld run since penetration and fusion at the root is the most critical feature. This is performed for plate thicknesses of 8, 10, 12 mm with V-butt joints. The quality assessment for weld bead geometry in these cases was therefore only involved with under weld bead width (UBW), under weld bead height (UBH), and weld width side penetration (WPe), fig 7.2, as well as freedom from porosity, inclusions and/or cracks. For plate thicknesses 2 and 3 square-butt joints and 4, 5, and 6 mm V-butt joints one weld run was sufficient to achieve full penetration, and to satisfactorily fill the joint with acceptable weld bead geometry.

Five welding variables with different magnitudes were identified as significantly affecting the penetration and weld bead geometry though a further three variables have also been included which provides full capabilities of the system. These latter variables are weave pattern (WP), weave amplitude (WA) and weave frequency (WF). However, acceptable penetration and weld beads could not be produced without recourse to a weave welding technique when the root gap was larger and/or root face thickness lower than British Standard tolerances.

7.3.1 Selection of Variables and Levels

Following the initial discussion with welding experts at the Welding Institute and Loughborough University, a literature survey on mathematical modelling

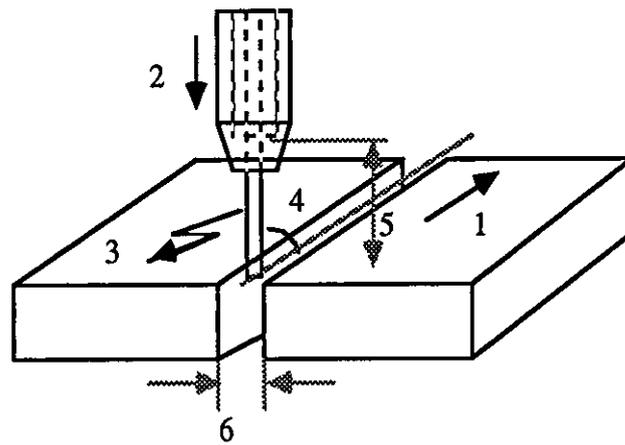
[3,93-99], and a number of initial tests, the following primary and secondary variables [192] and levels were identified;

- a) For square-butt joints with plate thicknesses of 2 and 3mm, one joint variables (gap) at five tolerance levels (upper and lower expertly established absolute tolerances, upper and lower British Standards tolerances, and at nominal joint parameters, and five welding variables (TS,WFS,V,TA,SO) at three levels (low, medium, and high).
- b) For V-butt joints with plate thicknesses of 4 to 12mm, three joint variables (RG,RFT,BV) at five tolerance levels, the same as those in (a) above, and five welding variables also as in (a).

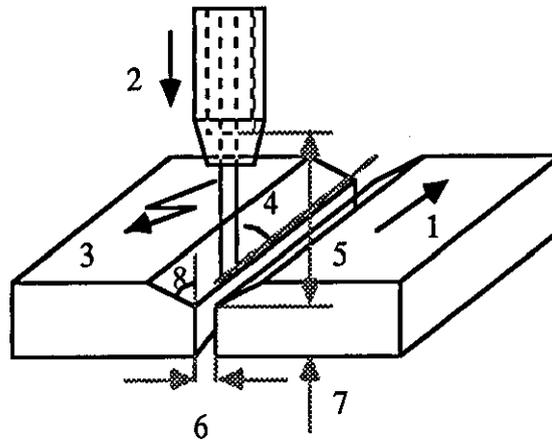
These variables are shown diagrammatically in fig 7.1. An example of joint variable(s) and their tolerance levels and welding variables and their magnitudes together with weaving parameters for 2mm square-butt and 4mm V-butt joint are respectively listed in tables 7.1 (a) and table 7.5. The purpose of this study was to test, develop, and refine the non-mathematical models for PIKBES. This was essentially a compromise between including enough factor to ensure the adaptive strategy was sufficiently general to cope with all likely inputs, yet not including so many variable factors that the experimental load became prohibitive. Therefore, five levels of each joint variable at their extreme limits were adopted.

1) The Effect of Torch Speed on Weld Penetration and Weld Bead Quality

The torch speed is a primary controllable variable in that the depth of penetration decreases as the welding speed is increased [192]. Three magnitudes of torch speed were used in the experiment. The experiment showed that as the gap/root gap decreases and or root face thicknesses are increased, the torch speed has to decrease. The relationship between the joint area and welding torch speed was shown to be a relatively linear relationship. Logically it is seen to be acceptable that if the joint area is decreased, the torch speed has to increased in order to prevent too much weld metal being deposited in the joint. This can result in lack of penetration. However, a number of other factor such as welding current (wire feed speed), voltage, or torch angle are used to achieve weld penetration as well as decrease in torch speed. It must also be remembered that for economic welding torch speed should be maintained as high as possible.



(a)



(b)

Controllable Welding Variables

- 1 - Travel Speed (Torch Speed (TS))
- 2 - Wire Feed Speed (WFS)
- 3 - Arc Voltage (v)
- 4 - Torch Travel Angle (TA)
- 5 - Stand-Off Distance (So)

Uncontrollable Joint Variables

- 6 - Gap/Root Gap (RG)
- 7 - Root Face Thickness (RFT)
- 8 - Bevel Angles (BV)

Fig (7.1) - Controllable and uncontrollable variables.

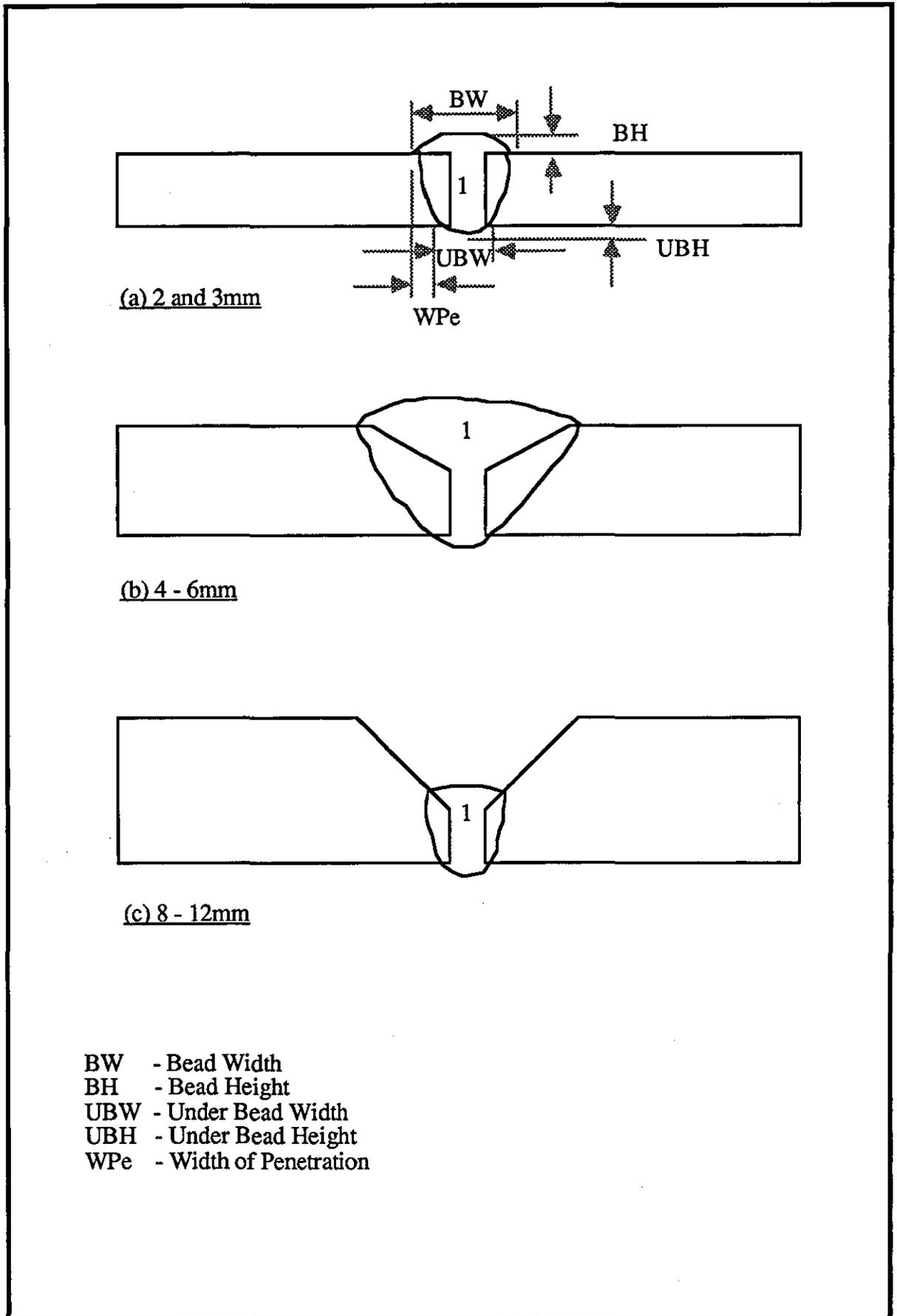


Fig (7.2) - The weld bead quality parameters for square and V-butt joint.

2) The Effect of Wire Feed Speed on Weld Penetration and Weld Bead Quality

The wire feed speed is also a primary controllable variable in that the depth of penetration increases as the current level increases [192]. The wire feed speed and weld penetration relationship is linear and is most effective in controlling the weld characteristic. Different magnitude of wire feed speed were used in the experiment tests. The relationship between the joint area and wire feed speed is also a linear relationship. As gap/root gap and/or root face thicknesses are respectively decreased and/or increased, wire feed speed had to increased. Burn-through can occur or too much weld will be deposited if this control variable is not set properly.

3) The Effect of Arc Voltage on Weld Penetration and Weld Bead Quality

The arc voltage is also a primary controllable variable and the relationship of weld penetration and arc voltage is not linear [192]. There is an optimum arc voltage where penetration is maximum. Two voltage levels are mainly used. As the gap/root gap was reduced and/or root face thicknesses were increased, the voltage increase was necessary to increase the weld penetration. The reverse of this is used where less penetration was required. The voltage level, however, is determined primary by the arc length, shielding gas composition, and the welding current level. Arc voltage has a straight line relationship with weld bead width and height. As the voltage increases the weld bead width increases but weld height decreases.

4) The Effect of Torch Travel Angle and Stand-off Distance on Weld Penetration and Weld Bead Quality

The torch travel angle is a secondary controllable variable in that the relationship between torch angle and penetration is not a linear relationship [192]. Up to 75-80 degree, increasing torch drag angle increases penetration and above these limit the penetration will decrease. A drag torch angle beyond 75-80 degree tends to produce a high, narrow bead. This has already been shown in fig 6.19 in chapter 6. Stand-off distance also has an effect on weld penetration, an increase in wire stickout will reduce the welding current in the arc and hence, reduces penetration.

5) The Effect of Gap/Root Gap and Root Face Thicknesses on Weld Penetration and Weld Bead quality

Increasing either the joint gap/root gap or included angles (bevel angles) and

reducing root face thickness leads to increased penetration, ultimately ending in burn-through if the welding conditions become critical [192]. Conversely, reducing gap/root gap and/or included angle and/or increasing root face thickness leads to decrease in penetration. Consequently, these variables will also effect weld bead geometry.

7.3.2 Design of Factorial Experiment

In factorial experiment several variables are controlled and their effects at each level are investigated. The experiment plan carried out for PIKBES consists of taking an observation at each one of all possible combinations of joint variables (i.e. RG,RFT,BV) that can be formed for the different tolerance levels of the variables. Each such different combination is termed a treatment combination.

The principle advantage of factorial experiments over the more common "one-variable-at-a-time" experiment where all variables except one are held constant is that interactive effects within the range of interest can be determined. The "one-variable-at-a-time" experiment describes the effect of a variable but is valid only when all other variables are at a particular combination. Doherty [99] has concluded that anything but the most carefully designed set of experiments could give misleading results as variables interact with each other in a complicated manner. Many researchers [96-98] have reported the use of factorial technique for experimental tests. To design such factorial experiment, the reader may refer to "Quality Control and Industrial Statistics" by Duncan [193]. An experiment tests was designed for PIKBES; a factorial experiment design for 2 and 3mm square-butt joints and for 4,5,6,8,10,12mm V-butt joints.

1) Square butt Joints

In the factorial experiment designed for square-butt joints of 2mm and 3mm plate thickness only one joint variable (gap (G)) is explored at five tolerance levels, with five types of response measurement. Therefore, one joint variable, five tolerance levels, two different plate thicknesses gave $2 \times 5^1 = 10$ experiment tests. These tests were also ideally concerned with five welding variables at three levels. However, Five welding variables at three levels give $10 \times 3^5 = 2430$ experiment tests for only 2mm and 3mm square butt joints. There is no advantages of carrying out such experiments as this would end up with traditional mathematical modelling development. Therefore

the tests were reduced by using magnitudes of welding variables expected to provide satisfactory penetration and weld bead geometry. For each of these ten tests welding variables and their magnitude were selected according to the expert rules relating weld variables to joint area ratio. Tests which resulted in unsatisfactory welds were indicative of errors in the welding variable rules. Through further consultation with the welding experts the rules were modified and the test repeated. This iterative procedure was carried out until all rules have shown to produce satisfactory welds, a total of 20 tests was carried out. Details of the rules developed have been discussed in chapter 6 section 6.6.2. Table 7.1 (a) and (b) shows respectively one joint variable at five tolerance levels and five welding variables at different magnitude for 2mm square-butt joint. The tolerance levels were: expertly established gap absolute lower limits (RG_ABSLL) or 'level 3'; established modified BS 5135 tolerance gap lower limits (RG_LOLIM) or 'level 1' [4], nominal joint gap, established BS tolerance gap upper limits (RG_UPLIM) or 'level 1', and finally expertly established gap absolute upper limits (RG_ABSUL) or 'level 3'. For ease of recording and processing the experimental data, levels of joint variable were coded as -2, -1, 0, +1, +2 and levels of welding variables were respectively coded as -1,0,+1. When welding variables TS and/or WFS are modified, the modification may lie between the upper and lower magnitudes (i.e. medium magnitudes). Therefore, for clarity of these values, the actual value of variables are sometimes recorded instead of coded values. For example, the torch speed variable for 2mm plate thickness varies between 25m/min to 72m/min whereas other variables are used at their lower or higher levels with exception of voltage and stand-off distance. Table 7.3 shows this together with the factorial experiment design tests used. This is a block of 5 treatment combinations. Table 7.2 and 7.4 also show the treatment combinations for 3mm square-butt joint.

2) One-sided V-butt Joints

A factorial experiment is designed for 4 to 12mm thicknesses (i.e. 4, 5, 6, 8, 10, and 12mm) one-sided V_butt joints. In the design, three joint variables RG, RFT, BV at five tolerance levels, five welding variables at different magnitudes, with five types of response measurement are considered. Utilising their interaction effects, three joint variable, five tolerance levels, six different plate thickness would give $6 \times 5^3 = 750$ experiment tests. These tests were also ideally concerned with five welding variables at three levels. However, five welding variables at three levels would give $750 \times 3^5 = 182250$ experiment tests for 4 to 12mm one-sided V-butt joints. There is no advantages of carrying out such experiments as this would end up with traditional

(a)

No.	Variable Factor	Unit	Levels				
			Absolute Lolim	BS5135 Lolim	Nominal	BS5135 Uplim	Absolute Uplim
1	Gap (G)	mm	0	0.25	0.5	0.75	1.25
			-2	-1	0	+1	+2

(b)

No.	Variable Factors	Unit	Magnitude		
			Low	Medium	High
1	TS	m/min	25	52-62	72
2	WFS	cm/min	3.1	-	5.1
3	V	volts	17	-	21
4	TA	deg.	70	-	90
5	SO	mm	15	-	17
			-1	0	+1

Weaving

Weave Pattern (WP) No. 2

$$\text{Weave Amplitude (WA)} = (\text{RG}/2 + 2 \times \text{wire diameter})/0.1$$

$$= 25 \text{ units (0.1mm/unit)}$$

$$\text{Weave Frequency (WF)} = 18 \text{ units (0.1 Hz/unit)}$$

(This is a maximum frequency).

Table (7.1) - Shows (a) - one joint variable at five tolerance levels for 2mm square-butt joint and (b)- welding parameter s at different magnitude.

(a)

No.	Variable Factor	Unit	Levels				
			Absolute Lolim	BS5135 Lolim	Nominal	BS5135 Uplim	Absolute Uplim
1	Gap (G)	mm	0	0.5	1	1.5	1.55
			-2	-1	0	+1	+2

(b)

No.	Variable Factors	Unit	Levels		
			Low	Medium	High
1	TS	m/min	30	42 - 56	57
2	WFS	cm/min	7.8	-	7.8
3	V	volts	17	-	21
4	TA	deg.	70	-	90
5	SO	mm	15	-	17
			-1	0	+1

- No weaving used.

Table (7.2) - Shows (a) - one joint variable at five tolerance levels for 3mm square-butt joint and (b)- welding parameters at different magnitude.

No.	TS (cm/min)	WFS (m/min)	V (volts)	TA (deg)	SO (mm)	G (mm)	Area Ratio	Rule No.	WP	WA (unit)	WF (unit)
1	51.75	+1	+1	-1	-1	-2	0	10	-	-	-
2	61.61	+1	+1	-1	-1	-1	0.55	10	-	-	-
3	72	+1	+1	+1	-1	0	1.1	WRAPS welding proc. (nom.)	-	-	-
4	72	+1	+1	+1	-1	+1	1.65	11	-	-	-
5	25	-1	+1	-1	-1	+2	2.75	11	2	25	18

Table (7.3) - 5¹ factorial experiment tests for 2mm square-butt joint (using table 7.1).

No.	TS (cm/min)	WFS (m/min)	V (volts)	TA (deg)	SO (mm)	G (mm)	Area Ratio	Rule No.	WP	WA (unit)	WF (unit)
1	30	+1	+1	-1	-1	-2	0	12	-	-	-
2	42.46	+1	+1	-1	-1	-1	0.5	12	-	-	-
3	57	+1	+1	+1	-1	0	1.066	WRAPS welding proc. (nom.)	-	-	-
4	56.62	+1	+1	+1	-1	+1	1.60	13	-	-	-
5	55.10	+1	+1	+1	-1	+2	1.65	13	-	-	-

Table (7.4) - 5¹ factorial experiment tests for 3mm square-butt joint (using table 7.2).

mathematical modelling development. Therefore, the tests were reduced by using different magnitude of welding variables expected to provide satisfactory penetration and weld bead geometry.

Following discussions with experts, it has been decided that bevel angles could be kept at nominal reducing the experiment to a 6×5^2 factorial experiment. i.e. the total experiment tests for six different plate thicknesses will be; $6 \times 5^{3-1} = 150$. Bevel angles have an effect on weld penetration but their effects are insignificant compare to RG and RFT within the range of angles and tolerance considered. In contrast, bevel angles have a large effect on weld bead geometry.

