Development of an Expert System for Cutting-off Process Selection

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CONTENTS

ITEMS	PAGE

Abstract

The manufacturing engineer is faced with many different processes and a wide variety of alternative combinations of parts and cutting-off tools. The problem is therefore to select the optional and most economical combinations of processes and parameters for cutting-off a given product. To assist in this problem, each cutting-off tool or machine manufacturer and supplier recommends cutting conditions for their products which are neither consistent nor have a scientific base. As with other machining technologies, the cutting-off process domain has an abundance of data, but very little documented knowledge.

It was proposed to undertake an investigation into the possibility of using a knowledge-based system for the selection of cutting-off processes, cutting-tools and the associated parameters.

This project uses a survey to investigate the U.K. industry practice in the selecting of cutting-off process and machines used in their business and the nature of their business. The survey method, design and survey questionnaires as well as the findings are also reported.

From the survey finding and interviews with experts, a prototype system structure has been developed. This system is similar to an expert's thinking in solving a problem. The structure of the system and how it works is also revealed in this report.

The steps in building an expert system are discussed in this report, it states what is knowledge acquisition and the problems and methods used in knowledge acquisition.

After the system was built, it was subjected to a through test programme. The testing procedure and industry validation process are discussed in the report. The testing results are analysed to show that the use of using an expert system in the selection of cutting-off process is feasible.

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List of figures

Page

List of tables

Chapter 1

Introduction

1.1 Background

Cutting-off process selection know-how is built up over time by practical experience by practitioners. As with other machining technologies, the cutting-off process domain has an abundance of data, but very little documented knowledge. Problems faced by the cutting-off companies include the loss of expertise as skilled personnel leave and who cannot be replaced. There is no procedure or systematic approach in selecting cutting-off process and their cutting parameters. This work is therefore aimed at capturing expert knowledge in this field and making this knowledge available to assist manufacturing engineers, who need to select cutting-off processes and their parameters.

The situation described above is a common occurrence in many companies. It is therefore necessary to collate all of the cutting-off process, parameters and their selection information. This may be stored in a knowledge base and be used to provide a comprehensive assistance for the selection of cutting-off processes, parameters and their selection. Therefore the errors can be eliminated and time savings made in decision making. This results in enhanced efficiency and hence reduced cost of manufacturing, with an additional gain in product quality.

Therefore the feasibility of using a knowledge based system for the selection of cutting-off processes, cutting tools and associated machining parameters needs to be investigated by developing a prototype system for demonstrating the suitability of this approach.

1.2 Aims and objectives

The aims of this project are therefore to:

a. Review the cutting-off processes.

b. Research the current industrial practice in U.K. for cutting-off.

c. Review the published research work and develop a methodology for cutting-off process selection.

The objectives of this project are therefore to

a. Carry out a feasibility of knowledge base approach to cutting-off process selection.

b. Investigate the feasibility of automating the selection of cutting-off process in order to assist the manufacturing and engineers.

c. Test and validate the system, and comment upon the results and conclusions.

1.3 Cutting-off process

Today there is a diverse range of processes and tooling available to perform the basic function of cutting-off. These techniques can be divided into processes that do not generate waste and those that do. These can be classified into the broad process categories of shearing, sawing and abrading.

A. Shearing

Shearing is the process of cutting materials without the formation of chips or the use of burning or melting. The required shape of work is sheared from the metal strip by blades, the metal being deformed to shear failure. When both of the blades are straight, the process is called shearing. If the edges of either the blades or the dies are curved, the processes have special names, such as blanking, piercing, notching, shaving and trimming. All of these are essentially shearing operations.

The amount of clearance allowed between the punch and the die effects the appearance of the blanked edge and the accuracy of the finished blank. The clearance varies with the thickness and hardness of the metal being sheared, and can be up to 10% of the strip thickness.

B. Sawing

Sawing is the process in which chips are formed by a succession of small cutting edges, arranged in a narrow line on a saw "blade". Appendix 1 discusses the different sawing processes. To facilitate the sawing process, various motions and forces are required. The feed motion and feed force causes the tips of the teeth to penetrate the workpiece (figure 1.1). The cutting motion causes the sawing which ensures chip removal. The sawing rate varies with the feed rate and cutting speed. The sawing rates are limited by the following factors:-

a. The material to be cut e.g. uniformity and hardness.

b. The saw blade material.

c. The heat treatment of the cutting edge.

d. Feed per tooth.

e. Size of chip space in the gullet.

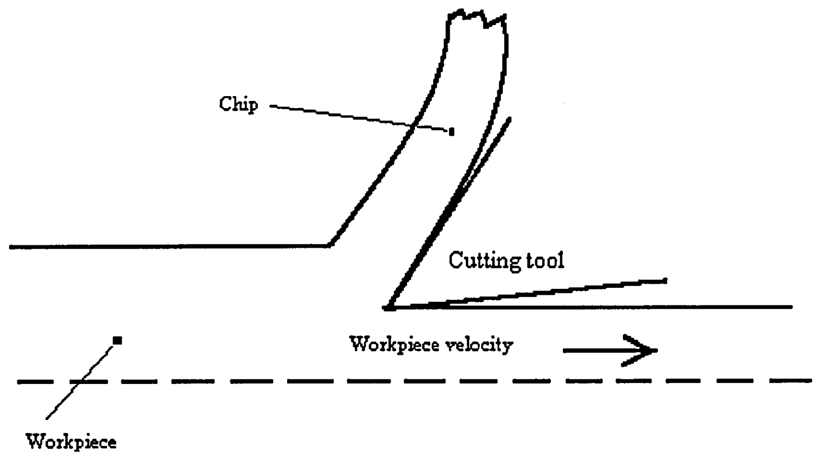

Figure 1.1 Cutting action

The properties of material to be cut, those of the saw blade material, and the heat treatment of the cutting edges all greatly affect the cutting speed. Soft steels and non ferrous metals may be cut at relatively high speeds. This can prevent the teeth clog in the workpiece. With increased alloying of the workpiece ,or heat treatment increasing material hardness, the cutting speed must be reduced [1]. This is because more cutting force is required to perform the operation, hence the temperature increases. In order to maintain the tool life, cutting speed must be reduced.

Heat treatment of the saw blade cutting edges increasing their hardness permits higher surface speeds. However a high degree of heat treatment will increase the susceptibility to fracture of the cutting edge. By contrast, a hardened high speed steel or a bimetal tool is considerably less sensitive [1]. This is because the saw blade is tougher than heat treated saw blade.

C. Abrading

Abrading is the process in which chips are formed by the small cutting edges on abrasive particles or abrasive grit. Description of abrasive cutting is shown in Appendix 1 (A.1.4). Abrading is the oldest of the basic machining processes. Abrading has two unique characteristics. Firstly, the cutting edge is very small and many edges are cutting simultaneously. When suitable machines are employed, very fine cuts are possible, and very smooth surfaces and close dimensional control can be obtained. Second, the abrasive cutting edge can be made by very hard abrasive particles. Very hard materials can be machined with ease.

The abrading tool presents a series of multi-point cutting tools to the work. The size of the chips removed depends upon the grit size used in the cutting tool. Therefore a fine grit should be used for finishing operations as it will remove finer chips and leave a smoother surface finish.

The ideal cutting action is achieved when the work is wearing away the bond at the same speed as the grains are dulled. Hence the dulled grains are torn away, exposing fresh grains. This action is known as 'self sharpening'.

1.4 Problems in selecting cutting-off processes

Sawing is the most widely used method for performing the cutting-off process. Sawing machines that perform this function include bandsaws, hacksaws and circular saws. Different machines have different speeds, material losses, surface finish and power consumption. Therefore the choice of a cutting-off process can be a complex one and to complicate the choice, there are non-sawing techniques available for cutting materials. Whereas all sawing involves the cutting action of a series of small teeth, other basic machining methods can be adapted so that essentially the same job can be accomplished.

Power hacksawing is characterised by the reciprocating action of a relatively short, straight toothed blade that is drawn back and forth over the workpiece in much the same manner as a hand hacksaw. It differs from other sawing methods in that the back-and-forth motion of the blade makes a non-continuous cut.

Circular sawing machines are used exclusively for cut-off operations. The work is positively clamped and the saw blade fed into the work. The machine should have the necessary speeds and feeds to cover the range of work to be cut.

Band sawing machines are considered more versatile than any sawing machine previously discussed. They can perform simple cut-off, cutting along straight, curved lines. Band saws employ the continuous cutting action of an endless high speed toothed blade. Band saw machine can be classified as vertical machines (for straight and contour sawing), horizontal machine and vertical machine (used exclusively for friction sawing). More and detailed description of cutting-off process is given in Appendix 1.

The manufacturing engineer is faced with many different process specifications and a range of combinations of parts and cutting-off processes. To assist in the cutting-off process selection and its parameters, each manufacturer and supplier recommends cutting conditions for their products which are neither consistent nor do they have a scientific basis [2, 3, 4]. This is primarily due to the following factors:

i. Long term research into the machining processes associated with cutting-off have not yet produced comprehensive and widely applicable process parameters.

ii. There has been no attempt to collate and assimilate the body of knowledge used for cutting-off process selection purposes.

iii. Manufacturers regarded cutting-off process as a low level (technically) process.

Due to these problems, the cutting-off machine suppliers are dependent upon qualitative data and experience from tool manufacturers and users in order to select the appropriate process and cutting conditions.

In selecting cutting-off processes for a range of materials and cross sections, the manufacturing engineer is faced with many options. Currently, selection is based upon individual experience, knowledge, tool suppliers recommendations and known machine capabilities. The engineers approach to problem solving in these processes has been intuitive rather than systematic .

Each process has its own characteristics, the selection activities involve matching the requirement of the workpiece with the process capabilities of the selected processes. Selection of a particular cutting-off process depends not only on the parts to be cut-off but also on a large number of other factors. Some processes can cause change in the properties of the workpiece. Size, thickness and shape complexity of the part have a major bearing on the process selected to produce it. Before considering the type of cutting-off process or the saw type, the requirements of the operation should be carefully defined. For example, what productivity is required, how important is the surface finish, squareness, is the kerf loss (width of cut) critical, what space and power are available, workpiece configuration, material, size, weight, metal removal rate, tolerance etc.. This specification should then enable the basic process type to be identified, if not the actual saw type. Both the machine and saw manufacturers should be asked to recommend a suitable combination. If a particular process is found to be unreliable for producing the accuracy or surface finish required, another process must be chosen.

Sometimes these factors are closely related and the influences of quality on selection possibilities is an important consideration. For fast metal removal rate, fast cutting speed and feed will leave a poor surface finish on the workpiece compared, with a fine feed.