The 150 treatment combinations were divided into 6 blocks of 25 treatment combinations. Table 7.6 and 7.8 shows blocks of treatment combinations for 4 and 5mm V-butt joints, whereas, table 7.5 and 7.7 shows joint and welding variables at their different magnitudes together with weaving parameters. The remaining 4 blocks of 25 treatment combinations for 6,8,10,12mm V-butt joints are given in appendix A8. Each block corresponds to about two weeks of intensive work. This includes cutting, machining of plate edges, welding, etc.

A further 40 experiment tests were necessary to refine welding variable rules. 40 experimental tests of five welding variables at different magnitudes (low, medium, high) during knowledge base refinement, a total of 190 experiment tests were performed for 4 to 12mm with V-butt joints.

Experimental tests were carried out on two techniques. That is 'window' and 'linear relationship' techniques. These experiments are discussed in section 7.7. The detailed information about these two techniques are discussed in chapter 6, section 6.6.1 and 6.6.2.

7.4 Plate Edges Preparation

After the joint variables and their tolerance levels, and their treatment combinations at different levels are identified, the plate edges were cut, machined, and prepared for testing. The prepared plates had a size 30mm (+_ 2mm) width and 100mm (+_ 10mm) long. The longer face edges of plates were first ground straight and parallel on both side. The machining accuracy was 0.001 of an inch (0.0254mm). The plate edge bevels were then machined by milling machine which gave root face

(a)

No.	Variable Factor	Unit	Levels				
			Absolute Lolim	BS5135 Lolim	Nominal	BS5135 Uplim	Absolute Uplim
1	RG	mm	0	0.5	1	1.5	1.55
2	RFT	mm	0	0.5	1	1.5	1.75
3	BV	deg.	25	27.5	30	32.5	35
			-2	-1	0	+1	+2

(b)

No.	Variable Factors	Unit	Magnitude		
			Low	Medium	High
1	TS	m/min	12	13 - 18	20
2	WFS	cm/min	-	5.08	-
3	V	volts	17	-	21
4	TA	deg.	70	-	90
5	SO	mm	15	-	17
			-1	0	+1

Weaving

Weave Pattern (WP) No. 2

Weave Amplitude (WA) = 10 units (0.1mm/unit)

Weave Frequency (WF) = 10 units (0.1 Hz/unit)

Table (7.5) - Shows (a) - one joint variable at five tolerance levels for 4mm V-butt joint and (b) - welding parameters at different magnitude.

No.	TS (cm/min)	WFS (m/min)	V (volts)	TA (deg.)	SO (mm)	RG (mm)	RFT (mm)	Area Ratio (mm)	Rule No.	WP	WA (Unit)	WF (Unit)
1	12.8	0	+1	+1	-1	-2	0	0.64	21	WRAPS weld. Proc. (nominal)	-	-
2	15.6	0	+1	+1	-1	-1	0	0.78				
3	20	0	+1	+1	-1	0	0	1.19				
4	20	0	+1	+1	-1	+1	0	1.21				
5	15.96	0	+1	+1	-1	+2	0	1.35	22			
6	17.89	0	+1	+1	-1	-2	-2	1.1	35	-	-	-
7	18	0	+1	+1	-1	-1	-2	1.33	36	2	10	10
8	18	0	+1	+1	-1	0	-2	1.56	36			
9	18	0	+1	+1	-1	+1	-2	1.79	36			
10	18	0	+1	+1	-1	+2	-2	1.90	36			
11	16	0	+1	+1	-1	-2	-1	0.85	35	-	-	-
12	17	0	+1	+1	-1	-1	-1	1.06	35	2	10	10
13	18	0	+1	+1	-1	0	-1	1.32	36			
14	18	0	+1	+1	-1	+1	-1	1.46	36			
15	18	0	+1	+1	-1	+2	-1	1.66	36			
16	12	0	+1	+1	-1	-2	+1	0.45	33	-	-	-
17	15	0	+1	+1	-1	-1	+1	0.68	33			
18	18	0	+1	+1	-1	0	+1	0.91	34			
19	18	0	+1	+1	-1	+1	+1	1.14	34			
20	20	0	+1	+1	-1	+2	+1	1.16	34			
21	12	0	+1	+1	-1	-2	+2	0.37	33	-	-	-
22	15	0	+1	+1	-1	-1	+2	0.6	33			
23	18	0	+1	+1	-1	0	+2	0.83	33			
24	18	0	+1	+1	-1	+1	+2	1.06	34			
25	18.37	0	+1	+1	-1	+2	+2	1.086	34			

Table (7.6) - 6×5^2 factorial experiment tests (block 1) for 4mm V-butt joint using table 7.5.

(a)

No.	Variable Factor	Unit	Levels				
			Absolute Lolim	BS5135 Lolim	Nominal	BS5135 Uplim	Absolute Uplim
1	RG	mm	0	0.5	1	1.5	1.75
2	RFT	mm	0	0.5	1	1.5	1.75
3	BV	deg.	25	27.5	30	32.5	35
			-2	-1	0	+1	+2

(b)

No.	Variable Factors	Unit	Magnitude		
			Low	Medium	High
1	TS	m/min	11	12 - 14	15.96
2	WFS	cm/min	5.08	5.1 - 5.6	5.7
3	V	volts	17	-	21
4	TA	deg.	70	-	90
5	SO	mm	15	-	18
			-1	0	+1

Weaving

Weave Pattern (WP) No. 2

Weave Amplitude (WA) = Varies with variation in RG
= 18 - 29 units (0.1mm/unit)

Weave Frequency (WF) = 10 units (0.1 Hz/unit)

Table (7.7) - Shows (a) - one joint variable at five tolerance levels for 5mm V-butt joint and (b)- welding parameters at different magnitude.

No.	TS (cm/min)	WFS (m/mim)	V (volts)	TA (deg.)	SO (mm)	RG (mm)	RFT (mm)	Area Ratio (mm)	Rule No.	WP	WA (Unit)	WF (Unit)
1	-1	+1	+1	-1	-1	-2	0	0.715	23			
2	+1	+1	+1	-1	-1	-1	0	1.081	23			
3	+1	+1	+1	+1	-1	0	0	1	WRAPS weld. Pro. (nominal)	-	-	-
4	+1	+1	+1	+1	-1	+1	0	1.26	25			
5	13.48	+1	+1	+1	-1	+2	0	1.35	25			
6	13	-1	+1	-1	-1	-2	-2	1.097	40	-	-	-
7	14	-1	+1	+1	-1	-1	-2	1.28	41	2	23- 29	10
8	14	-1	+1	+1	-1	0	-2	1.46	41			
9	14	-1	+1	+1	-1	+1	-2	1.64	41			
10	14	-1	+1	+1	-1	+2	-2	1.73	41			
11	13	5.6	+1	-1	-1	-2	-1	0.89	39	2	18- 19	10
12	13	5.3	+1	-1	-1	-1	-1	1.08	39			
13	14	-1	+1	+1	-1	0	-1	1.26	41			
14	14	-1	+1	+1	-1	+1	-1	1.44	41			
15	14	-1	+1	+1	-1	+2	-1	1.53	41			
16	-1	5.6	+1	-1	-1	-2	+1	0.55	37			
17	-1	5.3	+1	-1	-1	-1	+1	0.73	37			
18	-1	-1	+1	-1	-1	0	+1	0.92	37	-	-	-
19	13	-1	+1	+1	-1	+1	+1	1.103	35			
20	13	-1	+1	+1	-1	+2	+1	1.19	35			
21	-1	5.6	+1	-1	-1	-2	+2	0.48	37			
22	-1	5.3	+1	-1	-1	-1	+2	0.66	37			
23	-1	-1	+1	-1	-1	0	+2	0.85	37	-	-	-
24	13	-1	+1	-1	+1	+1	+2	1.031	38			
25	13	-1	+1	+1	-1	+2	+2	1.12	38			

Table (7.8) - 2^2 factorial experiment tests (block 2) for 5mm V-butt joint using table 7.7.

thicknesses accuracy of $\pm 0.1\text{mm}$ and bevel angles accuracy of ± 1 degree. 230 pairs of test specimens with different combination of plate thicknesses (2-12mm), root face thicknesses and bevel angles were prepared.

Root gap and root face thickness only are considered in this investigation. Tests were then performed on plate thickness of 2 and 3mm square-butts and 4 to 12mm one-sided single V-butts using robotic GMAW process, Ar 20% Co₂ gas and 1mm wire diameter electrode.

7.5 Preparation of Weld Tests

After all plate edges were machined, they were degreased using "Genklene" solvent. Each pair of plates were clamped using J-clamp and tack welded using manual gas metal arc welding kit. The tack welds are used in order to eliminate any dislocation movement and variation in the joint gap during the test welding process which may be caused from the heat input to the prepared plates. Shims are also used to control the gap/root gap of prepared joint during experimental tests. Although, this is not a practical way of controlling the joint gap/root gap by manufacturers, from an experimental point of view this was necessary in order to eliminate shrinkage at joint gap/root gap since it was clear that the narrow test specimens was more liable to distortion than would normally be encountered in practice. The gap/root gap was measured using slip gauges. This was done before and after joints were tack welded for each pair of joints to make sure that there was no error in experiment test specimens.

7.6 Quality Assessment Techniques

The following sequences were adopted for examination of the test runs:

- a) Visual inspection of both the surface bead and under bead,
 - b) Cross Sectioning the weld bead for macroscopic examination,
 - c) Radiographic examination of test runs to detect any discontinuities including cracks, porosity, lack of fusion, incomplete penetration, etc.
- Figure 7.7 (a) and (c) show typical radiographs.

7.7 Welding Experiment Tests

Initially, all nominal joints were test welded using their nominal welding procedures to confirm the validity of manual GMA welding standard data [189] for the mechanised GMA welding process. The results of these tests were a sound weld bead geometry with adequate weld penetration. Fig 7.3 (a) shows the test for nominal 2mm square-butt joint (gap = 0.5mm) using nominal welding procedures.

Following these tests and after discussion with welding experts BS 5135 tolerance limits were modified to $\pm 0.25\text{mm}$ for 2mm square-butt joint, $\pm 0.5\text{mm}$ for 3mm square-butt joint, and $\pm 0.5\text{mm}$ for V-butt joints when using a mechanised welding process. Furthermore, nominal welding procedures for different plate thicknesses and joint types were tested for joints at their established British Standard (BS5135) tolerance limits. The result showed that for most plate thicknesses the establish BS lower tolerance limits on gap/root gap had to be changed so that earlier modification of welding procedures takes place. This is accomplished by raising the lower tolerance limit on joint gap/root gap to the same as nominal gap/root gap value for each different joint. If the actual joint gap/root gap decreases below the nominal gap/root gap, modification of welding procedures will start. Fig 7.3(b) and (c) shows the experiment tests on British Standard lower tolerance limit for 2mm square-butt joint gap before and after modification of gap limits.

Nominal welding procedures were also tested at different plate thicknesses when the joints were at their British Standard upper tolerance limits. The test results showed that for all plate thicknesses and joint types satisfactory weld bead geometry was achieved. Fig 7.4 (a), (b), and (c) shows this for 3mm square-butt joint, and 4mm and 5mm V-butt joints.

Nominal welding procedures were tested for number of joints at intermediate tolerance level. This test was carried out in order to observe whether nominal welding procedures would produce satisfactory weld bead geometry at these levels. The test results showed that using nominal welding procedures, increase in joint gap will result in external undercut and excessive weld penetration, fig 7.5 (a). Further increase in joint gap resulted in weld burn-through. However, when the joint gap was reduced to less than the established British Standard lower tolerance limit and welded using the nominal welding procedures, this resulted in lack of penetration even when torch drag angle (torch travel angle of 70 degree from horizontal) was used. Fig 7.5 (b) and (c) shows the cross-section of welded joints for 2mm and 3mm square-butt joints.

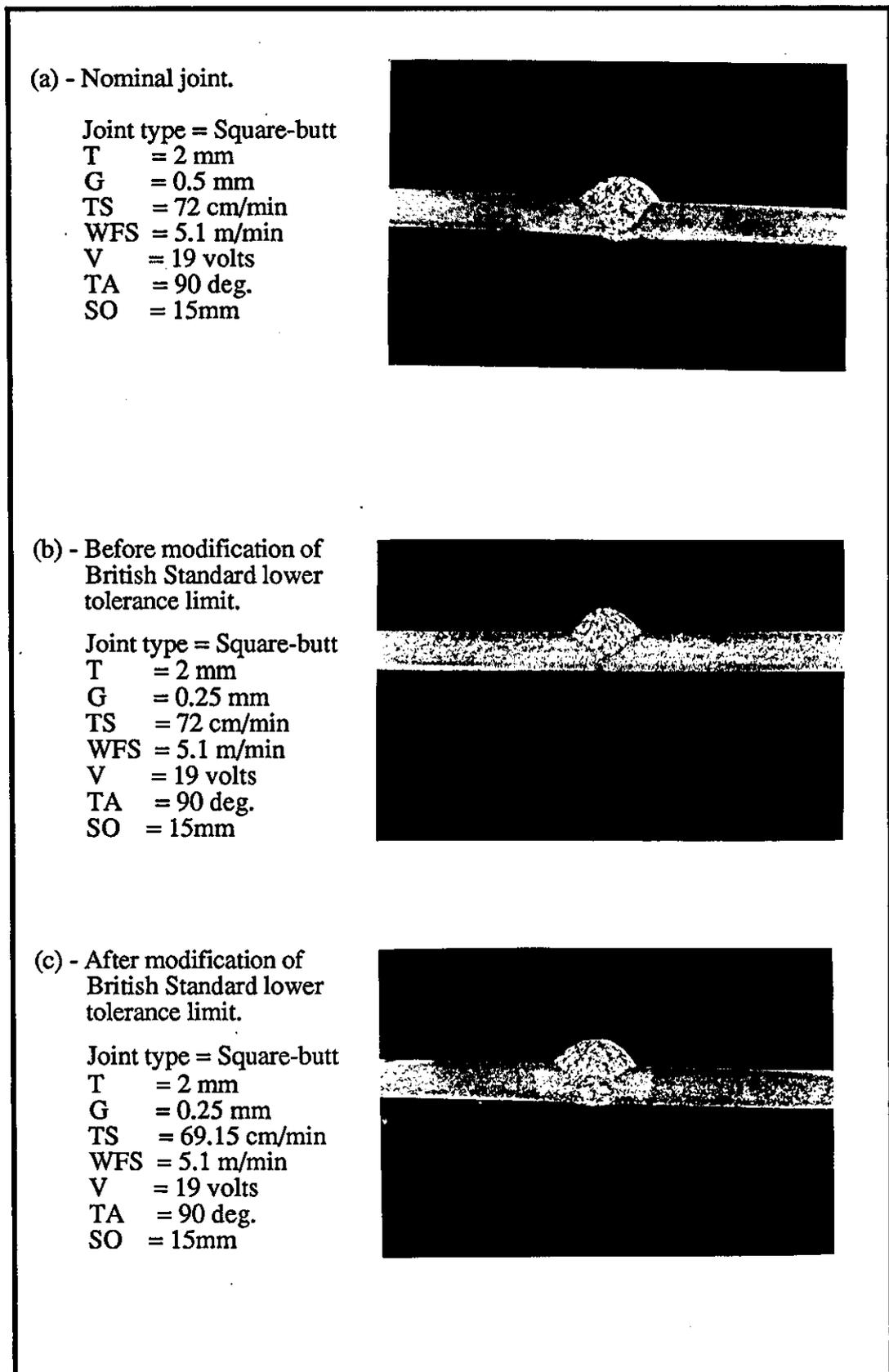


Fig (7.3) - Shows weld cross-section of experiment tests.

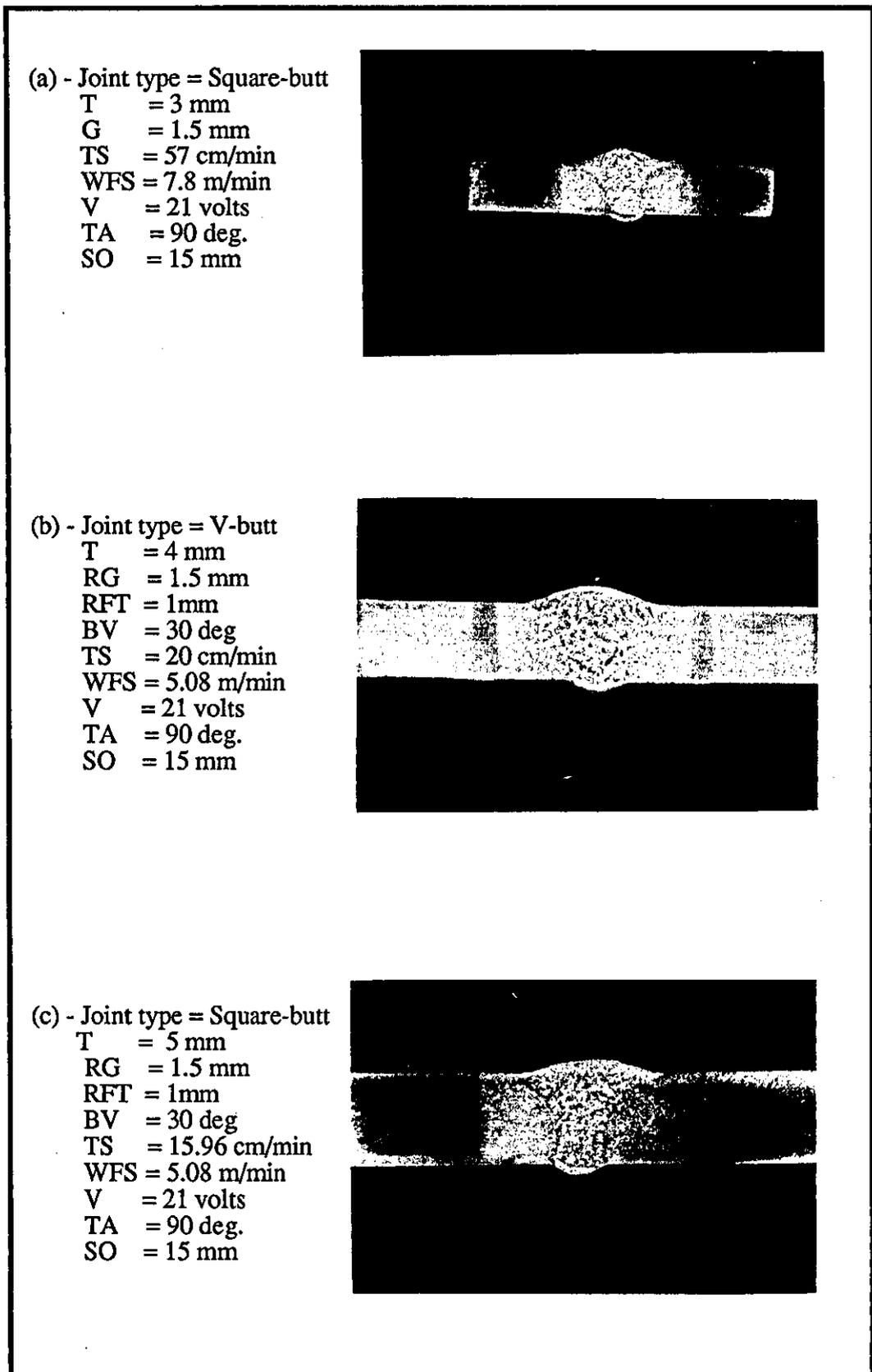
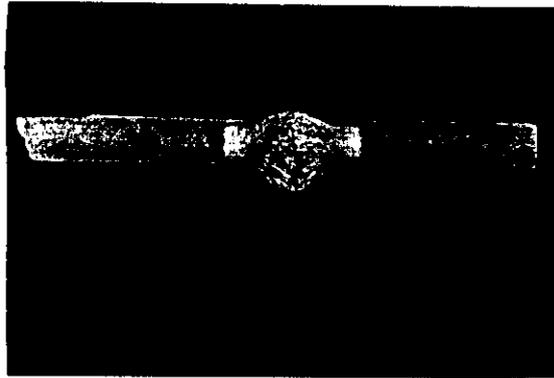


Fig (7.4) - Shows weld cross-section of experiment tests on British Standard upper tolerance limits using nominal welding procedure.