Good results can be obtained by proper selection of parameters and careful operation. High production requirements usually necessitate using more rigid and costly machines, often equipped with automation devices. Therefore the approach of process selection and manufacturing cost must be considered and balanced.

It is now widely accepted that a systematic approach to problem solving is needed for routine use. The program designer must implement a set of specific objectives for investigating the needs and circumstances of the selection activity, and the synthesise these selection objectives into an optimum solution. The manufacturing engineer and sometimes the machine operator builds up a pool of knowledge and experience over time; this is used to select cutting-off processes.

All cutting-off processes have their characteristics, advantages and limitations. For example, tolerances and surface finishes are important aspects of manufacturing. This information can be elicited from experts, handbooks and put it into a knowledge base. In the case of manual selection, the expert uses trial and error methods to test for the optimum result.

Chapter 2

Literature Review

2.1 Introduction

This chapter reviews the existing cutting-off processes, expert systems in related selection work and cutting-off process selection.

2.2 Cutting-off process selection

K. Ishli, C. H. Lee and R. A. Miller [5] pointed out many handbooks which provide a qualitative guidance in selecting a process. However they do not provide a systematic means of comparing the suitability of each process for a given specification. Therefore many engineers select a process based on their experience, trial and error and testing programmes.

The major factors that influence the selection process are:

a. Workpiece material condition
b. Tolerance
c. Surface finish
d. Kerf loss
e. Workpiece material
f. Part shape and size

These factors are normally referred to as the functional requirements [5].

Before discussing the process selection method, it is useful to give a brief summary of how each major factor affects process selection:

a. Material condition

The workpiece material hardness can determine the use of saw material. For example different saw blade materials have their own characteristics, such as an H.S.S. saw blade, which can only saw workpieces up to 400 Vickers hardness. More power is required to cut material with higher strength so temperature will increase. Therefore cutting must be reduced to maintain the tool life. Figure 2.1 shows the hot hardness of different cutting tool materials. The hardness of materials reduce when the temperatures increase. It can be seen that for lower temperatures, carbon steel are used and for higher temperatures, carbides and ceramics need to be used.

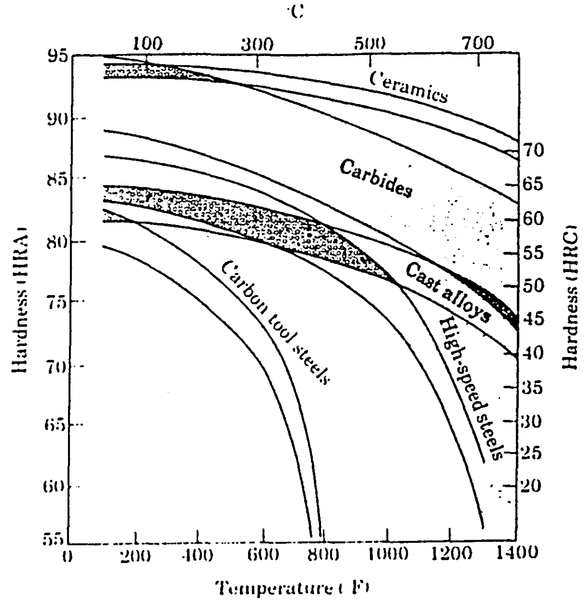

Figure 2.1 Hardness of various tool materials as a function of temperature [1].

b. Tolerance

Different cutting-off processes have different tolerance limitations (figure 2.2). In fact, there is a range of tolerances for which each process can be employed most economically. It is noted that tolerances are usually derived from mechanical, environment or aesthetic requirements.

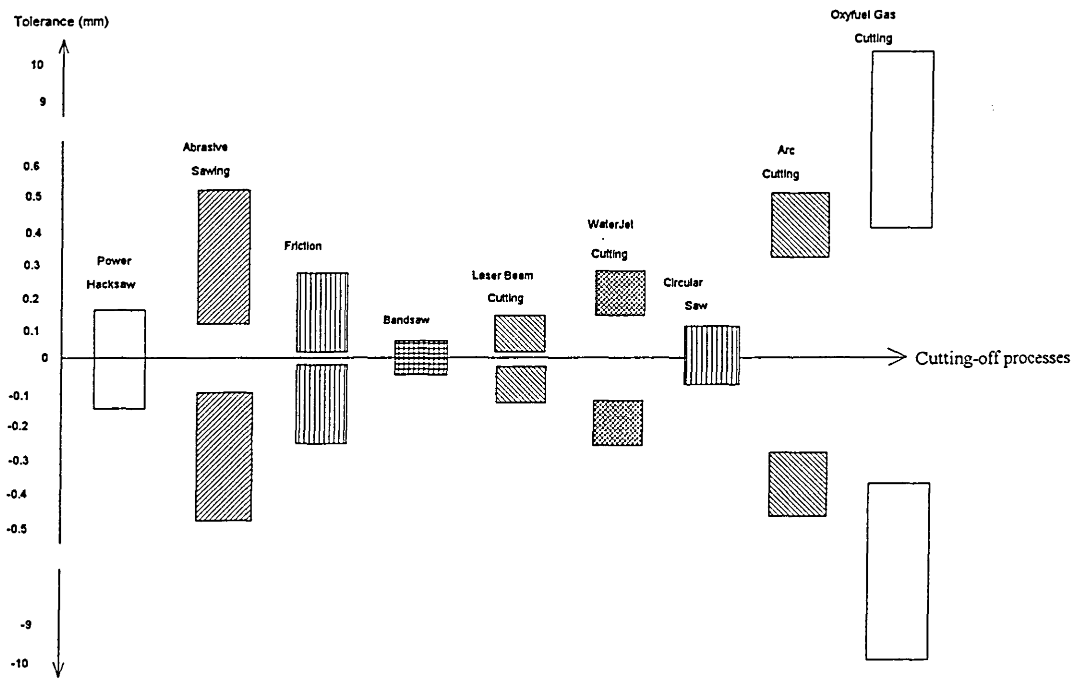

Figure 2.2 Different cutting-off process tolerance range [6, 13, 14].

c. Surface finish

There are many types of surface finish specifications, and each process has its limitation (figure 2.3). This can also be effected by speed and feed rates used in the processing.