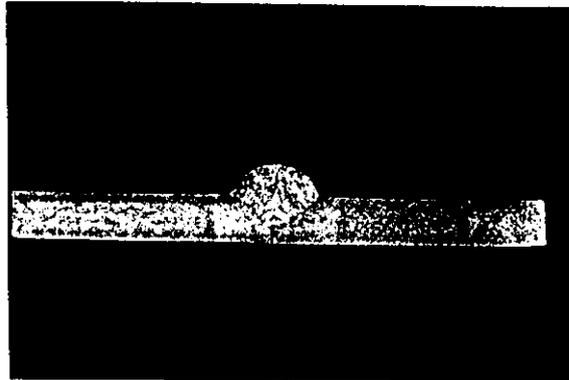
(a) - Joint type = Square-butt

T = 2 mm
 G = 1 mm
 TS = 72 cm/min
 WFS = 5.1 m/min
 V = 19 volts
 TA = 90 deg.
 SO = 15 mm



(a) - Joint type = Square-butt

T = 2 mm
 G = 0
 TS = 72 cm/min
 WFS = 5.1 m/min
 V = 19 volts
 TA = 70 deg.
 SO = 15 mm



(c) - Joint type = Square-butt

T = 3 mm
 G = 0
 TS = 57 cm/min
 WFS = 6.5 m/min
 V = 21 volts
 TA = 70 deg.
 SO = 15 mm

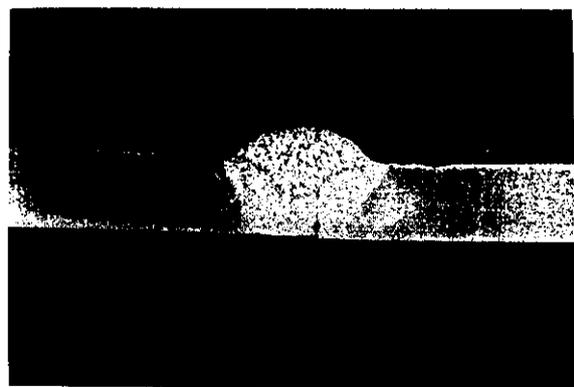


Fig (7.4) - Shows weld cross-section of experiment tests for joint at intermediate level (level 3) using nominal welding procedures.

7.7.1 Welding Experiments on 'Window' Technique

A number of treatment combination test cases were used to evaluate the 'window' modelling technique. A test case with 2mm square-butt joint at its absolute lower limit (i.e. gap is zero (or RG_ABSLL = 0)) was presented to PIKBES. PIKBES consultation result showed that the welding procedure had to be modified as a result of increase in joint metallic area within the 'window' (chapter 6 section 6.6.1 has already discussed this technique). The consultation display resulting from PIKBES are shown below:

```
*****
      USE MODIFIED WELDING PROCEDURE BELOW
*****
PALLET NUMBER      (pallet number) = 3
JOB NUMBER         (job number)    = 2
RULE NUMBER        (Rule_num)      = RULE_1
AREA RATIO         (X)              = 0
TORCH MOTION       (torch_motion)  = LINEAR
WEAVE AMPLITUDE   (weave amp)      = unknown unit (0.1mm/unit)
WEAVE FREQUENCY   (weave fre)      = unknown unit (0.1Hz/unit)
TORCH SPEED        (TS)             = 54 cm/min
WIRE FEED SPEED   (WFS)            = 5.1 m/min
VOLTAGE           (Voltage)        = 19 volts
TORCH ANGLE       (Torch_Angle)    = 70 degree (drag)
TORCH STAND OFF   (Stand_Off)      = 15 mm
*****
```

PIKBES was asked to justify its course of action. This was presented as below:

Name: RULE_1 & RULE_4

Kind of entity: Production Rule

```
if RG_act le RG_LOLIM and
   A_metact gt A_metnom
```

```
then
```

```
    TS      = TS_act.
```

```
    WFS     = WFS_nom.
```

```
    Voltage = V_nom.
```

```
endif.
```

```
if TS le TS_min
```

```
then
```

```
    TS      = TS_max.
```

```
    WFS     = ((2-X)+0.4)*WFS_nom.
```

```
endif.
```

{explanation:"RULE_1: For plate thicknesses, if the actual gap/root gap ",
 "become less than or equal gap/root gap lower limit and ",
 "the actual metallic area is greater than the nominal metallic",
 "area, then: ",
 " - Torch speed (TS) has to be reduced to keep nominal specific",
 " energy constant.",
 " - Wire feed speed (WFS) has to be kept the same as nominal.",
 " - Voltage (Voltage) has also to be kept the same as nominal."}

" " ,
 " NB - The minimum value which torch speed can reduce to, should",
 " not be less than 40% of nominal torch speed (i.e. TS_min ",
 " = 0.6 TS_nom). Below this value WFS has to increase by",
 " 10%. " }.

The above modified welding procedures were tested using 2mm square-butt and MIG/MAG mechanised welding process. Fig 7.6(a) shows the cross-section of the test weld. The result shows inadequate weld penetration and excessive weld reinforcement (BH). The under weld bead is not in the form of continuous bead.

Inadequate joint penetration is undesirable, particularly if the root of the weld is subject to either tension or bending stresses. The unfused area permits stress concentrations that could cause failure of components. Even though the service stresses in the structure may not involve tension or bending at this point, the shrinkage stresses and consequent distortion of the parts during welding will frequent cause a crack to initiate at the unfused area [194]. The most frequently cause of this type of welding failure is an abnormally high rate of torch speed, or insufficient welding current (or wire feed speed).

A further test case carried out on 3mm closed square-butt joint (using the same 'window' technique) was tested. Here, the gap of square-butt joint was at its absolute lower limit (i.e. gap is zero (or RG_ABSLL=0)). The nominal welding procedures for this joint are; gap of 1mm, torch speed of 57 cm/min, wire feed speed of 7.8 mm/min, voltage of 21 volts, torch angle of 70-80 degrees, stand-off distance of 15mm. The consultation for this case with PIKBES is carried. PIKBES suggested that nominal welding procedures has to be modified. The result of this consultation is shown below:

USE MODIFIED WELDING PROCEDURE BELOW

PALLET NUMBER	(pallet number)	= 5
JOB NUMBER	(job number)	= 4
RULE NUMBER	(Rule_num)	= RULE_1
AREA RATIO	(X)	= 0
TORCH MOTION	(torch_motion)	= LINEAR
WEAVE AMPLITUDE	(weave amp)	= unknown unit (0.1mm/unit)
WEAVE FREQUENCY	(weave fre)	= unknown unit (0.1Hz/unit)
TORCH SPEED	(TS)	= 38 cm/min
WIRE FEED SPEED	(WFS)	= 7.8 m/min
VOLTAGE	(Voltage)	= 21 volts
TORCH ANGLE	(Torch_Angle)	= 70 degree (drag)
TORCH STAND OFF	(Stand_Off)	= 15 mm

PIKBES was asked to justify the result. The same justification as in the previous case was presented. The above modified welding procedures were tested. Fig 7.6(b) shows cross-section of welded joint test using above modified welding procedures. This result also shows inadequate weld penetration and excessive weld reinforcement.

This butt joint was also tested at joint gap absolute limits of just below British Standard lower limit (or RG_LOLIM=0.5mm). Hence, the square-butt joint with gap of 0.49mm was consulted with PIKBES. The consultation result suggested that the modified welding procedure has to be used. These procedures are shown below:

```
*****
      USE MODIFIED WELDING PROCEDURE BELOW
*****
PALLET NUMBER    (pallet number)  = 5
JOB NUMBER       (job number)     = 4
RULE NUMBER      (Rule_num)       = RULE_1
AREA RATIO       (X)              = 1.35
TORCH MOTION     (torch_motion)   = LINEAR
WEAVE AMPLITUDE (weave amp)       = unknown unit (0.1mm/unit)
WEAVE FREQUENCY (weave fre)      = unknown unit (0.1Hz/unit)
TORCH SPEED      (TS)             = 45.6 cm/min
WIRE FEED SPEED (WFS)            = 7.8 m/min
VOLTAGE          (Voltage)        = 21 volts
TORCH ANGLE      (Torch_Angle)    = 70 degree (drag)
TORCH STAND OFF (Stand_Off)       = 15 mm
*****
```

The above modified welding procedure was tested. Fig 7.6(c) shows the cross-section of weld for the above modified welding procedures. This result also shows inadequate weld penetration and excessive weld reinforcement.

The 'window' technique was also tested on the V-butt joints and it showed little success in producing an acceptable weld bead geometry. The 4mm V-butt joint test case at its root gap absolute lower limit (i.e. root gap of zero) was presented to PIKBES. Nominal joint parameters and welding parameters for 4mm V-butt joint are: root gap of 1mm, root face thicknesses 1mm, bevel angles 30 degree, torch speed of 20cm/min, wire feed speed of 5.08m/min, voltage of 21 volts, torch angle of 70-80 degree, and stand-off distance of 15mm. The PIKBES consultation result suggested that the nominal welding procedure has to be modified. The result of this modification is shown below:

```

*****
USE MODIFIED WELDING PROCEDURE BELOW
*****
PALLET NUMBER    (pallet number) = 5
JOB NUMBER       (job number)    = 4
RULE NUMBER      (Rule_num)       = RULE_1
AREA RATIO       (X)              = 1.35
TORCH MOTION     (torch_motion)   = LINEAR
WEAVE AMPLITUDE  (weave amp)      = unknown unit (0.1mm/unit)
WEAVE FREQUENCY  (weave fre)     = unknown unit (0.1Hz/unit)
TORCH SPEED      (TS)             = 11.12 cm/min
WIRE FEED SPEED  (WFS)            = 5.08 m/min
VOLTAGE          (Voltage)        = 21 volts
TORCH ANGLE      (Torch_Angle)    = 70 degree (drag)
TORCH STAND OFF  (Stand_Off)     = 15 mm
*****

```

Above modified welding procedures was tested. Fig 7.6(d) shows the cross-section of a weld produced using the above procedures. The result shows excessive weld penetration which is recognised as unacceptable. The most frequent cause of this type of failure is low torch speed or high welding current (wire feed speed).

The test results of this technique suggest that it may be worthy of further research and development to provide a general rule for modifying welding procedures. However, the technique or its rules have had little success in its application to PIKBES. Hence, more control over the heuristic rules regarding welding procedure modification is required.

7.7.2 Welding Experiments on 'Linear Relationship' Technique

The factorial experiment design (section 7.3.2) was used to develop, refine, and evaluate PIKBES using 'linear relationship' technique. 'Linear relationship' takes advantage of joint area ratio (the actual joint area over the nominal joint area (X)) and compensates for variation in the joint. This will be accomplished by means of linear relationships between welding parameters such as torch speed and/or wire feed speed, etc, and the joint area ratio (X). Chapter 6 section 6.6.2 has already discussed the use of this technique for development of rules in this research.

In the factorial experiment test cases for assessment of this technique, one joint variable at five levels for 2mm and 3mm square-butt, two joint variables at five levels for 4mm to 12mm V-butt joints, and five welding variables at three levels are considered. As mentioned above, all joints with their nominal welding procedures are

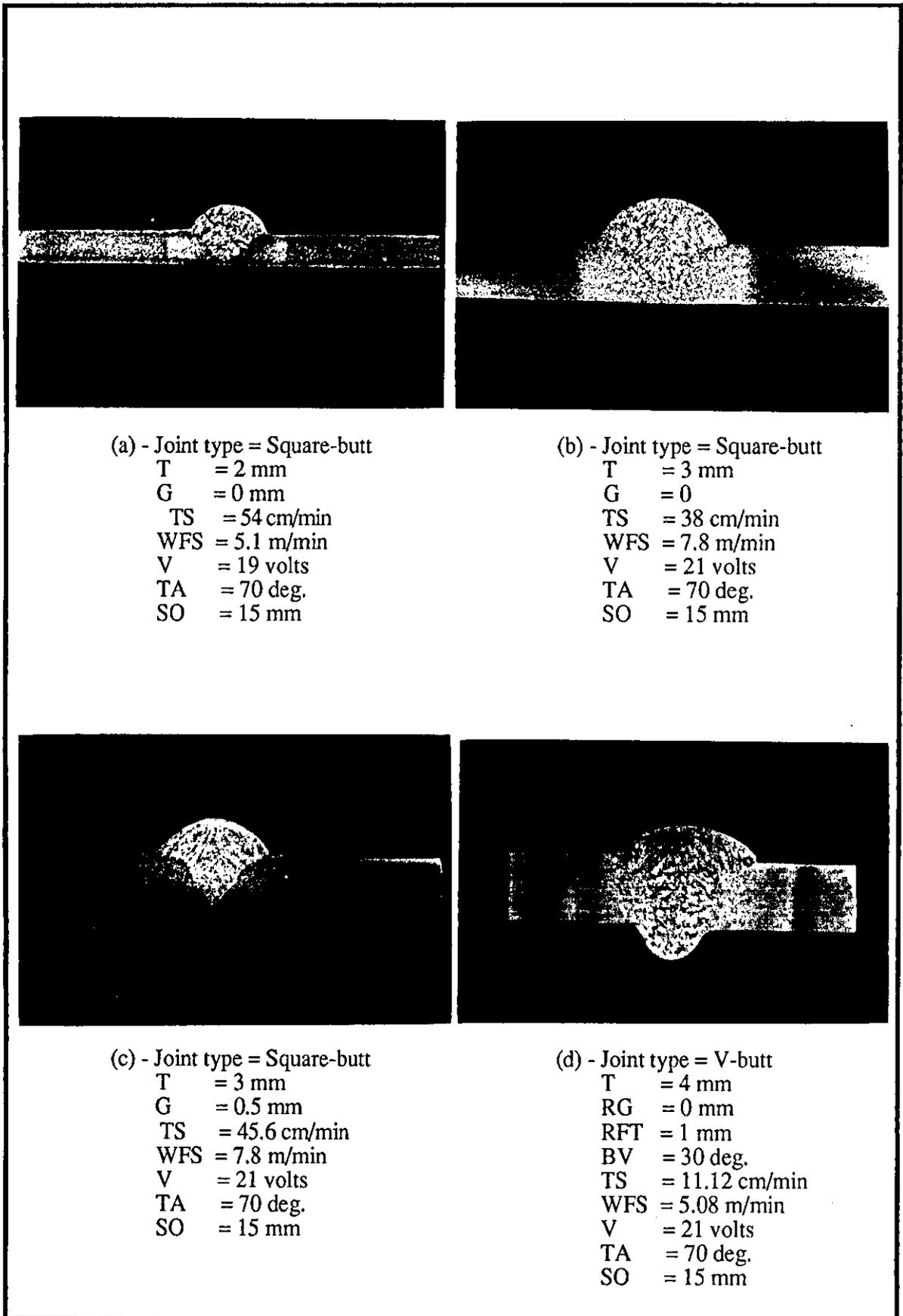


Fig (7.6) - Shows weld cross-section of test welds for 2, 3 and 4 mm Square and V butt joint using 'window' technique.

tested to confirm the established data for mechanised welding process used in this research. Furthermore, all joints at their British Standard (BS) upper and lower tolerance limits were also tested to confirm the validity of established tolerance for PIKBES and where it was necessary the BS lower tolerance limits were modified to provide early warning for modification of welding procedures.

The whole total of 90 rules were tested. 2mm square-butt joint test case with a gap of 1.25mm was initially tested through PIKBES. The consultation results from the system suggested that welding procedures have to be modified. This is shown below:

```
*****
USE MODIFIED WELDING PROCEDURE BELOW
*****
PALLET NUMBER    (pallet number) = 3
JOB NUMBER       (job number)    = 2
RULE NUMBER      (Rule_num)      = RULE_14
AREA RATIO       (X)             = 2.75
TORCH MOTION     (torch_motion)  = WEAVE PATTERN NO. 2
WEAVE AMPLITUDE (weave amp)     = 26.25 unit (0.1mm/unit)
WEAVE FREQUENCY (weave fre)     = 18 unit (0.1Hz/unit)
TORCH SPEED      (TS)           = 24.48 cm/min
WIRE FEED SPEED (WFS)          = 3.11 m/min
VOLTAGE          (Voltage)      = 19 volts
TORCH ANGLE      (Torch_Angle)  = 90 degree
TORCH STAND OFF (Stand_Off)     = 15 mm
*****
```

PIKBES was asked to justify its course of action. This was presented as shown below:

```
Name: RULE_14
Kind of entity: Production Rule
  if  T1_act gt 1.5 and T2_act gt 1.5      and
      T1_act le 2.5 and T2_act le 2.5    and
      RG_act gt RG_UPLIM                 and
      RG_act le RG_ABSUL                 and
      X gt 2                             and
      X le 3
  then
      Rule_num          = 14.
      result            = mod_wld_proc.
      torch_motion     = weave2.
      weave amp        = amplitude.
      weave fre       = 18.
      TS               = 0.34*TS_nom.
      WFS              = 0.61*WFS_nom.
      Voltage          = V_nom.
      Torch_Angle     = TA_nom.
      Stand_Off       = SO_nom.
  endif
```

```
{explanation:"RULE_14: For the plate thickness 2+_0.5mm. If the Actual Root",
"Gap (RG) is greater than Root Gap Upper Limit (RG_UPLIM) but",
"less than Root Gap Absolute Upper Limit (RG_ABSUL), and the",
"Actual joint area increases by more than 100% of the Nominal",
"joint area i.e. Root GAP=1.25 :-",
"* Torch Speed (TS) has to decrease by 66%. of nominal",
" Torch Speed (TS_nom).",
"* Wire Feed Speed (WFS) has to decrease by 39% of nominal.",
" Wire Feed Speed (WFS_nom).",
"* Torch Angle (TA) has to be kept the same."}.
```

Furthermore, the system was asked to provide supporting knowledge sources regarding weave amplitude. This is given as:

```
Name: Weave_amp
Kind of entity: Production Rule
    if  T1_act gt 1.5 and T2_act gt 1.5      and
        T1_act le 2.5 and T2_act le 2.5      and
        RG_act gt RG_UPLIM                    and
        RG_act le RG_ABSUL
    then
        amplitude = (RG_act/2 + 2*wire dia)/0.1.
    endif.
```

The above modified welding procedure was tested. Fig 7.7(b) shows the weld cross-section of the test using above modified welding procedure. The test results shows that a reasonable sound weld bead geometry and good weld penetration were achieved, but some undercut occurred. The radiograph of the welded joint also confirms this, fig 7.7(a).