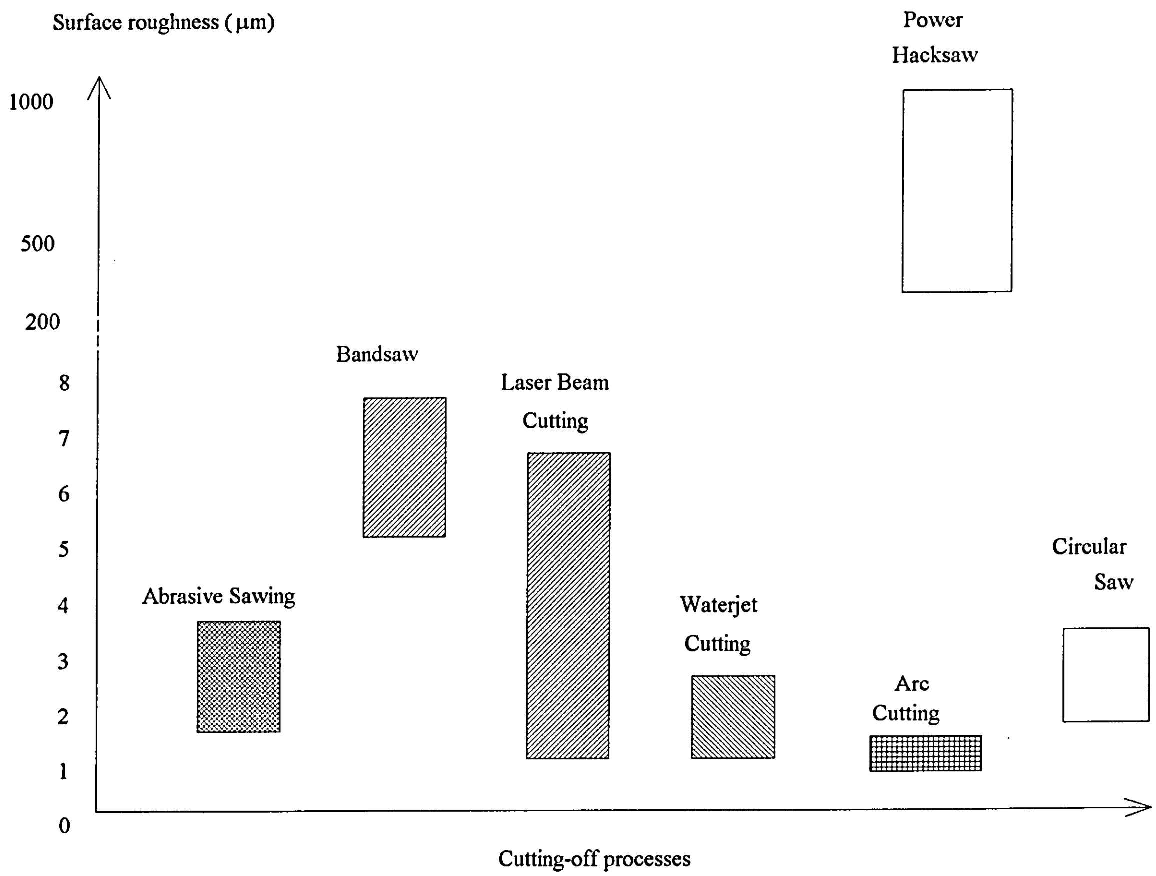

Figure 2.3 Different cutting-off process surface finish ranges obtainable [6, 13, 14].

d. Kerf loss

The cutting-off process removes material in the form of chips. For economical use of material, the width of cut (kerf loss) must kept to as small as possible, minimising material waste. Each process has its limitations (figure 2.4).

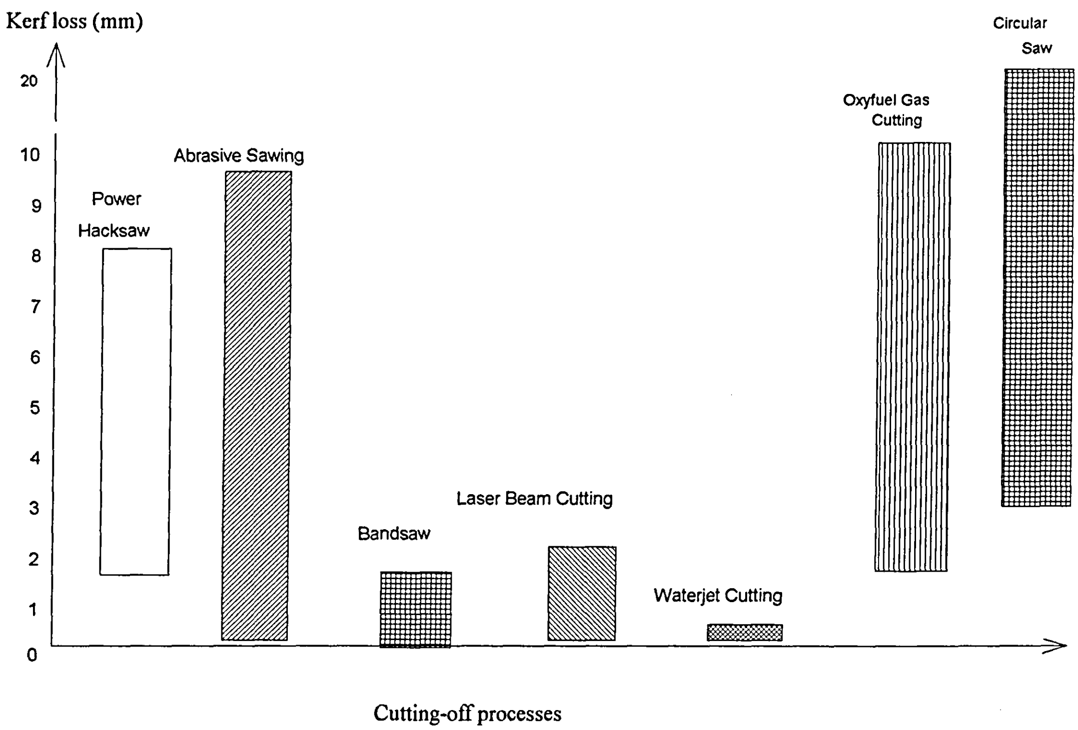

Figure 2.4 Kerf loss of different cutting-off process [6, 13, 14]

e. Material

The physical properties of the material to be cut have a major effect on the part design, tooling, feed and speed rates used and the capacity of the sawing machine required. Their influence on the type of machine is generally minimal [6]. The material is primarily dependent on the physical and mechanical properties required [5]. In actual practice, the properties are considered are strength, hardness, and stiffness/ weight ratio. These material properties directly influence the production methods by which the material is worked.

f. Part shape and size

Both the size and geometry of the stock to be cut are important considerations because they determine the machine capacity and affect the type of sawing machine and process to be used [6].

Early published work (before 1970) on cutting-off process are concerned with a general description of the power hacksawing, circular sawing and bandsawing [7, 8, 9] and comparisons between these alternative processes [10, 11, 12]. From cutting-tool manufacturer's recommendation and handbooks [13, 14], the manufacturing engineer can select the cutting-off process and tools.

2.3 Reported uses of expert systems for selection tasks

Expert systems have provided business organisations with practical solutions to complex problems over the last decade. As computers increase in power while costs decline there is an increasing expectation that high volume low-level decision making will be delegated to machines releasing people for low volume high level decision making. These are factors which conventional computer systems cannot handle. The number of companies that use expert systems has grown significantly in the past few years, and many more organisations are now introducing them. Expert systems technology is receiving attention from industry, commercial businesses, as well as medical concerns and government departments because of its potential to help solve previously intractable problems and increased competitiveness.

Expert systems allow companies to save time and money, distribute and preserve expertise, build upon knowledge, and as a result gain competitive advantages. The term expert system is taken to include the full range of techniques available to provide solutions to the machining process problems of planning, parameter selection, optimisation, parameter identification, monitoring, decision making and operational control [15].

Many expert system projects already have been completed in various related applications such as scheduling, cutting tool selection and robot gripper selection dtc..

Hyuk-Soo Jang and Amit Bagchi [16] attempted to combine the information from the part design and manufacturing data bases on machining processes, and use this knowledge base to select the parameters for milling, drilling, boring and other machining processes. The selection and use of the data bases can be done in several ways. Firstly, by manual examination of the data and selection of the appropriate speed and feed rates. A second possible method is more automated, it is to interface the data base manager with a rule based system to select the feed rate and speed. The data bases contain information regarding tool materials, workpiece materials, tool geometries and machining parameters for the milling, turning, boring and drilling processes.

H. S. Abdalla and J. Knight [17] use the approach of composing an integrated expert and computer aided design system (CAD) to enable products to be designed for manufacturability. The expert system contains rules for analysing the part features (topology and geometry), as well as their physical characteristics i.e. limits on pressure, and temperature, and possible materials, etc. These rules consist of a series of necessary and sufficient conditions. When the conditions of a rule are satisfied, then the conditions are "valid". The expert system rules have been used for recognising the feature types by matching the available feature's data with predefined feature characteristics.

Rules are the most popular technique for representing knowledge. In fact, they provide a formal way of presenting recommendations, directives or strategies. Rules are often appropriate when the domain knowledge results from empirical associations, which have been developed through years of experience of solving problems in an area [18].

W. A. Taylor [19] describes how welding engineers produced welding procedure. Initially, all relevant information about the weld is collected, such as the material thickness, and parent metal composition. Depending on the welding position and material, the knowledge is used to narrow down the options and select the most appropriate welding process.

R. Razfar and K. Ridgway [20], have aimed to use expert systems to replace humans in the selection of cutting tools and conditions for milling. Different kinds of milling process are involved in the knowledge bases, such as face milling and slot milling, etc.. The selection rules are elicited from books, technical catalogues and domain experts. The factors which effect the selection are: tolerance, geometric features, surface finish, workpiece material and machine tool characteristics. Minimum production cost or maximum production rate criteria are used in calculating the optimum machining parameters.