A similar experiment was carried out for 3mm square-butt joint with a gap of 1.52mm. This gap was at intermediate level (level 3) and PIKBES suggested the modified welding procedure below should be used:

```
*****
USE MODIFIED WELDING PROCEDURE BELOW
*****
PALLET NUMBER    (pallet number) = 5
JOB NUMBER       (job number)    = 4
RULE NUMBER      (Rule_num)      = RULE_13
AREA RATIO       (X)              = 1.621
TORCH MOTION     (torch_motion)   = LINEAR
WEAVE AMPLITUDE (weave amp)       = unknown unit (0.1mm/unit)
WEAVE FREQUENCY (weave fre)       = unknown unit (0.1Hz/unit)
TORCH SPEED      (TS)              = 56.14 cm/min
WIRE FEED SPEED (WFS)              = 7.80 m/min
VOLTAGE          (Voltage)         = 21 volts
TORCH ANGLE      (Torch_Angle)     = 90 degree
TORCH STAND OFF (Stand_Off)        = 15 mm
*****
```

The above modified welding procedures was tested, fig 7.7(d) shows the weld cross-section of the test specimen. The test result shows that a sound weld bead geometry and good weld penetration was achieved. The radiograph of the above test also confirms this. This is shown in fig 7.7(c).

A total of 210 experiment test cases were tested for this technique. The test cases use 2mm and 3mm square-butt joints and 4mm, 5mm, 6mm, 8mm, 10mm, and 12mm V-butt joints with joint parameters gap/root gap and/or root face thicknesses at their different levels. During the experimental test, if any of the rules were found to produce a modified welding procedures which resulted in lack of weld penetration, under cut, burn-through, etc, the rule has been refined and tested again.

For 8mm to 12mm V-butt joints only the first weld run was carried out to test that weld penetration at the root could be achieved. Subsequent filling of these joints may be the subject of further research. Fig 7.8 and 7.9 show some of the weld cross-section of experiment test cases for 5mm and 6mm V-butt joints with the joints filled with one run, whereas for 8mm to 12mm V-butt joints only the first run was tested. All experiment test cases are at their intermediate tolerance level (level 3).

The 'linear relationship' technique is shown to be a successful technique. Most of the experimental test cases have shown that sound weld bead geometry and weld bead penetration can be achieved.

7.8 PIKBES/End-user Interaction Capability

PIKBES can operate in two modes. The first mode is designed for on-line quality control operation and does not provide the end-user with 'display' or 'interaction' facilities for consultation. The purpose is to provide on-line automatic communication with the pre-weld inspection station and WRAPS supervisory system. Automatic selection and running of the appropriate knowledge for different joint types is provide at this mode using 'level 1' embedding technique.

The second mode was designed to provide the end-user with a 'user-friendly' facility allowing manual interrogation of PIKBES. There are 'help' facilities such as 'display attachments', 'question' facilities which may be asked of the end-user if the system does not receive the required information from the inspection station or WRAPS supervisory system [1] (this is also provided in the first mode). 'Explanation'

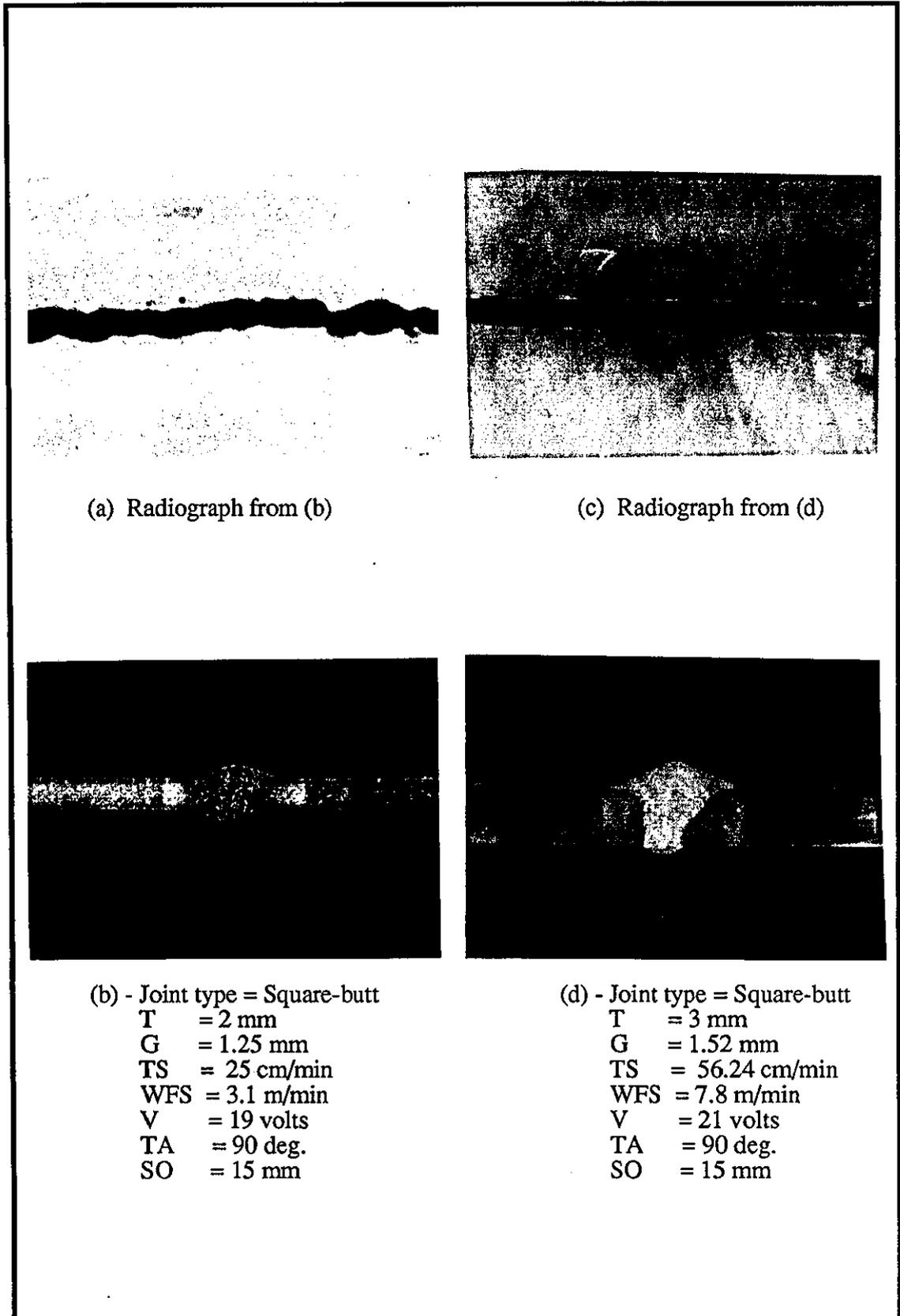
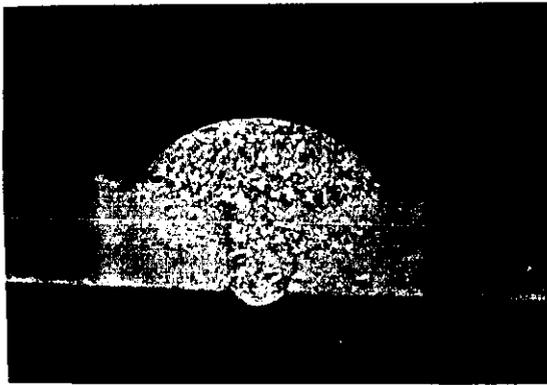
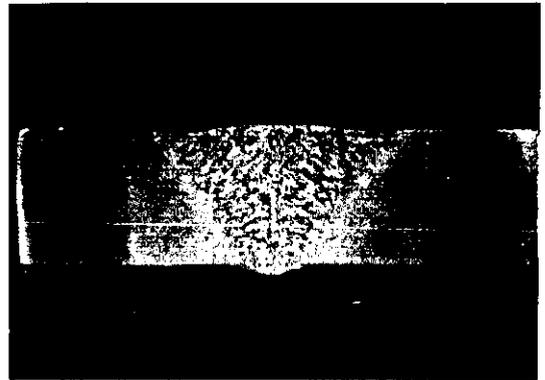


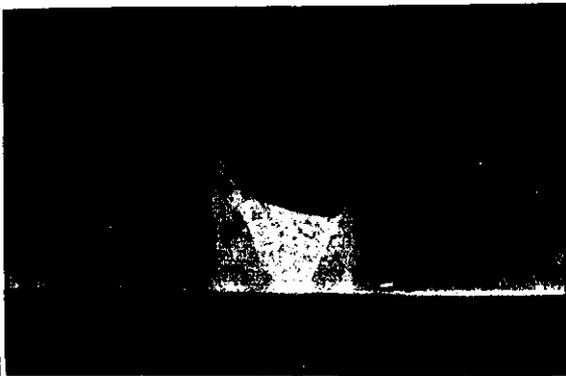
Fig (7.7) - Shows weld cross-section of test welds and their radiograph for 2mm and 3mm square-butt joints using 'linear relationship' technique.



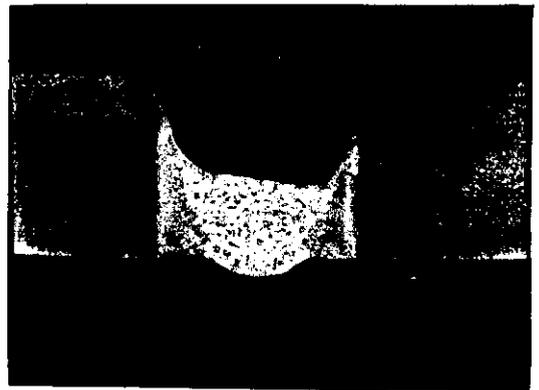
(a) - Joint type = V-butt
 T = 5 mm
 RG = 0
 RFT = 1.75 mm
 BV = 30 deg.
 TS = 11 cm/min
 WFS = 5.6 m/min
 V = 21 volts
 TA = 70 deg.
 SO = 17 mm



(b) - Joint type = V-butt
 T = 6 mm
 RG = 1.75 mm
 RFT = 0.5 mm
 BV = 30 deg.
 TS = 12 cm/min
 WFS = 5.2 m/min
 V = 21 volts
 TA = 90 deg.
 SO = 17 mm

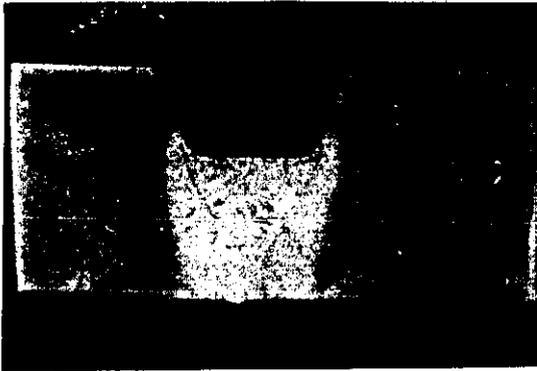


(c) - Joint type = V-butt
 T = 8 mm
 RG = 1 mm
 RFT = 1 mm
 BV = 30 deg.
 TS = 30 cm/min
 WFS = 5.08 m/min
 V = 21 volts
 TA = 70 deg.
 SO = 18 mm



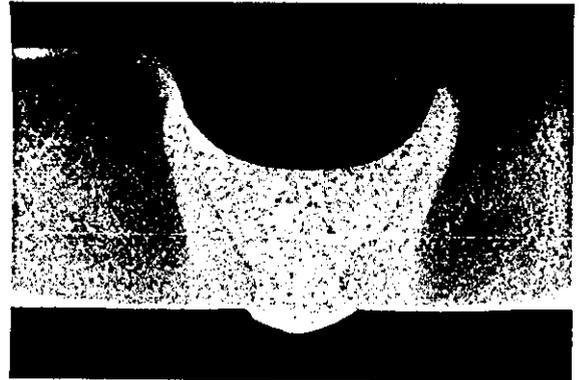
(d) - Joint type = V-butt
 T = 8 mm
 RG = 2.5 mm
 RFT = 0.5 mm
 BV = 30 deg.
 TS = 30 cm/min
 WFS = 6.5 m/min
 V = 21 volts
 TA = 90 deg.
 SO = 18 mm

Fig (7.8) - Shows weld cross-section of test welds for 5, 6, and 8mm V-butt joint using 'linear relationship' technique.



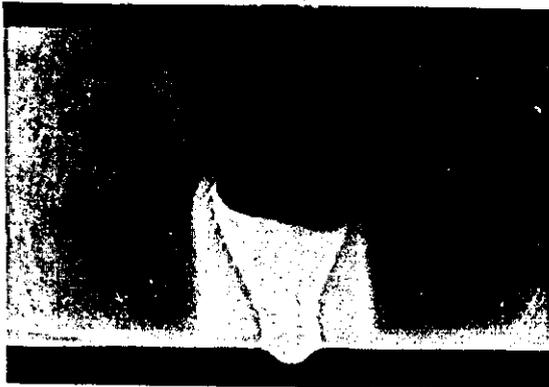
(a) - Joint type = V-butt

T = 10 mm
 RG = 1 mm
 RFT = 2 mm
 BV = 25 deg.
 TS = 37 cm/min
 WFS = 8.66 m/min
 V = 25 volts
 TA = 70 deg.
 SO = 18 mm



(b) - Joint type = V-butt

T = 10 mm
 RG = 2.5 mm
 RFT = 0.5 mm
 BV = 25 deg.
 TS = 21 cm/min
 WFS = 8.66 m/min
 V = 25 volts
 TA = 90 deg.
 SO = 18 mm



(c) - Joint type = V-butt

T = 12 mm
 RG = 2mm
 RFT = 2.5mm
 BV = 25 deg.
 TS = 40 cm/min
 WFS = 8.66 m/min
 V = 25 volts
 TA = 70 deg.
 SO = 19 mm



(d) - Joint type = V-butt

T = 12 mm
 RG = 2.5 mm
 RFT = 0.5 mm
 BV = 25 deg.
 TS = 30 cm/min
 WFS = 8.66 m/min
 V = 25 volts
 TA = 90 deg.
 SO = 19 mm

Fig (7.9) - Shows weld cross-section of test welds for 10mm and 12mm V-butt joint using 'linear relationship' technique.

and 'explain' facilities with which the end-user may obtain explanation of rules selected or questions asked, 'justify' facilities where justification of the course of action may be required, etc, are also provided. Appendix A9 shows typical help facilities used during PIKBES run-time. However, the second operation is evaluated and discussed thoroughly here with a view to show the interaction capability between PIKBES and the end-user.

To evaluate how well PIKBES interacts with the end-user a number of test cases were used. Test cases consisted of sets of data related to different joint type and parameters, and welding procedures submitted to PIKBES. These data are respectively assumed to be received from the pre-weld inspection station and WRAPS supervisory system. A typical example of these test cases are considered here to reveal the capability of PIKBES. This is shown below as:

Data from the
Pre-weld inspection station

Joint type = V_buttp_unback.
T1_act = 5.20.
T2_act = 5.30.
RG_act = 1.75.
RFT1_act = 0.00.
RFT2_act = 0.00.
BV1_act = 29.00.
BV2_act = 31.00.
AM1_act = 1.00.
AM2_act = 1.30.
A_act = 24.71.

Data from the WRAPS supervisory system

Welding process = MIG_MAG mechanised.
Root Run process = MIG_MAG mechanised.
Joint type = V_buttp_unback.
Welding position = Flat.
Material type = C_Mn steel.
British_std = BS5135.
wire dia = 1.00.
T_nom = 5.
RG_nom = 1.
RFT_nom = 1.
BV_nom = 30.%.
pallet number = 2.
job number = 3.
TS_nom = 15.96.
WFS_nom = 5.08.
V_nom = 21.
SO_nom = 15.%

All data entry to PIKBES is performed automatically via communication files, and the end-user is only required to enter data from the keyboard if any data in communication files is missing.

PIKBES is designed to be user friendly. An interactive session begins with a series of messages to the end-user. It begins by displaying the information regarding the KES expert system shell [129] and informs the end-user that the system is in process of 'loading' the required parsed knowledge base. Then, a welcome message (on page 1 of consultation display) and explanation regarding the purpose of PIKBES (page 2) are displayed to the end-user. Each display is provided in a page. The

explanation gives a brief introduction about the system so that the user can understand the nature and limitation of each knowledge base for the inspection station. An example of run-time display during above data consultation are shown below:

Knowledge Engineering System (KES), Release 2.5.
Copyright (C) 1988, Software Architecture & Engineering, Inc.
Loading the knowledge base 'd2.pkb'.

```
*****
*           Welcome to Pre_Inspection Knowledge           *
*           Base Expert System (P.I.K.B.E.S)             *
*****
*****
*
*           This is the pre_weld inspection knowledge base *
*           expert system (PIKBES). This knowledge base rule is *
*           only applicable to the mechanised MIG/MAG welding *
*           process for flat position one sided V_butt joints *
*           for C_Mn steels of 4-12mm plate thickness using *
*           British Standard BS5135. This knowledge base has *
*           been experimentally tested and validated. It uses *
*           expert knowledge and information collected from *
*           the pre-weld inspection station, WRAPS supervisory *
*           system, and WELDSPEC database, in order to modify *
*           welding procedure based on any out of tolerance *
*           variation found in the joint. The modified procedure *
*           will then be transferred to WRAPS overall supervisory *
*           system and then via peripheral Equipment Control and *
*           Interface Software (PECIS) to robot controller for *
*           welding.                                       *
*
*****
```

The actual joint parameters received from the inspection station are displayed in (page 3). This message/display is shown below for a joint in 5mm plate thickness with one-sided open V-butt in C_Mn steels:

```
*****
*           Actual Joint Parameters Received from the     *
*           Pre-Inspection Station                       *
*****
Actual Plate 1 Thickness      (T1_act)      = 5.20
Actual Plate 2 Thickness      (T2_act)      = 5.30
Actual Root Gap               (RG_act)      = 1.75
Actual Root Face Thickness 1  (RFT1_act)    = 0
Actual Root Face Thickness 2  (RFT2_act)    = 0
Actual Bevel Angle 1         (BV1_act)     = 29
Actual Bevel Angle 2         (BV2_act)     = 31
Actual Plate 1 Angular       (AM1_act)     = 1
Misalignment
Actual Plate 2 Angular       (AM2_act)     = 1.30
Misalignment
Actual Cross-Sectional Area  (A_act)       = 24.71
*****
```

Page 4 of the PIKBES consultation display informs the end-user about the lower and upper nominal tolerances established from BS 5135 (tolerance 'level 1'). This information is displayed to the user as shown below:

```
*****
*           Established Tolerances on Nominal Joint Parameters           *
*           using BS5135 (Tolerance 'Level 1')                          *
*****
Plate Thickness Lower Limit      (T_LOLIM)      = 4.5
Plate Thickness Upper Limit      (T_UPLIM)      = 5.5
Gap Lower Limit                  (RG_LOLIM)      = 1
Gap Upper Limit                  (RG_UPLIM)      = 1.5
Root Face Thicknesses           (RFT_LOLIM)     = 0.5
Lower Limit Root Face Thicknesses (RFT_UPLIM)  = 1.5
Upper Limit Bevel Angles Lower Limit (BV_LOLIM)  = 27.5
Bevel Angle Upper Limit         (BV_UPLIM)     = 32.5
Plate Angular Misalignment      (AM_LOLIM)     = 0
Lower Limit
Plate Angular Misalignment      (AM_UPLIM)     = 5
Upper Limit
*****
```

Enter your option:

1. Continue
2. Justify limits

=? 1

Following this page, a user will be given an opportunity to ask questions regarding the justification of lower and upper nominal limits, and tolerances on joint parameters. This opportunity is also given for lower and upper expertly established absolute limits which are retrieved from the WELDSPEC database [120]. Hence, in this way, it is possible for the user to trace and look at supporting knowledge sources and/or demons. As the consultation session goes ahead, data retrieval from the WELDSPEC database is displayed. This information helps the end-user to find the number of records stored, number of records found for the particular situation, and finally a record is selected. Data regarding absolute limits are displayed to the user. This is shown below.

The message command is used in the knowledge bases to display the above data regarding expertly established absolute tolerance (tolerance 'level 2') in a form readable to the end-user (page 5). This is shown below. This display is also used when a script of PIKBES run-time screen output is required to be saved in a file, because the above display can not be saved.

RETRIEVE OF DATA FROM 'WELDSEPC' DATA-BASE.

No. of Records Found = 3
Total Records Stored = 20

Record Found : TEXT0006.DAT

RG_ABSLL = 00
RG_ABSUL = 1.750
A_nom = 14.230
H_nom = 3.500
U_nom = 3.880
A_net = 6.4650
RFT_ABSLL = 00
RFT_ABSUL = 1.750
BV_ABSLL = 250
BV_ABSUL = 350

```
*****
*           Expertly Established Absolute Tolerances on Joint           *
*           Parameters (Tolerance 'Level 2')                             *
*****
Root Gap Abs. Lower Limit      (RG_ABSLL)      = 0
Root Gap Abs. Upper Limit     (RG_ABSUL)      = 1.75
Root Face Thickness           (RFT_ABSLL)      = 0
Abs. Lower Limit
Root Face Thickness           (RFT_ABSUL)      = 1.75
Abs. Upper Limit
Bevel Angle Abs. Lower Limit  (BV_ABSLL)      = 25
Bevel Angle Abs. Upper Limit  (BV_ABSUL)      = 35
Plate Angular Misalignment    (AM_ABSLL)      = 5
Abs. Lower Limit
Plate Angular Misalignment    (AM_ABSUL)      = 5
Abs. Upper Limit
*****
```

Enter your option:

1. Continue
2. Justify limits

=? 1

Finally, the conclusion from the consultation is displayed in page 6. An example is shown below and shows that the nominal welding procedures are required to be modified. The welding procedure data will be then automatically written into a communication file 'super.dat' and is ready to be transferred to WRAPS supervisory system.

```

*****
                USE MODIFIED WELDING PROCEDURE BELOW
                *****
PALLET NUMBER    (pallet number) = 2
JOB NUMBER       (job number)    = 3
RULE NUMBER      (Rule_num)      = RULE_41
AREA RATIO       (X)             = 1.736
TORCH MOTION     (torch_motion)  = WEAVE PATTERN NO. 2
WEAVE AMPLITUDE (weave amp)     = 28.75 unit (0.1mm/unit)
WEAVE FREQUENCY (weave fre)    = 10 unit (0.1Hz/unit)
TORCH SPEED      (TS)          = 14.36 cm/min
WIRE FEED SPEED (WFS)         = 5.08 m/min
VOLTAGE          (Voltage)     = 21 volts
TORCH ANGLE      (Torch_Angle) = 90 degree
TORCH STAND OFF (Stand_Off)    = 10.25mm
*****

```

After the consultation is completed, the user will be asked to enter one of five options;

- 1) shows the supporting knowledge source(s) followed with the explanation of the course of action.
- 2) The system will ask the user to type: justify attribute-name (or parameter name), in order to provide justification for the required attribute-name.
- 3) Pass the command to the command line (i.e. Ready for command:).
- 4) restarts a new consultation session.
- 5) ends consultation session and exit the PIKBES.

At (2) and (3) the user can use three especially useful KES commands for evaluation of the user interaction with PIKBES. These commands are, display tree, display attribute, and justify which has been implemented in PIKBES to provide better interaction with the user. An example of this is also shown below:

```

What would you like to do ?
1. Justify the result
2. Justify each parameter
3. Command line
4. New case
5. Quit
=? 1

```

If the user requests justification of the result, the system provides the user with the rule number. Furthermore, the user can request for display of the supporting knowledge source.

```

*****
The justification is:
*****

```

Rule_num = 41

Reasons for belief:rule: RULE_41

Would you like to see the supporting knowledge sources and demons? (y/n) y

The rule which supported the conclusion can then displayed as below together with explanation of the rule:

Name: RULE_41

Kind of entity: Production Rule

```

if  T1_act gt 4.5 and T2_act gt 4.5          and
    T1_act le 5.5 and T2_act le 5.5          and
    RG_act le RG_nom                          or
    RG_act gt RG_nom                          and
    RFT1_act lt RFT_LOLIM and RFT1_act ge RFT_ABSLL and
    RFT2_act lt RFT_LOLIM and RFT2_act ge RFT_ABSLL and
    X gt 1.2                                   and
    X le 2

```

then

```

Rule_num          = 41.
result            = mod_wld_proc.
torch_motion      = weave2.
weave amp         = amplitude.
weave fre         = 10.
run_num           = run_no1.
TS                = 0.9*TS_nom.
WFS               = WFS_nom.
Voltage           = V_nom.
Torch_Angle       = TA_nom.
Stand_Off         = stand off1.

```

endif

```

{explanation:"RULE_36: For the plate thickness 5+_0.5mm. If ",
  "the Root Face Thicknesses are less than RFT Lower Limit",
  "(RFT_LOLIM) but greater than or equal RFT ABSolute Lower Limit",
  "(RFT_ABSLL), and the Actual joint area increases by more than",
  "20% of the Nominal joint area :-",
  " ",
  " * Torch Speed (TS) has to decrease by 10%.",
  " * Wire Feed Speed (WFS) has to be kept the same as nominal.",
  " * Torch Angle (TA) has to be kept the same as nominal.",
  " * WEAVING PATTERN NO. 2 has been used (Ref.User's Manual",
  " page(193).",
  " - Weave Amplitude = half of actual Root Gap + ",
  "   two wire diameter if actual RFT < half RFT ",
  "   Lower Limit and one wire diameter if actual RFT",
  "   > RFT Lower Limit.", " - Weave Frequency = 10"}.
```

To justify any parameters (or attributes) type: justify
parameter_name (or attribute_name) at 'Ready for command:
'line (e.g. justify RG_LOLIM)

Otherwise type: 'c' to continue, 'n' to start again, or 's' to quit.

Ready for command: s

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At this point, the end-user consultation with PIKBES will be completed. If the end-user still requires to consult with PIKBES, the continue ('c') command returns the user to the above main menu again.

Other facilities are also provided in PIKBES (as discussed at the beginning of this section) and can be used for textual attachment at the command line, such as 'display', 'explain', 'why', etc. As PIKBES is designed to automatically collect all the attribute values from communication files, any values which are not found, will be asked from the user by KES 'question' attachment. 'Explain' attachments to each question are also available and these help the user during his consultation with the system.

CHAPTER 8:

Future Work

CHAPTER 8 : FUTURE WORK

8.1 Introduction

The objective of this research was to produce a system which will assure good quality welds are produced from a flexible welding cell. The major thrust of the work has been the development of a system for feedforward control of the welding procedure to be employed to compensate for variable fit-up of joints. This chapter discusses further research and development work on the pre-weld inspection station and its knowledge based expert system, PIKBES, in order to improve the utility of the system. The additional or alternative requirements for quality control of welding in the flexible welding cell are real-time in-process control, and feedback control using data collected from the completed weld. These possibilities are also discussed with particular emphasis on an expert system based post-weld inspection system, POKBES.

8.2 Future Research and Development Work

8.2.1 Pre-Weld Inspection Station

Further development of the pre-weld inspection station involves two areas:

- 1) The inspection station itself.
- 2) Its knowledge based expert system (PIKBES).

1) Inspection Station

The limitations of the pre-weld inspection station as currently developed are; small coverage of work pallet area, dealing only with linear flat position joints, and bulkiness of the laser sensor which can restrict access to joints, and relatively slow data processing time. Therefore it is suggested that:

- i) The sensor manipulator be enhanced by motorising the two major linear x and y axes already provided to give complete coverage of the work pallet area. (At present, these are moved manually) Also to provide additional axes of manipulation to the laser range-finder (Optocator), three additional axes of manipulation such as pitch, yaw and roll are required to be

implemented in order to accommodate real components of complex geometry. This may be better facilitated by use of an alternative sensor such as a stripe laser.

- ii) Stripe laser sensor to be implemented. As these are more readily miniaturised and accurate in data collection, it is suggested such a sensor be implemented for the pre-weld inspection station. An example of such sensor is MetaTorch sensor [76,77]. These sensors also eliminate the requirement of a scanning x-axis.
- iv) The existing PDP11/23 minicomputer should be replaced with a more powerful microcomputer. Since it will be inadequate to deal with the large amount of data which will be collected from the joints of a real component as compared to the 45mm long samples used in this research.
- v) KES expert system shell may be used to develop a knowledge base expert system for joint recognition at the pre-weld inspection station. Features extracted from the joint geometry can be classified, and based on these features the joint type can be identified. For example;
 - If two plate edges were detected in the joint geometry, then the joint can be recognised as a square-butt joint.
 - If four plate edges were detected in the joint geometry, then the joint can be recognised as a V-butt joint.
 - If four plate edges and two half semi-circles were detected in the joint geometry, then the joint can be recognised as a U-butt joint, and so on.

Hence, in this way the knowledge based expert system for joint recognition can be developed. This will improve computer processing time compared to the conventional program currently used for the same task and provides an efficient way for joint recognition during inspection.

2) Pre-Weld Inspection Knowledge Base Expert System (PIKBES)

At present, PIKBES is only capable of providing solutions to joint geometry variation problems for 2mm to 12mm square-butt and V-butt joints using C-Mn steel and MIG/MAG mechanised welding in the flat position. Although this accounts for a

large proportion of industrial joints, the system should be extended to accommodate a wider range of joints, materials and processes. Further knowledge regarding other joint types (such as fillet joint, U-butt joint, etc), welding processes, etc should be elicited and implemented in additional rules for PIKBES.

The communication between PIKBES, WRAPS and the pre-inspection station is required to be implemented for receiving and transferring data or command between the systems. This can be accomplished via the communication ring network (LAN). Communication between WRAPS supervisory system and robot controller is also required to transfer welding procedures data.

8.2.2 In-Process Inspection Station

After WRAPS consultation with PIKBES, if the component is accepted to be welded, it will be welded at the welding station. During the welding operation, in-process data may be gathered from the under-side of the weld joint as feedback information to control weld penetration at the root run. This could be achieved by using back-face penetration sensor [195]. Information regarding radiation of light at different wavelengths from the back face can be used to monitor weld penetration. However, the application of such sensors are constrained by the need to access the back-face of the joint simultaneous to welding at the front-face. Also in real-time control, these sensors are constrained by the need for mathematical models and fast data processing time. However, if such a sensor is going to be implemented, an expert system could be used for process modelling. Data processing would also require a fast and powerful computer.

8.2.3 Post-Weld Inspection Stations

It is proposed to control welding procedure by post-weld inspection and feedback control using an expert system in a similar manner to PIKBES.

Procedures selected by WRAPS (which are collected from WELDSPEC) and those modified by PIKBES may not be optimum. It is possible that some of the rules in PIKBES may not be valid for all situations, the result may be welds produced that are less than optimal. Therefore, to compliment PIKBES it is proposed to carry out automatic inspection of finished welds and where it is necessary to use the data collected to further refine welding procedures.

8.2.3.1 Automatic Inspection

The automatic post-weld inspection station will perform inspection of the weld bead geometry for its shape and size. The author has already commissioned the 'hardware' for this station for the research. Fig 8.1 shows the overall configuration of the post-weld inspection station. The post-weld inspection station consists of:

- i) A laser stripe sensor. This laser sensor together with its control unit, a "PCVISION plus" frame grabber board [197], and a software to collect and store weld bead profile images were provided by one of the collaborators of this research the CEGB, Marchwood Engineering Laboratories.
- ii) A four axis cartesian robot (SILVER-REED ARY4) and its control unit. The X and Y axes of the robot are used to carry the laser inspection sensor to different sections of the work pallet and also provide the inspection scanning motion along the joint. The laser sensor is mounted at the end of the manipulator system. The Z axis provides control of the height of the sensor to maintain the joint within the depth of field. The rotary axis maintains the stripe perpendicular to the direction of the joint. A further yaw axis is required to provide full orientation capability for the laser sensor relative to the location of joints around welded component.

The image collected of the weld bead geometry is transferred to "PCVISION plus" frame grabber board on DELL 200 (under MS-DOS operating system) to be stored. "PCVISION plus" frame grabber can be used [197] with IBM Personal Computer AT, XT, PC, or 100% hardware compatibles. This Board together with appropriate software allows complex digital image processing functions, such as; image averaging, image subtraction, edge-enhancing algorithms to be used.

Software provided by the CEGB Marchwood Engineering Laboratories can store the image from the topface of the weld bead. Further software and algorithms are required to be developed to extract features such as weld bead width, height and shape from the image stored. Reference can be made to weld profile monitor algorithms already developed. Based on these features a weld bead can be recognised as acceptable or rejected i.e. welding procedure required further modification, etc. Weld bead width and height can be simply measured from the first differential reading (f.d.r.) of XYZ data of points on the stored weld profile image (the same technique is

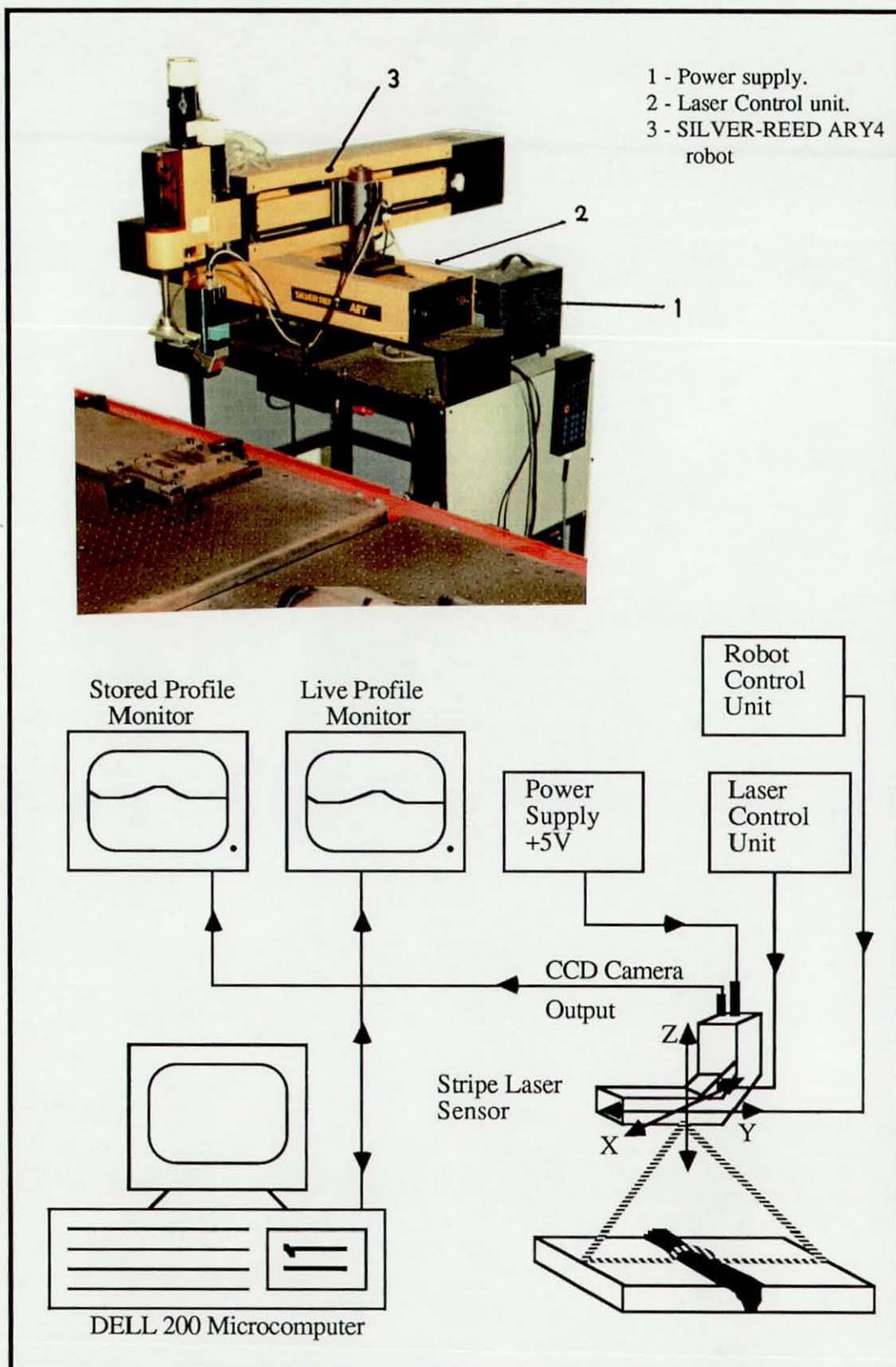


Fig (8.1) - Shows the overall configuration of post-weld inspection station.