The first stage in their selection process is to identify a tool or tools which can mill the specified materials. The system uses geometry rules to identify the tools which are suitable for all features. The remaining tools are eliminated from the next stage of the process. After all the tools have been selected, the appropriate cutter diameter and inserts for every feature are selected using rule based constraints. The final stage is to select the remaining parameters such as insert grade, tool holding system, number of inserts and chip space.

P. G. Marpoulos, divides his selection method into five levels [21]. The method commences by deriving a local optimum solution at the process planning level, which is progressively optimised in the wider context of the shop floor. The selection method allows the implementation of the minimal storage tooling (MST) concept, by linking the ordering of new and replacement tools to production control. Intelligent tool selection (ITS) also uses the concept of tool resources structure (TRS), which specifies all tooling resources required for producing a component. By using the framework provided by ITS, TRS and MST it can be shown that tooling technology interfaces with diverse company functions from design and process planning to material/ tool scheduling and tool management. The selection methodology results in higher utilisation of tools, improved efficiency of machining processes and reduced tool inventory [21].

The first level is to provide tools which can produce the required geometry and machine the workpiece material efficiently, whilst satisfying all quality assurance considerations. Multiple tools are selected for each machining operation, and tool lists are formed by sorting selected tools in order of preference.

The second consideration is the tool replacement strategy. The main consideration at the second selection level provides a tooling solution for a component by considering all the operations required as well as the characteristics of the machine tool. The first objective of the tool replacement strategy is to machine an integer number of components with each cutting edge. The second objective is to balance the wear rates of tools so that tools are changed at optimal intervals and as many tools as possible are changed at the same time.

The third selection level is based on material orders and schedules produced by the material requirement planning (MRP) system. The selected tools are then rationalised by forming a set of tools for machining a variety of components on a given machine tool at level 3. When the number of tool positions on the machining centre is smaller than the total number of tools selected, the number of tools must be reduced so that it becomes equal to the number of tool positions and in this process geometric suitability is usually the first consideration.

The fourth level is multi-machine selection level which includes detailed considerations with regard to the layout of resources. It attempts to use common and standard tools within a group of machines. Having completed the first three tool selection levels, there is a set of tools allocated to each machine tool for machining either a certain product (level 2) or a product range (level 3) over a given period of time [21].

The fifth level is very much a planning phase and its various functions have widely different time cycles. The main objectives of the fifth level are to reduce tool inventory by classifying existing tools into categories according to their usage . This level is also used for introducing new tools into the manufacturing system, and to define the overall tool requirements and manage the efficient allocation and distribution of tools to machining resources.

After the processes were selected, the general machine selection function was based upon machine availability [21]. Along with the general performance of the machining process, the machine must meet other specifications in order to qualify for the machining process of the part [22]. The prototype system will use the six major factors to sort out the specific process and its cutting parameters. Any process which can not satisfy the six factors requirement when cutting a part, will be eliminated from the selection process for that particular part.

The selection of a cutting-off parameters from the knowledge base can be achieved in several ways. One may, for instance, scan a section of the data manually and select the most appropriate speed and feed rate. The expertise of the user plays an important role here because the choice between a higher feed rate and a low speed or a lower feed rate and a higher speed combination (both of which can have the same material removal rate), for example, has to be made [23].

Metal removal rate = Cutting speed * Feed * Depth of cut

If depth of cut is kept constant, the cutting speed and feed varies, it can obtain the same metal removal rate.

The second method is a more automated method. The cutting-off parameters are saved in a spreadsheet program, which interfaces with a rule based system to select parameters including the speed, feed rate and cutting tool pitch. For this research, the second approach was adopted in order to automate the process and parameter selection, making its results less error prone and more consistent with different users.

2.4 Reasons for using an expert system in preference to conventional program

Expert systems attempt to produce results identical to such as those produced by people. Computers already emulate some of the simpler activities of the human mind, greatly speeding up some aspects of the human thought process, and usually exceed humans in performance. Expert systems enable us to go further: and allow us to automate or enhance more complex tasks which are normally only carried out manually [25]. For example, Davy Mckee is using an expert system for designing rolling mill instead of manual designing process. The expert system contains the equations and informations needed for designing the rolling mill. The solution come out in several minutes by expert system. The manual process takes several days to calculate the equation (such as roller size, roller distance) and look through the informations to arrange the bearings and its accessories.

Expert systems have several advantages over human knowledge [25].

a. Artificial intelligence (AI) is more permanent. If humans change their places of employment or forget information, it causes a knowledge loss. AI, however, is permanent as long as the computer systems and programs remain unchanged.

b. AI offers ease of duplication and dissemination. Transferring a body of knowledge from one person to another usually requires a lengthy process of apprenticeship; even so, expertise can never be duplicated completely. However, when knowledge is embodied in a computer system, it can be copied and transferred to other computers, sometimes across the globe.

c. AI can be less expensive than human knowledge. There are many circumstances in which buying computer services costs less over a long period compared with having corresponding human experts to carry out the same tasks.

d. AI, being a computer technology, is consistent and thorough. Human knowledge is erratic because people are erratic; they do not perform consistently.

e. AI can be documented. Decisions made by a computer can be easily documented by tracing the activities of the system. Human knowledge is difficult to reproduce.