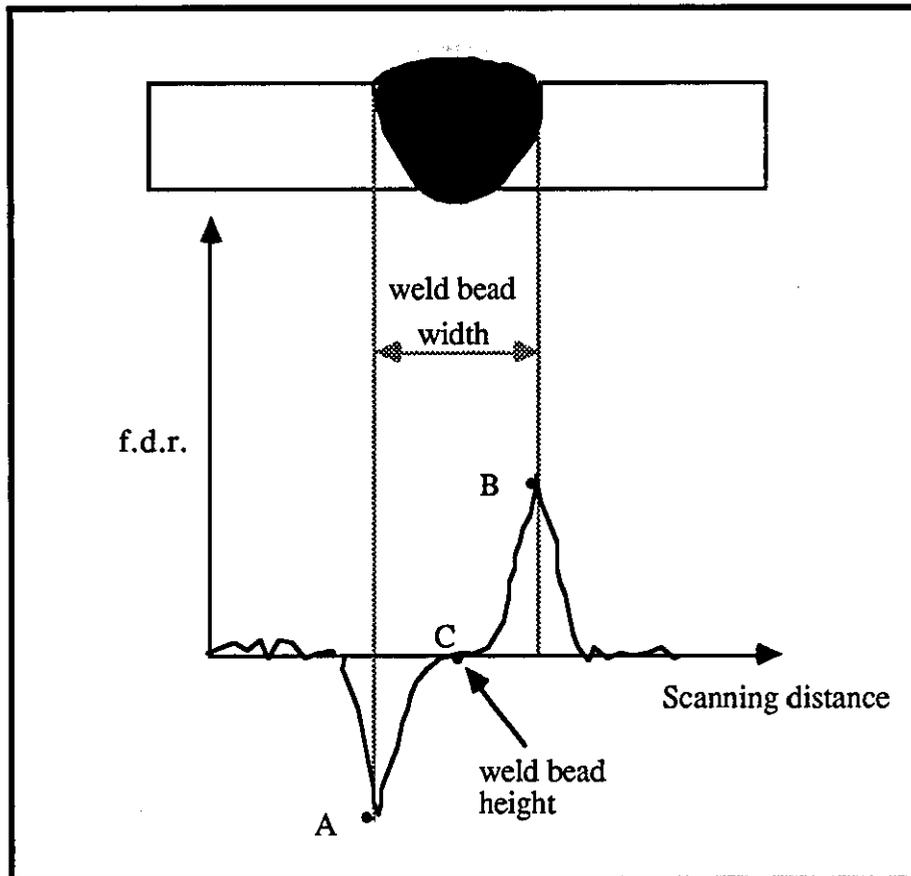


Fig (8.2) - shows example of measuring weld bead width and height using f.d.r. technique for the post-weld inspection station.

used to measure gap/root gap, etc of the joint which is explained in chapter 5 section 5.6.3.2(ii) and maximum point-of-inflexion (point A and B in fig 8.2 respectively) in the f.d.r. could be used to indicate weld bead width. The point of inflexion itself (point C) shows the maximum height of weld bead. Information from the automatic post-weld inspection station regarding weld bead geometry may then be provided as a block and transferred to the WRAPS supervisory system and POKBES (POSt-weld inspection Knowledge Base Expert System).

8.2.3.2 POKBES

POKBES can be developed using similar concepts and techniques to those used for PIKBES. Knowledge regarding weld bead quality control has to be elicited, formulated, and implemented using KES expert system shell [129]. Approved and unapproved knowledge regarding weld bead criteria such as shape and size for different joint types and plate thicknesses is required to be elicited and implemented for POKBES.

Components arriving at the post-weld inspection station would be inspected for its weld bead shape and size. This information would then be transferred to POKBES for consultation regarding quality 'level' of the weld. POKBES will use this data to establish the conformity of the weld to required quality standards. If a weld is found to be acceptable then the PIKBES generated welding procedure used to produce it is given approved status for any joints with similar characteristic and filed in the permanent WELDSPEC database. Where there is non-conformity to quality standards then POKBES will use its knowledge and rule base to further modify the PIKBES procedure and these are then filed as unapproved procedures in a temporary WELDSPEC database for further welding operation. Fig 6.1 (in chapter 6 section 6.3) has already illustrated this concept for POKBES.

Manual operation of POKBES by welding experts would provide him with explanation regarding the decision made by POKBES, therefore, enabling further refinement of rules in PIKBES.

8.2.3.3 Manual Inspection

After post-weld inspection is carried out, manual inspection of welded joint will be performed to provide further process control by collecting more information about the quality of the weld. Manual inspection refers to weld appearance and surface finish or NDT (non-destructive testing) to inspect porosity, cracks, etc. There is evidence that expert systems have been developed for non-destructive testing and they have great potential to improve the performance of NDT [196]. This information can also be used in POKBES to additionally modify welding procedures and for further modification of PIKBES rules.

CHAPTER 9:

Discussions and Conclusions

CHAPTER 9 : DISCUSSIONS AND CONCLUSIONS

2.1 Introduction

This chapter discusses and summarises the conclusions and results of this research.

The production of assembled fabrication to close geometric and dimensional tolerances to facilitate automated welding can required costly development of components. The work described here has shown that it is possible to use a knowledge base system for the modification of welding procedures which facilitates relaxation of the joint fit-up requirement. This work also demonstrates potential opportunities for the use of knowledge base expert systems in the control of welding processes.

2.2 Discussions

A number of problems were encountered during development of PIKBES. These are:

- i) Difficulties were experienced during knowledge elicitation when disagreement between welding domain experts arose. Consequently, it was sometimes necessary to make compromise judgments when implementing knowledge where difference of opinion existed. It was also necessary to seek additional opinion all of which extended the time necessary for the knowledge elicitation of this research.
- ii) While expert in making judgments and decisions on specific problems, some welding domain experts had not encountered problems of a more generic nature. Therefore, the author felt it necessary in such cases to empirically test the knowledge elicited.

- iii) In common with other research, the knowledge elicitation occupied a considerable amount of time for this research. This was often exacerbated by domain experts not always being readily available for consultation due to the demand of their professional position.

- iv) Many of the more complex problems for which knowledge was required fell outside the practical experience of the experts who were consulted. In some of these cases although the experts could develop a logical solution to the problems, they were found not to be effective in practice. Therefore, the author needed to develop other methods, such as 'linear relationship' technique base on both expert knowledge and published empirical data in order to tackle the problems.

Empirical experiments have been conducted to validate the expert system rules and to provide for necessary adjustment to the rules. Since the "one-variable-at-a-time" experimental method would have incurred potentially thousand of experimental tests, a factorial experimental design was used to reduce the number of tests whilst retaining suitable representation of the range of application of PIKBES system. The result of 230 tests have shown that PIKBES is capable of assuring satisfactory welding within the limitation of its specification.

9.3 Conclusions

This research can be considered as successful and has achieved the objectives of this research. The achievements are:

- i) A pre-weld inspection station has been successfully designed, calibrated and implemented on flexible welding system. The system is capable of receiving/ transmitting, commands/messages from/to different supervisory systems (i.e. WRAPS and PIKBES). Information regarding components joint (such as gap/root gap, root face thicknesses, etc.) can be collected, processed, and transferred between the above systems. Facilities for communication between the conveyor controller and the inspection station are also provided.

- ii) An expert system with ability to handle non-mathematical models for the quality control of welds has been successfully developed and implemented (PIKBES). PIKBES can be used to provide feedforward control of the process and weld quality in robotic welding systems. Significant time and cost savings compared to traditional mathematical modelling technique were realised. The system is suited to applications where otherwise many mathematical models would be needed, as in small batch fabrication operations.

This confirms the view of several researches [3,93,99] who have shown that the development of mathematical models for only one or two different plate thicknesses, welding processes, or joint types would required several years of intensive research and costly development. Early research at Loughborough University by shepherd [3] required more than three man-years of research to develop mathematical models capable of dealing only with the flux cored arc welding of plain carbon steel of 12mm thickness with the single J joint type and having little potential for generalisation.

- iii) PIKBES has been validated using factorial experiments and the ability of the system to interface with the end-user has been evaluated. The test validation results showed that PIKBES is capable of compensating for joint geometry variation and assessing the production of satisfactory welds of joints having:

- a) 0 - 1.75mm gap or root gap, 0 - 1.75mm root face thickness, and 25 - 35 degree bevel angles for 2 - 3mm square-butt and 4 - 6mm one-sided V-butt joints,
- b) 0.5 - 2.5mm root gap, 0 - 2.5mm root face thickness, and 25 - 35 degree bevel angles for 8mm one-sided V-butt joint,
- c) 1 - 2.5mm root gap, 0.5 - 2.5mm root face thickness, and 20 - 30 bevel angle for 10mm and 12mm one-sided V-butt joints.

As currently developed the system is suitable for flat position MIG/MAG welding of C/C-Mn steels.

In the development of rules for PIKBES two new concepts in the representation of knowledge relating to relationships between joint parameters and elements of welding procedures have been established. These are the 'window' technique in which energy input to the joint metal at the root of the weld is kept constant to assure good fusion and penetration, and the 'linear relationship' technique which controls penetration and deposition rate relative to the change in joint geometry. These two techniques effectively separate the normally conflicting requirements of penetration and joint filling which has been problematical to all researchers seeking to automatically or adaptively control the GMAW process.

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APPENDICES

Appendix A1

Additional Features of KES PS

FEATURES OF KES PS

CLASSES

Classes allow you to:

- 1) Define the characteristics of a group of objects.
- 2) Specify each object in the group.
- 3) Infer values for each characteristic of each object.
- 4) Define multiple entities at runtime.

Objects are referred to as MEMBERS of the class. Members are created by being inferred or asserted. Class inheritance is the organisation of classes into hierarchical relationships. Class inheritance makes it easier to manipulate the knowledge through rules and demons.

CERTAINTY FACTORS

Certainty factors (CF) can be applied:

- 1) As a measure of belief in the value of an attribute.
- 2) As a measure of belief in the rule.

Certainty factors are based on a numeric scale from 1.0 to -1.0. A CF of 1.0 indicates an absolute belief in a value and a CF of -1.0 is an absolute belief that the value is false.

Certainty factors may:

- Calculate the proper certainties in complex assignments involving multiple attributes or values.
- Calculate the certainty of values determined during inferencing.
- Allow the end user to express the likelihood of competing results.

DEMONS

Demons provide a method of performing EVENT DRIVEN INFERENCING or forward reasoning. They contribute values to attributes, classes and externals. Demons enhance the end user interface in several areas:

- 1) Providing a menu driven interface.
- 2) Controlling question order.
- 3) Defending against invalid end user input.
- 4) Monitoring new or changed attribute values.

Demons consist of two parts: a 'guard' and a 'body'. The guard is the condition and the body is a list of commands that KES performs. When an attribute is determined, KES checks the list of demons associated with that attribute and evaluates the associated demons in the order they appear in the demon section. KES immediately executes a demon if its guard is true. After evaluating and executing all the associated demons, KES returns to what it was doing before it executed the demons.

KES PS INFERENCE ENGINEKnowledge Representation

The term KNOWLEDGE REPRESENTATION refers to the method in which domain knowledge is organised in an expert system, so that the inference engine can use the knowledge. Knowledge representation express facts about the domain and the relationship between these facts. Facts are represented by classes with members (the members being attributes) and by attributes with values. There are various ways that values can be assigned to attributes but the KES PS inference engine uses its Knowledge Sources to determine an attributes value.

HOW DOES THE PS INFERENCE ENGINE WORK?

The obtain command activates the PS inference engine. It can either be entered by the end user when the prompt appears or it can be placed in the ACTIONS section. The inference engine is thus given the goal of finding the attributes named in the command.

When the inference engine has a goal it automatically consults the knowledge sources. There are three types of knowledge sources in PS other than the user:

- 1) Externals
- 2) Rules
- 3) Default and Calculation clauses

The order in which the knowledge sources are consulted is important because it allows you to specify precedences for assigning values to an attribute during an inference process. For example:

actions:

obtain Restaurants.

First, the inference engine checks the externals section. An external can be any program or another KES knowledge base or an external data base. If it no relevant external is found then KES uses its expert knowledge represented in rules that may have values assigned to that attribute. If this also fails ie there are no rules that assert the attribute in their consequent, the inference engine checks if a default or calculation clause is specified. If no knowledge source contributes a value then the status of the attribute is set to "unknown". If an attribute has no knowledge sources, the Knowledge Base Author must decide whether the system should ask the end user to enter a value.

The above describes a type of backward chaining process (goal driven) in KES PS. However as described previously demons in KES allow event driven inferencing outside the actions sections. Demons are declared in the demon section. Example:

demons:

```
Fast Car Demon:
  when
    Car Speed gt 70
  then
    run Slowdown.
  endwhen.
```

This is an example of a demon. It is evaluated when the attribute Car Speed is being determined. The demon is executed when car speed is greater than 70 then it runs the external program Slowdown

KES FEATURESEXTERNALS

Externals are a simple way of communicating with and executing programs outside the expert system. Information can be sent or received using communication files. A KES expert system can communicate with a program or file external to KES by the following methods:

- 1) Read and Write commands.
- 2) Interfaces defined in the externals section.
- 3) The message command.

If the KES expert system only needs to retrieve values from, or store values in a communication file then the read and write commands are used. If however, it is necessary for the KES expert system to run an external program then the externals section may be used. The externals section allows a KES expert system to call other applications. These applications (externals) can receive command line parameters and can read and write to communication files, just like the read and write commands.

CONSISTENCY MAINTENANCE

Consistency maintenance is the process of updating or modifying dependent values so they are consistent with new attribute values or class members. This ensures that all inferences are made with current attribute values and class members. Consistency maintenance allows you to do what-if scenarios to determine what happens if a particular value changes. The ability to examine various outcomes based on a changing environment is an important criterion for selecting the PS subsystem. To achieve consistency maintenance:

- 1) Reassign the value of an attribute or the members of a class.
- 2) Eliminate the values of dependent attributes and classes when needed.
- 3) Obtain new values for the dependent attributes and classes when needed.

These can be accomplished differently depending on whether you are the Knowledge Base Author or the end user.

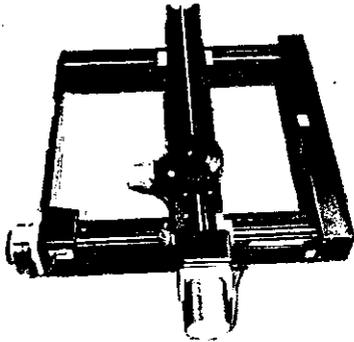
EMBEDDING

Embedding in KES is the ability to integrate KES expert systems into other software applications written in the 'C' programming language. KES provides a collection of functions which can be called from inside a 'C' program thus communicating directly with the knowledge base. There are three phases to building an embedded program:

- 1) Development of the 'C' program.
- 2) Knowledge Base development.
- 3) Integration of 'C' and the Knowledge Base.

Appendix A2

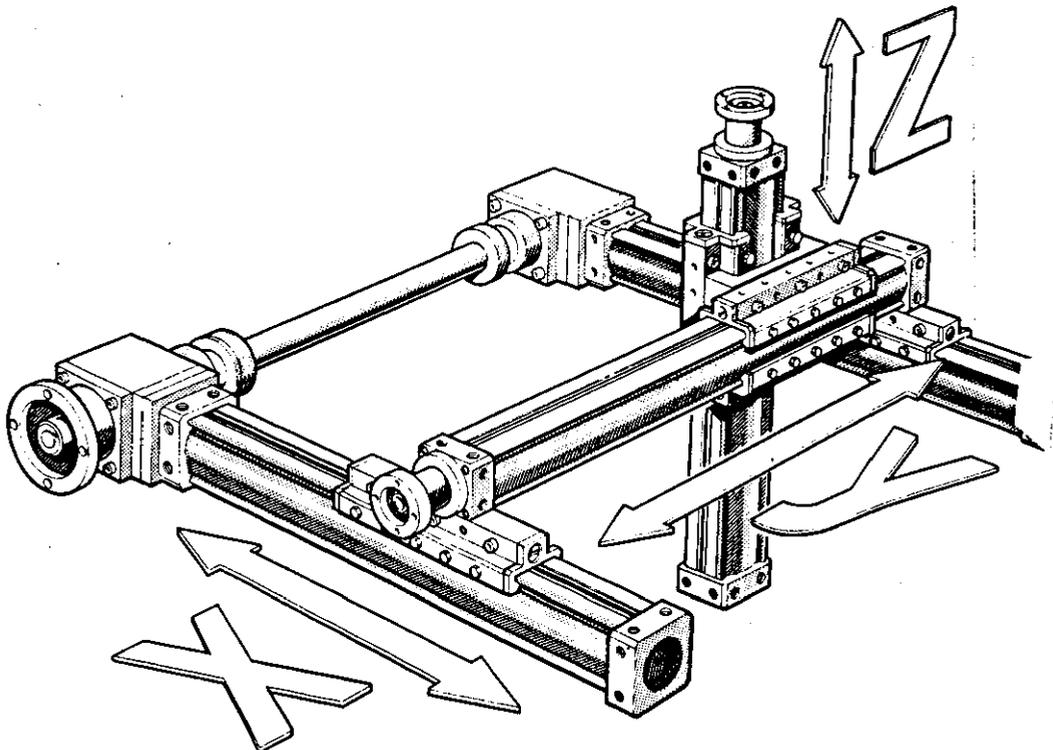
Example of XYZ Linear and Rotary Motorised Axes



(a) - Parallel Coupled - Multi axis [163].



(b) - Rotary Stages [163].



(c) - 3 Coordinate MOVAC System from MRS Company.

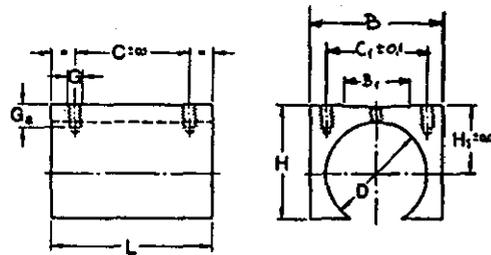
Appendix A3

Information Regarding Shaft and Ball Bearing Specification Used for The Position Holder in the Pre-Weld Inspection Station

Type SR-OUV Plummer Blocks for Open Bearings

Type SR-OUV is made of steel and is designed for use with our Sferax open bearings, either with or without seals. Parallelism between the shaft and the support surface is guaranteed to ± 0.01 mm. The bearing's play or stress can be regulated using two adjusting screws. The plummer block is fastened with four screws.

Type SR-OUV blocks are designed for use in combination with our SA-OUV shaft supports or MB bases in all applications requiring long, accurate linear movements with no deflection of the shaft.