There are several reasons of using artificial expertise to assist the practitioners [25].

a. Artificial expertise is permanent, whereas human expertise can quickly fade, whether it involves mental or physical activity. The expert needs continuous work to maintain his/ her professional knowledge in an area, but artificial expertise is not related to its use.

b. Once an expert leaves the company his expertise is lost, however this does not apply to the artificial expert.

c. Artificial expertise is easy to transfer [26]. Data can be copied from one computer and installed into another computer.

d. Artificial expertise gives more consistent results than the human expert, who may make different decisions in the same situation because of emotional factors [27].

e. The most obvious advantage is the cost; human experts are very scarce and are therefore very expensive. Expert systems are relatively inexpensive, they are costly to develop but cheap to operate [27].

f. Human experts do not explain why they make such decisions, but expert systems can provide explanations of the result easily. It is a straight forward mapping between the way in which the knowledge is represented in the system and the natural language description of the representation [27].

Reasons for using expert system rather than a conventional program

a. Expert systems contain declarative data - statements of "what" instead of "how". Often the very reason an expert system is used is that there is no known algorithm for solving the problem, or there may be more than one acceptable solution. These issues which complicate attempts at a solution using conventional programming languages [26]. Therefore expert system exhibit expert performance and have a high level of skill. They uses their knowledge to produce a solution both efficiently and effectively, using the shortcuts or tricks that human experts use to eliminate unnecessary calculations.

b. Expert systems use an inferential process to solve problems so that they can provide explanations for the decisions made [27].

c. Expert systems use a "rule of thumb" or other devices which simplify, or limit the search in large problem areas where conventional programs use algorithms [27].

Expert systems have their origins in traditional data processing. They are the result of continuous attempts to improve and extend the automation of some aspects of human information processing. In order to accomplish this task it is necessary to represent in a computer system the nature of the data and processes involved. An expert system uses knowledge, facts and reasoning techniques to solve problems that normally require the abilities of human expert.

Sometimes an expert system is called an "Intelligent Knowledge Based system". It is a computer system containing expertise in a particular area [26]. If anybody has professional knowledge in a particular field, he can describe the problem solving method, and by using this method an expert system can be built.

An expert system is a program containing a large body of knowledge in one specified field. The program encodes the knowledge of experts and uses techniques other than conventional computer languages to represent that knowledge. This is provided by one or more human experts and the system is able to achieve the same performance in problem solving as those experts. Frequently, experts posses knowledge which is extremely valuable but which can not be expressed easily in conventional computer programs. Their knowledge often relies on experience from past situations which is reapplied when necessary to deal with a similar situation.

In general, this knowledge will be organised as a collection of rules that allow the system to draw conclusions from given data or premises [27]. It also acts as a diagnostic system: given an appropriate set of information it will make some form of judgement or recommendation. If it cannot do either of these, it will ask for further information which will help it to make such a judgement.

To build an expert system program, extract the relevant and all necessary information and build around it. The selected problem (selection of cutting-off process) is a relatively fixed system whose data is unchanging and which requires a great deal of work from a knowledge engineer to build. However once the system is complete, it is robust and likely to work consistently within the tolerance that the industry requires.

This system can help to solve problems that cannot be handled effectively by conventional systems. The types of problems that normally lend themselves to successful expert system solutions include diagnosis, configuration, planning, scheduling, selection, matching and routing. Many of these tasks have the characteristics listed below:

i. The problem cannot be solved easily using a conventional solution because (1) no algorithm is known for solving it completely, or (2) the problem is too complex to be presented in conventional programming languages. For example, Dustpro is a small rule based system developed by the U.S. Bureau of Mines [25]. This system can replace dust control engineer to re-evaluate and reassign facilitates each time operating conditions change. Dustpro advises in three areas: control of methane gas emission, ventilation in continuous operation, and dust control for the mine's machines [25].

ii. The problem requires primarily symbolic, not numeric, reasoning. For example, help desks are important in providing technical information about procedures and regulations. Due to the increased complexity and quantity of the stored information, traditional computerised solutions include searching database is becoming less effective. An expert system help desk is created at Harris Corp's headquarters [25], this help desk provides a hot line for employees to troubleshoot problems in computer hardware and networks.

iii. A tool is needed to facilitate prototyping (building an early version of the application), for recording later in a conventional language. For example, EXTELCSYS was built using rapid prototyping methodology [25]. This system contains fifteen rules and ten choices. It can determine: what type of instrument should be installed; what make; what model; if the line should be capable of receiving incoming calls from offpost; how it should be installed depending on the required location within the medical centre; and a selection of user requirements [25]. After the first prototype was tested, new rules, qualifiers, variables, values, choices, and so forth, were continually added until the basic features and/ or requirements known to the experts were included.

2.5 Expert system tool selection

Choosing a suitable expert system tool is a major decision in the development process. Different kinds of expert system tools are listed in appendix 2. The selection will depend on several important factors. For example, is the programming capability available in house, and which languages are used? What type of computer system will be used to develop the software and what is the user's host computer? The time and funds available to develop the software will also affect the selection of the tool.

If knowledge engineer or programmer is familiar with programming language, it is the best to use programmable language and try to match those language with tools that can run on the computer.

A programmer should be able to write code quickly if he is familiar with the language.

If sufficient funding and time is available and other systems are also to be designed and built, it may be worthwhile to acquire expertise in LISP or PROLOG languages. LISP and PROLOG interpreters are available for almost any machine [25]. PROLOG has a built-in inference engine. The knowledge engineer need to format the knowledge in terms of facts and rules. LISP also has an inference engine, but with LISP knowledge engineer have to implement search, pattern-matching, and other system features from scratch [25].