Dimensions										Weight	Description
D	B	B ₁	C	C ₁	G	G _s	H	H ₁	L		
mm										kg	-
15	24,5	5	16	16,5	M4	5	18,5	12	34	0,070	SR-OUV 815
22	29	6	22	19	M5	5	24	14,5	41	0,112	SR-OUV 1222
26	39	10	25	28	M5	5	30,75	19,5	44	0,214	SR-OUV 1626
32	44	12	30	32	M5	5	36,5	22,5	49	0,316	SR-OUV 2032
40	54	18	37	36	M6	10	44,5	27	61	0,540	SR-OUV 2540
45	59	30	48	45	M6	10	49,5	30	68	0,737	SR-OUV 3045
60	79	37	64	58	M8	16	66	40	92	1,76	SR-OUV 4060
75	98	40	82	59	M8	16	82,5	50	110	3,06	SR-OUV 5075
90	115	*)	100	*)	M10	*)	96,5	57,5	130	4,76	SR-OUV 6090
105	130	*)	120	*)	M10	*)	110,5	65	156	6,95	SR-OUV 70105
120	150	*)	134	*)	M10	*)	127	75	176	10,49	SR-OUV 80120
135	165	*)	154	*)	m10	*)	141	82,5	196	13,7	SR-OUV 90135
150	180	*)	174	*)	M10	*)	155	90	216	17,0	SR-OUV 100150

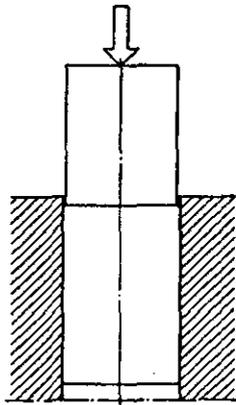
*) Available in any size

Assembly

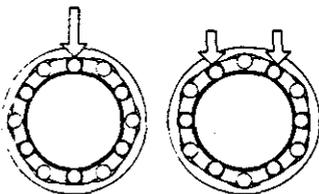
Sferax ball bearings are easy to fit in position, but accuracy and cleanliness are essential if they are to function properly. However, these requirements are by no means unusual when one is dealing with machinery elements. It is equally essential to follow the correct procedure and to use the right tools for the job.

The packaging should never be opened before the bearing is to be fitted in position. Use a sleeve to press the bearing into the plummer block (see Fig 1). Position the sleeve in such a way that it is only pressing on the jacket of the bearing, as otherwise the bearing tray may be damaged. The diameter of the sleeve should be 0.1 mm less than the external diameter of the bearing.

Lock the bearing in position with circlips, a threaded



cover or sealing liquid, e.g. Loctite. A little pressure can also be used. For tolerances, please see Table 1.



The length of a bearing's service life is calculated on the basis that the load falls on a row of bearings. Maximum service life can be obtained if bearings in linear movements are fitted in such a way that the load falls between the rows of bearings.

Special Purpose Bearings

The ball bearings described in this catalogue are standard models, but we can also supply stainless steel bearings, bearings with stainless steel jackets and brass trays and bearings with chromium-plated trays. Please contact us if you would like more information.

Shafts

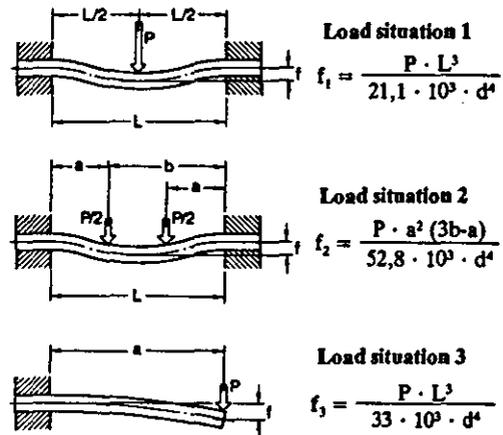
Sferax shafts are surface hardened and ground steel which are specially produced to provide very good quality linear movement used in conjunction with Sferax ball bearings.

If the ball bearing is to function satisfactorily the deflec-

tion of the shaft must not exceed 0.01 mm over the length of the load-carrying bearings (see the Table of Dimensions for the relevant ball bearing). Deflection in the three most commonly occurring load situations can be calculated with the help of the equations shown in Fig 2, where

- f = Deflection in mm
- P = Load in N
- L = Length of shaft subjected to the load
- d = Shaft Diameter
- a = Distance between the bearing supports and the load
- b = Distance between bearing support and load (Situation 2)

The elasticity module for steel is 220,000 N/mm².



However, the part of the shaft which is directly loaded by the ball bearings must also be calculated, i.e. deflection there too must not exceed 0.01 mm.

A rough calculation can be made using the "ready reckoner" in Fig 3. However, remember to check that the ball bearing will also be able to withstand the load.

Maximum permissible shaft load

Shaft Diameter d	Stroke Length in mm						
	100	250	500	750	1 000	1 500	2 000
mm	N						
6	287	46	11	-	-	-	-
8	720	138	34	-	-	-	-
10	-	337	84	37	20	-	-
12	-	588	147	65	28	-	-
15	-	1 196	299	133	75	-	-
16	-	1 327	333	149	84	-	-
18	-	2 531	632	281	157	-	-
20	-	3 080	771	342	193	85	48
25	-	5 489	1 373	610	343	152	85
30	-	9 115	2 279	1 012	570	253	142
35	-	-	3 618	1 608	904	402	226
40	-	-	5 443	2 418	1 360	604	340
45	-	-	7 690	3 410	1 920	850	480
50	-	-	10 550	4 687	2 637	1 170	660
60	-	-	-	8 102	4 573	2 025	1 140

Appendix A4

Technical Specification of the Selcom Optocator Laser Probe

Technical specifications

Environmental specifications

Shock:	Standard: IEC 68-2-27 Half sine: 250 m/s ²
Vibration:	Standard: IEC 68-2-6, B3 Resonance sweep: 5 – 16 Hz max. 0.5 mm 16 – 500 Hz max. 5 m/s ² Fatigue sweep: 5 – 27 Hz max. 3.5 mm max. 10.5 m/s ² 27 – 500 Hz max. 0.35 mm max. 50 m/s ² Sweep speed: 1 octave/min
Temperature:	0 °C – +40 °C operating –25 °C – +50 °C tested interval –30 °C – +70 °C not operating

Power supply

+20 V ±1 V max. 60 mA
–20 V ±1 V max. 50 mA
+15 V ^{+5 V} –4 V max. 350 mA
+18 V ^{+6 V} –3 V max. 150 mA

Output specifications

Digital output:	16 bit serial, incl. 12 bit data, 3 bit invalid signal (see figure 4)
Updating frequency:	16 kHz (optional 32 kHz)
Bandwidth:	2 kHz (optional 5 kHz)
Max. load:	V _{OH} > 2 V I _{OH} > –40 mA V _{OL} < 0.8 V I _{OL} < 40 mA

Scale factor:

Measurement range mm (at least)	Scale factor/Resolution/LSB µm
8	2
16	4
32	8
64	16
128	32
256	64
512	128

Optical specifications

Light source	
Laser diode (GaAs)	Class III b
Mode of operation:	Pulsed, modulated (standard 16 kHz), intensity controlled
Output power:	Pulse duration 350 ns Pulse peak power max. 112 mW Average power max. 10 mW
Wave length:	850 nm (typical)
Detector	
Position sensitive photodetector (single element surface diode, Si)	
Sensitivity:	Min. 0.7 A/W
Resolution:	Better than 10 ⁻⁴

Gauge probe variants

(mm)

Gauge probe type	2005	2006 ¹⁾	2008 ¹⁾	2009 ¹⁾	22XX ¹⁾
Measurement range	8 – 512	8 – 64	256; 382	32	32
Stand off	95 – 1000	95 – 180	355; 500	103	95 – 180
Angle, lightsource-detector	26°, 30°, 45°	30°, 45°	30°	45°	18° – 30°
Measurements					
– Length	410 – 520	240 – 335	290; 370	270	120 – 155
– Height	200 – 340	200 – 260	180	160	80 – 135
– Width	90	90	90	90	50
Weight	7 kg	4 kg	3 kg	3 kg	0.6 – 1.0 kg

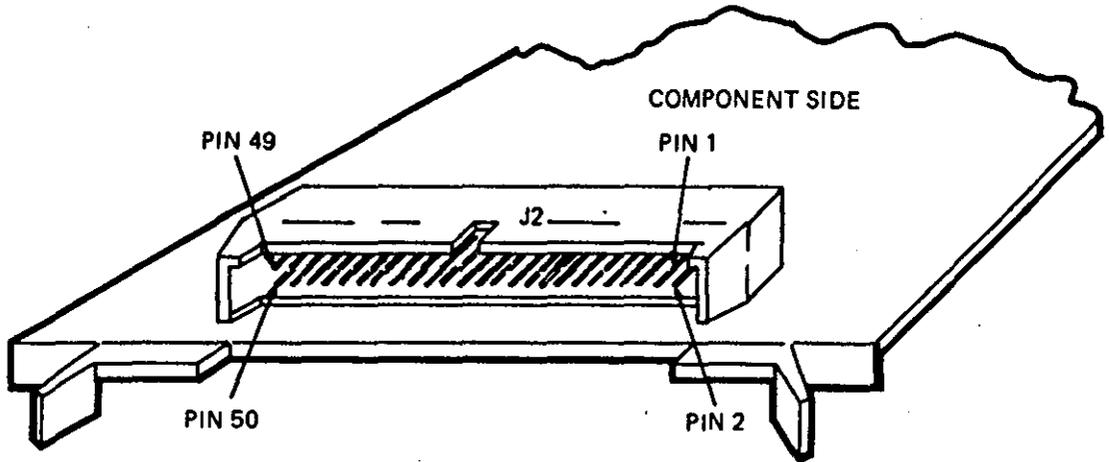
¹⁾ These types have a separate box for the gauge probe electronics. The issued data concerns the camera unit itself only.

Light spot size (with standard lens)

(mm)

	short	Stand off medium	long
	95 – 135	170 – 355	485 – 1000
Width	0.1 – 0.3	0.2 – 0.5	1.0 – 2.0
Length	1.5 – 2.0	1.5 – 7.0	6.0 – 36.0

The light spot size depends on the type of gauge probe and the location within the measurement range.

Appendix A5**I/O Signal Pin Connection for DRV11-J Interface Card**

MR-4311

Figure 4-1 DRV11-J I/O Connector Pin Locations

Table 4-1 I/O Connector Pin Assignments

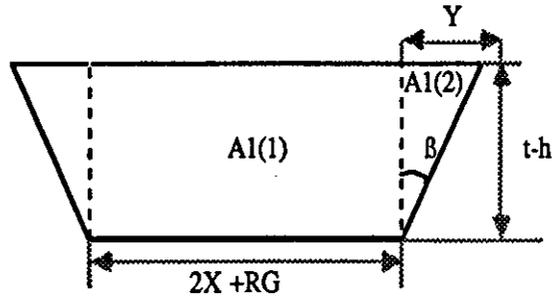
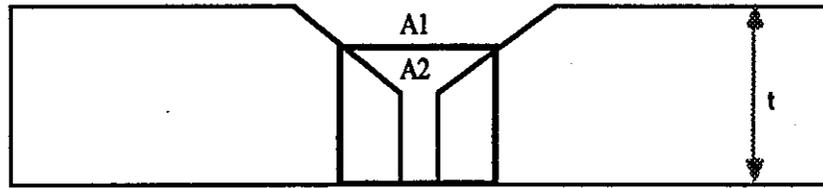
Signal Name	J1 Connector Pin	Signal Name	J2 Connector Pin
DRV11J RDY A	J1-29	DRV11J RDY D	J2-29
DRV11J RPLY A	J1-33	DRV11J RPLY D	J2-33
USER RDY A	J1-31	USER RDY D	J2-31
USER RPLY A	J1-27	USER RPLY D	J2-27
A I/O 15	J1-45	D I/O 15	J2-45
A I/O 14	J1-46	D I/O 14	J2-46
A I/O 13	J1-43	D I/O 13	J2-43
A I/O 12	J1-49	D I/O 12	J2-49
A I/O 11	J1-48	D I/O 11	J2-48
A I/O 10	J1-44	D I/O 10	J2-44
A I/O 9	J1-50	D I/O 9	J2-50
A I/O 8	J1-47	D I/O 8	J2-47
A I/O 7	J1-41	D I/O 7	J2-41
A I/O 6	J1-36	D I/O 6	J2-36
A I/O 5	J1-42	D I/O 5	J2-42
A I/O 4	J1-35	D I/O 4	J2-35
A I/O 3	J1-40	D I/O 3	J2-40
A I/O 2	J1-38	D I/O 2	J2-38
A I/O 1	J1-39	D I/O 1	J2-39
A I/O 0	J1-37	D I/O 0	J2-37
GND	J1-26	GND	J2-26
GND	J1-28	GND	J2-28
GND	J1-30	GND	J2-30
GND	J1-32	GND	J2-32
GND	J1-34	GND	J2-34

Table 4-1 I/O Connector Pin Assignments (Cont)

Signal Name	J1 Connector Pin	Signal Name	J2 Connector Pin
DRVIIJ RDY B	J1-20	· DRVIIJ RDY C	J2-20
DRVIIJ RPLY B	J1-24	· DRVIIJ RPLY C	J2-24
USER RDY B	J1-22	· USER RDY C	J2-22
USER RPLY B	J1-18	· USER RPLY C	J2-18
BI/O 15	J1-6	· CI/O 15	J2-6
BI/O 14	J1-5	CI/O 14	J2-5
BI/O 13	J1-8	CI/O 13	J2-8
BI/O 12	J1-2	CI/O 12	J2-2
BI/O 11	J1-3	CI/O 11	J2-3
BI/O 10	J1-7	CI/O 10	J2-7
BI/O 9	J1-1	CI/O 9	J2-1
BI/O 8	J1-4	CI/O 8	J2-4
BI/O 7	J1-10	CI/O 7	J2-10
BI/O 6	J1-15	CI/O 6	J2-15
BI/O 5	J1-9	CI/O 5	J2-9
BI/O 4	J1-16	CI/O 4	J2-16
BI/O 3	J1-11	CI/O 3	J2-11
BI/O 2	J1-13	CI/O 2	J2-13
BI/O 1	J1-12	CI/O 1	J2-12
BI/O 0	J1-14	CI/O 0	J2-14
GND	J1-17	GND	J2-17
GND	J1-19	GND	J2-19
GND	J1-21	GND	J2-21
GND	J1-23	GND	J2-23
GND	J1-25	GND	J2-25

Appendix A6

Calculation of 'Window' Size for Nominal Joints



$$Y = (t-h) \tan \beta$$

$$X = (h-RFT) \tan \beta$$

$$A1(1) = (2X + RG) (t-h)$$

$$= (2[(h-RFT)\tan \beta] + RG)(t-h)$$

$$A1(2) = Y(t-h)$$

$$= (t-h)^2 \tan \beta$$

$$A(1)T = A1(1) + A1(2)$$

$$A(1)T = (2(h-RFT) \tan \beta + RG) (t-h) + (t-h)^2 \tan \beta$$

$$A1 = A2 = A/2$$

$$X / (h-RFT) = \tan \partial$$

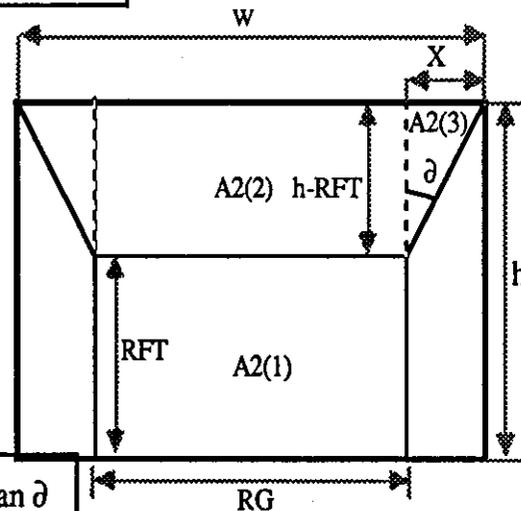
$$X = (h-RFT) \tan \partial$$

$$A2(1) = RFT \times RG$$

$$A2(2) = (h-RFT) RG$$

$$A2(3) = X(h-RFT) = (h-RFT)^2 \tan \partial$$

$$A2(T) = A2(1) + A2(2) + A2(3)$$



$$A2(T) = RFT \times RG + (h-RFT)RG + (h-RFT)^2 \tan \partial$$

$$A1 = A2 = A/2$$

$$(2(h-RFT)\tan \beta + RG)(t-h) + (t-h)^2 \tan \beta = RFT \times RG + (h-RFT)RG + (h-RFT)^2 \tan \partial$$

Appendix A7Program for Metallic Area calculation of different joint geometry

```

\*****
\*
\* PRE-INSPECTION EXPERT KNOWLEDGE BASED SYSTEM OF*
\* CALCULATION OF METALLIC AREA IN THE WINDOW *
\*
\*
\* FILE NAME      :   calc2.kb      *
\* ORIGINAL DATE  :   21-NOV-90    *
\* PURPOSE       :   metallic area calcution *
\*               :   in window.    *
\* PROGRAMMER    :   M.GHASEMSHAHI *
\*
\*****

```

constants:

Banner:

```
"*****"
```

%

attributes:

Joint type: sgl (V_butt_unback).

T1_act: real.

T2_act: real.

RG_act: real.

RFT1_act: real.

RFT2_act: real.

BV1_act: real.

BV2_act: real.

AM1_act: real.

AM2_act: real.

A_act: real.

RG_ABSLL: real.

RG_ABSUL: real.

RFT_ABSLL: real.

RFT_ABSUL: real.

BV_ABSLL: real.

BV_ABSUL: real.

H_nom: real.

W_nom: real.

A_nom: real.

A_met: real.

PI: real [default: 3.14159].

rdn: real [default: PI/180].

h1: real

[default: (((W_nom - RG_act)/2)*(sin((90 - BV1_act)*rdn)/
cos((90 - BV1_act)*rdn))) + RFT1_act].

h2: real

[default: $((W_nom - RG_act)/2) * (\sin((90 - BV2_act)*rdn) / \cos((90 - BV2_act)*rdn)) + RFT2_act$].

A1: real.
 A2: real.
 A3: real.
 A_1: real.
 A_2: real.
 A_3: real.
 AT: real.
 A_T: real.
 L1: real.
 L_1: real.
 L2: real.
 L_2: real.
 L3: real [default: L2 - L1].
 L_3: real [default: L_2 - L_1].
 A_metact: real.

%

```
\ *****
\ * ACTION SECTION *
\ *****
```

actions:

read "fact.dat",RG_act,RFT1_act,RFT2_act,BV1_act,BV2_act.

message "",

Banner,

combine("RG_act =",RG_act),
 combine("RFT1_act =",RFT1_act),
 combine("RFT2_act =",RFT2_act),
 combine("BV1_act =",BV1_act),
 combine("BV2_act =",BV2_act),
 Banner.

read "ouvl.dat",W_nom,H_nom,A_met.

message " ",

combine("h1 =",h1),
 combine("h2 =",h2).

\----- calculation of side1 -----.

if h1 lt H_nom

then

A1 = $((W_nom - RG_act)/2) * RFT1_act$.
 A2 = $0.5 * ((W_nom - RG_act)/2)^2 * (\sin((90 - BV1_act)*rdn) / \cos((90 - BV1_act)*rdn))$.
 AT = A1 + A2.

endif.

if h1 ge H_nom

then

L1 = $(H_nom - RFT1_act) * (\sin(BV1_act*rdn) / \cos(BV1_act*rdn))$.

```

L2 = (W_nom - RG_act)/2.
if L1 lt L2
then
  A1 = (((W_nom - RG_act)/2) * RFT1_act).
  A2 = 0.5 * ((H_nom - RFT1_act) * L1).
  A3 = L3 * (H_nom - RFT1_act).
  AT = A1 + A2 + A3.
endif.

if L1 = L2
then
  A1 = (((W_nom - RG_act)/2) * RFT1_act).
  A2 = 0.5 * (((W_nom - RG_act)/2)^2) *
(sin((90 - BV1_act)*rdn)/cos((90 - BV1_act)*rdn)).
  AT = A1 + A2.
endif.
endif.

\----- calculation of side2 -----

if h2 lt H_nom
then
  A_1 = (((W_nom - RG_act)/2) * RFT2_act).
  A_2 = 0.5 * (((W_nom - RG_act)/2)^2) * (sin((90 - BV2_act)*rdn)
/cos((90 - BV2_act)*rdn)).
  A_T = A_1 + A_2.
endif.

if h2 ge H_nom
then
  L_1 = (H_nom - RFT2_act) * (sin(BV2_act*rdn)/cos(BV2_act*rdn)).
  L_2 = (W_nom - RG_act)/2.
  if L_1 lt L_2
  then
    A_1 = (((W_nom - RG_act)/2) * RFT2_act).
    A_2 = 0.5 * ((H_nom - RFT2_act) * L_1).
    A_3 = L_3 * (H_nom - RFT2_act).
    A_T = A_1 + A_2 + A_3.
  endif.
  if L_1 = L_2
  then
    A_1 = (((W_nom - RG_act)/2) * RFT2_act).
    A_2 = 0.5 * (((W_nom - RG_act)/2)^2) *
(sin((90 - BV2_act)*rdn)/cos((90 - BV2_act)*rdn)).
    A_T = A_1 + A_2.
  endif.
endif.

A_metact = AT + A_T.
write "famet.dat",A_metact.

message"",
Banner,
combine("SIDE 1 METTALLIC AREA =",AT),
combine("SIDE 2 METTALLIC AREA =",A_T),
combine("TOTAL METTALLIC AREA OF ACTUAL JOINT =",A_metact),
Banner.
%
```

Appendix A8

Tables of Treatment Combinations (for Factorial Experiment Test) for 6, 8, 10, 12mm V-butt Joints.

(a)							
No.	Variable Factor	Unit	Levels				
			Absolute Lolim	BS5135 Lolim	Nominal	BS5135 Uplim	Absolute Uplim
1	RG	mm	0	1	1	1.5	1.75
2	RFT	mm	0	0.5	1	1.5	1.75
3	BV	deg.	25	27.5	30	32.5	35
			-2	-1	0	+1	+2

(b)					
No.	Variable Factors	Unit	Magnitude		
			Low	Medium	High
1	TS	m/min	9.19	10 - 11	12.03
2	WFS	cm/min	5.08	5.1 - 6.0	6.1
3	V	volts	17	-	21
4	TA	deg.	70	-	90
5	SO	mm	15	-	20
			-1	0	+1

Weaving

Weave Pattern (WP) No. 2

Weave Amplitude (WA) = Varies with variation in RG
= 10 - 29 units (0.1mm/unit)

Weave Frequency (WF) = 10 units (0.1 Hz/unit)

Table (1) - Shows (a) - one joint variable at five tolerance levels for 6mm V-butt joint and (b)- welding parameters at different magnitude.

No.	TS (cm/min)	WFS (m/min)	V (volts)	TA (deg.)	SO (mm)	RG (mm)	RFT (mm)	Area Ratio (mm)	Rule No.	WP	WA (Unit)	WF (Unit)
1	9.19	5.9	+1	-1	-1	-2	0	0.76	26			
2	+1	-1	+1	-1	-1	-1	0	1.067	26			
3	+1	-1	+1	+1	-1	0	0	1.1	WRAPS weld. Proc. (nominal)	-	-	-
4	+1	-1	+1	+1	-1	+1	0	1.22	27			
5	8.47	5.2	+1	+1	-1	+2	0	1.29	27			
6	10	5.4	+1	-1	-1	-2	-2	1.086	43	-	-	-
7	+1	5.2	+1	+1	-1	-1	-2	1.23	44	2	22- 29	10
8	+1	5.2	+1	+1	-1	0	-2	1.39	44			
9	+1	5.2	+1	+1	-1	+1	-2	1.54	44			
10	+1	5.2	+1	+1	-1	+2	-2	1.61	44			
11	10	5.7	+1	-1	-1	-2	-1	0.92	43	-	-	-
12	10	5.45	+1	-1	-1	-1	-1	1.07	43			
13	12	5.2	+1	+1	-1	0	-1	1.22	44	2	10- 22	10
14	12	5.2	+1	+1	-1	+1	-1	1.37	44			
15	12	5.2	+1	+1	-1	+2	-1	1.44	44			
16	-1	+1	+1	-1	-1	-2	+1	0.62	42			
17	-1	5.8	+1	-1	-1	-1	+1	0.77	42			
18	-1	5.5	+1	-1	-1	0	+1	0.93	42	-	-	-
19	-1	5.3	+1	-1	-1	+1	+1	1.08	42			
20	-1	5.2	+1	-1	-1	+2	+1	1.15	42			
21	-1	+1	+1	-1	-1	-2	+2	0.56	42			
22	-1	5.87	+1	-1	-1	-1	+2	0.71	42			
23	-1	5.6	+1	-1	-1	0	+2	0.86	42			
24	-1	5.4	+1	-1	-1	+1	+2	1.014	42			
25	-1	5.3	+1	-1	-1	+2	+2	1.09	42			

Table (2) - 6×5^2 factorial experiment tests (block 3) for 6mm V-butt joint using table 1.

(a)

No.	Variable Factor	Unit	Levels				
			Absolute Lolim	BS5135 Lolim	Nominal	BS5135 Uplim	Absolute Uplim
1	RG	mm	0.5	0.5	1	1.5	2.5
2	RFT	mm	0	0.5	1	1.5	2.0
3	BV	deg.	25	27.5	30	32.5	35
			-2	-1	0	+1	+2

(b)

No.	Variable Factors	Unit	Magnitude		
			Low	Medium	High
1	TS	m/min	18	23-50	60
2	WFS	cm/min	5.08	5.3 - 6.5	7.0
3	V	volts	17	-	21
4	TA	deg.	70	-	90
5	SO	mm	15	16 - 24	20
			-1	0	+1

Weaving

Weave Pattern (WP) No. 2

Weave Amplitude (WA) = Varies with variation in RG
= 12.5 - 33 units (0.1mm/unit)

Weave Frequency (WF) = 14 - 18 units (0.1 Hz/unit)

Table (3) - Shows (a) - one joint variable at five tolerance levels for 8mm V-butt joint and (b)- welding parameters at different magnitude.

No.	TS (cm/min)	WFS (m/min)	V (volts)	TA (deg.)	SO (mm)	RG (mm)	RFT (mm)	Area Ratio (mm)	Rule No.	WP	WA (Unit)	WF (Unit)
1	30	-1	+1	-1	0	-2	0	1.05	22			
2	-1	-1	+1	-1	0	-1	0	1.10	22			
3	30	-1	+1	-1	0	0	0	1.15	WRAPS weld. Proc. - (nominal)		-	-
4	30	-1	+1	-1	0	+1	0	1.164	29			
5	-1	-1	+1	-1	0	+2	0	1.27	29			
6	30	6.5	+1	+1	0	-2	-2	1.18	50	2	25- 33	15-18
7	30	6.5	+1	+1	0	-1	-2	1.20	50			
8	30	6.5	+1	+1	0	0	-2	1.29	50			
9	25	5.5	+1	+1	0	+1	-2	1.41	50			
10	18	5.1	+1	+1	0	+2	-2	1.63	51			
11	50	+1	+1	-1	0	-2	-1	1.056	48	2	12.5 23	15
12	50	+1	+1	-1	0	-1	-1	1.10	48			
13	30	6.5	+1	+1	0	0	-1	1.17	49			
14	30	6.5	+1	+1	0	+1	-1	1.28	49			
15	30	6.5	+1	+1	0	+2	-1	1.51	50			
16	-1	5.3	+1	-1	0	-2	+1	0.83	46			
17	-1	5.3	+1	-1	0	-1	+1	0.90	46	-	-	-
18	45	5.3	+1	-1	0	0	+1	0.94	46			
19	34	5.5	+1	+1	0	+1	+1	1.053	47	2	23	14
20	25	5.5	+1	+1	0	+2	+1	1.28	47			
21	+1	+1	+1	-1	0	-2	+2	0.61	45			
22	+1	+1	+1	-1	0	-1	+2	0.72	45	-	-	-
23	55	5.3	+1	-1	0	0	+2	0.83	46			
24	45	5.3	+1	-1	0	+1	+2	0.95	46			
25	23	5.3	+1	-1	0	+2	+2	1.17	47	2	23	14

Table (4) = 6×5^2 factorial experiment tests (block 4) for 8mm V-butt joint using table 3.

(a)

No.	Variable Factor	Unit	Levels				
			Absolute Lolim	BS5135 Lolim	Nominal	BS5135 Uplim	Absolute Uplim
1	RG	mm	1	1	1.5	2	2.5
2	RFT	mm	0.5	1	1	2	2.5
3	BV	deg.	20	22.5	25	27.5	30
			-2	-1	0	+1	+2

(b)

No.	Variable Factors	Unit	Magnitude		
			Low	Medium	High
1	TS	m/min	18	21 - 30	42
2	WFS	cm/min	8.66	-	10
3	V	volts	21	-	25
4	TA	deg.	70	-	90
5	SO	mm	15	16 - 24	25
			-1	0	+1

Weaving

Weave Pattern (WP) No. 2

Weave Amplitude (WA) = Varies with variation in RG
= 20 - 33 units (0.1mm/unit)

Weave Frequency (WF) = 10 units (0.1 Hz/unit)

Table (5) - Shows (a) - one joint variable at five tolerance levels for 10 mm V-butt joint and (b)- welding parameters at different magnitude.

No.	TS (cm/min)	WFS (m/min)	V (volts)	TA (deg.)	SO (mm)	RG (mm)	RFT (mm)	Area Ratio (mm)	Rule No.	WP	WA (Unit)	WF (Unit)
1	30	-1	+1	-1	0	-2	0	0.915	30			
2	30	-1	+1	-1	0	-1	0	0.96	30			
3	21	-1	+1	-1	0	0	0	1.039	WRAPS weld. Proc. - (nominal)		-	-
4	21	-1	+1	-1	0	+1	0	1.14	31			
5	-1	-1	+1	-1	0	+2	0	1.25	31			
6	21	-1	+1	+1	0	-2	-2	1.11	54			
7	21	-1	+1	+1	0	-1	-2	1.16	54			
8	21	-1	+1	+1	0	0	-2	1.21	54	2	25- 33	10
9	21	-1	+1	+1	0	+1	-2	1.32	54			
10	21	-1	+1	+1	0	+2	-2	1.42	54			
11	25	-1	+1	-1	0	-2	-1	1.02	53	-	-	-
12	25	-1	+1	-1	0	-1	-1	1.05	53			
13	21	-1	+1	+1	0	0	-1	1.125	54			
14	21	-1	+1	+1	0	+1	-1	1.23	54	2	20- 23	10
15	21	-1	+1	+1	0	+2	-1	1.33	54			
16	37	-1	+1	-1	0	-2	+1	0.85	51			
17	37	-1	+1	-1	0	-1	+1	0.87	51			
18	27	-1	+1	-1	0	0	+1	0.96	51	-	-	-
19	21	-1	+1	-1	0	+1	+1	1.063	51			
20	-1	-1	+1	-1	0	+2	+1	1.167	52			
21	42	-1	+1	-1	0	-2	+2	0.77	51			
22	42	-1	+1	-1	0	-1	+2	0.80	51			
23	33	-1	+1	-1	0	0	+2	0.83	51	-	-	-
24	26	-1	+1	-1	0	+1	+2	0.98	51			
25	-1	-1	+1	-1	0	+2	+2	1.091	51			

Table (6) - 6×5^2 factorial experiment tests (block 5) for 10mm V-butt joint using table 5.

(a)

No.	Variable Factor	Unit	Levels				
			Absolute Lolim	BS5135 Lolim	Nominal	BS5135 Uplim	Absolute Uplim
1	RG	mm	1	1	1.5	2	2.5
2	RFT	mm	0.5	1	1	2	2.5
3	BV	deg.	20	22.5	25	27.5	30
			-2	-1	0	+1	+2

(b)

No.	Variable Factors	Unit	Magnitude		
			Low	Medium	High
1	TS	m/min	28	30 - 53	58
2	WFS	cm/min	8.66	-	11
3	V	volts	21	-	25
4	TA	deg.	70	-	90
5	SO	mm	15	16 - 24	25
			-1	0	+1

Weaving

Weave Pattern (WP) No. 2

Weave Amplitude (WA) = Varies with variation in RG
= 23 - 33 units (0.1mm/unit)

Weave Frequency (WF) = 12 units (0.1 Hz/unit)

Table (7) - Shows (a) - one joint variable at five tolerance levels for 12mm V-butt joint and (b)- welding parameters at different magnitude.

No.	TS (cm/min)	WFS (m/min)	V (volts)	TA (deg.)	SO (mm)	RG (mm)	RFT (mm)	Area Ratio (mm)	Rule No.	WP	WA (Unit)	WF (Unit)
1	39	9.52	+1	-1	-1	-2	0	0.94	31			
2	33	-1	+1	-1	-1	-1	0	1.01	31			
3	32.36	-1	+1	-1	-1	0	0	1.03	WRAPS weld. Proc. - (nominal)		-	-
4	32.36	-1	+1	-1	-1	+1	0	1.13	32			
5	27.73	-1	+1	-1	-1	+2	0	1.21	32			
6	30.41	-1	+1	+1	-1	-2	-2	1.1	58	2	25- 33	10
7	30.41	-1	+1	+1	-1	-1	-2	1.13	58			
8	30.41	-1	+1	+1	-1	0	-2	1.18	58			
9	30.41	-1	+1	+1	-1	+1	-2	1.27	58			
10	30.41	-1	+1	+1	-1	+2	-2	1.36	58			
11	39	-1	+1	+1	-1	-2	-1	1.02	57		-	-
12	39	-1	+1	+1	-1	-1	-1	1.06	57		-	-
13	32	-1	+1	+1	-1	0	-1	1.11	58	2	23	12
14	30.41	-1	+1	+1	-1	+1	-1	1.19	58			
15	30.41	-1	+1	+1	-1	+2	-1	1.28	58			
16	52.52	9.9	+1	-1	-1	-2	+1	0.846	55			
17	52.52	9.9	+1	-1	-1	-1	+1	0.86	55			
18	42.75	-1	+1	-1	-1	0	+1	0.92	56		-	-
19	36.77	-1	+1	-1	-1	+1	+1	0.99	56		-	-
20	29.94	-1	+1	-1	-1	+2	+1	1.07	56		-	-
21	+1	+1	+1	-1	-1	-2	+2	0.81	55			
22	+1	+1	+1	-1	-1	-1	+2	0.85	55			
23	45.32	-1	+1	-1	-1	0	+2	0.896	56		-	-
24	37.67	-1	+1	-1	-1	+1	+2	0.98	56		-	-
25	28.23	-1	+1	-1	-1	+2	+2	1.071	56		-	-

Table (8) - 6×5^2 factorial experiment tests (block 6) for 12mm V-butt joint using table 7.

Appendix A9**Typical Help Facilities Provided During PIKBES Consultation**

Ready for command: h

List of KES Commands (abbreviations enclosed in brackets)

```

answer      changeclass  help [h]    run
askfor [a]  continue [c] justify [j] show
askforclass defrost     nextcase [n] stop [s]
assert      display [d] obtain [o] why [w]
assertclass explain [e] obtainclass write
change      freeze     read

```

To get more information about a command, type: 'help' COMMAND-NAME

For information about answering KES queries, type: 'help answer'

In all command descriptions, upper-case terms indicate that you should substitute a valid attribute, value, or pattern name, etc., for the upper-case term.

Ready for command: h a

askfor ATTRIBUTE-NAME

The 'askfor' command prompts the user to enter a value for ATTRIBUTE-NAME. For further information, enter 'help answer'.

Ready for command: h answer

KES queries you for the value of an attribute when the value cannot be inferred. To provide an answer, you may enter the number of the choice, or the choice (string) itself. Single or multiple answers are possible, depending on the attribute type. Multiple answers (for 'mlt' attributes) must be separated by an '&' (for 'and') or an

'|' (for 'or'). Example:

a | b & c

The connector '|' has precedence over '&' in a multiple answer expression, such that the expression above means 'either a or b, and also c'. Certainty factors can be used in angular brackets to weight alternatives.

An answer may be deferred whenever KES queries you for an attribute value. To defer an answer, enter a command instead of an attribute value when queried. This causes KES to set aside its question, putting you in deferred question mode. When you are ready to answer the question, enter 'continue'.

Ready for command: h explain

explain or explain POSSIBLE VALUE NUMBER

The 'explain' command allows the user to get additional information about an attribute or, in the PS subsystem, a class. If 'explain' is followed by a number, information about the corresponding possible value is displayed.

Ready for command: h justify

justify ATTRIBUTE-NAME
justify VALUE 'in' ATTRIBUTE-NAME

The 'justify' command provides two types of explanation for the values of attributes. The first option cites knowledge sources (rules, externals, etc.) used by the inference engine to infer the value of the attribute named by ATTRIBUTE-NAME. The second option explains why the value VALUE is currently assigned to the attribute named by ATTRIBUTE-NAME.

Ready for command: h show

show ATTRIBUTE-NAME or CLASS-NAME

The 'show' command obtains the value of an attribute or the members of a class, then displays the value of the attribute or the members of a class.

Ready for command: h why

why

The 'why' command, when entered as a response to an attribute value query, causes KES to display information that answers the question:

Why is KES asking for a value for this attribute?

KES shows which goal attributes led to this question. The goals are traced back to the initial request for a KES attribute value.

In addition to displaying the goal attributes, KES gives you the opportunity to examine those knowledge sources that were used to establish the shown goal chain.

Ready for command: h display

display OPTIONS

The 'display' command prints information about OPTIONS, which can be an entity within the knowledge base, or a section of the knowledge base.

OPTIONS are:

'actions', 'externals', 'patterns', 'rules',
 'attributes', 'inferred' 'attributes', 'input' 'attributes', 'classes',
 'subclasses', 'subclasses of' CLASS-NAME,
 'values', 'values of' MEMBER-NAME,
 'members of' CLASS-NAME, VARIABLE,
 'tree', 'tree' 'of' ATTRIBUTE-NAME or CLASS-NAME, NAMED-ENTITY,
 'attach' 'names' 'of' 'kb',
 'attach' ATTACHMENT-NAME 'of' 'kb',

'attach' 'names' 'of' NAMED-ENTITY,
'attach' ATTACHMENT-NAME 'of' NAMED-ENTITY

where NAMED-ENTITY can be:

PATTERN-NAME, EXTERNAL-NAME, RULE-NAME, DEMON-NAME,
CLASS-NAME
VALUE-NAME 'in' ATTRIBUTE-NAME,
'value' 'of' ATTRIBUTE-NAME

Ready for command: c

Enter your option:

1. Continue
 2. Justify limits
- =? 1