The quickest and simplest approach is to use a shell. If this is the first expert system development project, a using shell is most suitable. This is because an expert system shell contains: inference engine, explanation facility, interface subsystem, knowledge acquisition subsystem, knowledge base management facility and knowledge base. The knowledge engineer encode the knowledge in the knowledge base then the shell can be used for many applications. There is no need to program the first five subsystem. If a shell is available for the computer and within the project budget, it is necessary to determine whether its capabilities match the problem. The programmer will need to undertake some knowledge engineering to determine whether the domain can be expressed properly in rule format.

Xi plus [28] is an expert system shell. Xi plus provide a complete development environment on micros. The user interface is rich of commands, you can ask why the system asks this question, volunteer information, temporary pause the consultation process to review the data. The developer interface can allow the rules delete, move or copy from the knowledge base, checker, advisers, tracing and cross referencing tools.

It uses standard rule "If...Then", the inference mechanism is forward and backward chaining as well as demons and some other quite complex control methods[28]. In Xi Plus, the knowledge base items such as facts, rules etc. are expressed in a form similar to simple natural language.[28] The knowledge base contains the domain expertise. It is also known as Rule Base, specially when expert system uses production rules (If ... then ...) to represent knowledge. Since knowledge base is independent of the inference engine, any number of expert systems can be developed by creating knowledge bases for each application [28]. When production rules are used they can be appended to the knowledge base in any order. This permits the modular development of knowledge bases.

In an application, it can contain more than one knowledge base. When build a knowledge base, developer can define and control the contents of each knowledge base. When querying a consultation, one knowledge base is held in memory at any one time but each knowledge base still communicate and share data to each other [28].

Xi plus can display graphical image, retrieve data from lotus 1-2-3 and have some program interface such as Assembler, C and Basic [28].

Xi Plus is an expert system shell which can be embedded in any other software system is also available and in most expert system shells, knowledge items can be expressed in English.
The reasons of using Xi plus are:

1. Knowledge items can be expressed in English like a statements, such that it is easy for debugging and understanding the knowledge base.
   For example,
   IF number of wheels = 2
   AND power source is engine
   THEN vehicle type is two wheel motorbike
2. It can communicate with other software systems such as Lotus, Databases and graphics, etc.
3. It can be implemented in any type of computer system such as a main frame or a PC.
4. The knowledge base can be input by word processing so the spelling error can be corrected before import to the Xi plus.

2.6 Conclusions

From the reported expert system for selection tasks, their attempts are success. Therefore it is a possible solution for using expert system in selecting cutting-off process selection and its parameters. Expert system shell (Xi Plus) have the ability to build up a prototype system to undertake this project.

In order to make the prototype system easy for understanding, each knowledge base will contain one cutting-off process's characteristics. The consultation process follow a planned steps in each knowledge bases. After it has finished the consultation in one knowledge base, it will go to the next knowledge base.

Chapter 3

Cutting-off process selection: Industrial practice in U.K.

3.1 Introduction

Although the cutting-off process is used in all types of discrete manufacturing industry, different companies have different methods of selecting the cutting-off processes, tools and the cutting parameters. There is little published information available on how and what tools companies used to make these decisions and what type of cutting off processes are used by industry. Therefore a national survey carried out to obtain this information. This kind of information will be used in developing the selection prototype system.

3.2 Objectives of survey

Initially it is necessary to identify the real basis for the selection procedure, and also the current approaches to the selection process. Hence a U.K. national survey was undertaken to obtain the required information about the cutting-off process and practices. The companies involved are cutting-off process users, cutting-off tool suppliers and cutting-off machine tool suppliers. In the cutting-off process selection procedure, three major things need to be considered. They are the cutting-off processes, the cutting-off tools and the cutting-off machine tools. Therefore this national survey collected information on all these three categories.

3.3 Survey design

The "cutting-off " industry can be divided into two distinct sections, namely, (i) process user and (ii) the suppliers vendors. The suppliers can be further divided into machine tool supplier and cutting tool suppliers.

The survey was designed to elicit the following information from the categories shown:-

1. Process user

It is necessary to determine the actual practice in U.K. industry, i.e. the most widely used processes, the most common machine types, ages of the machines, and the capacities and production practices in U.K. industry.

2. Cutting-off tool manufacturers

It is necessary to determine the types of cutting-off tools, materials and quantities produced.

3. Cutting-off machine manufacturers

It is necessary to determine the types of machine tools produced, number of machine sales, the machine capacity and degrees of automation involved.

3.4 Selection of the survey method

There are several methods for carrying out surveys, including telephone interviews, personal interviews, and mail questionnaires [29]. Telephone interviews and personal interviews can provide very accurate information and a high response rates however costs can be high. For personal interviews, it is difficult to cover all U.K. companies to get all the information as it would be very time consuming and expensive [29].

The postal questionnaire method is by far the cheapest method [29] but it has the lowest response rate (that is, only those most interested or highly supportive are most likely to respond) [30].

3.5 Design of questionnaire

The problem was set out clearly and the logical implications see figure 3.1 for cutting-off process user, figure 3.2 for cutting-off tool manufacturer and figure 3.3 for cutting-off machine manufacturer. The questions are closely related to the problems under study. The questionnaire must not be too long because respondents would loose interest. Each complex question was broken down into further smallest questions, so that the questions were simple and straight forward in order to avoid ambiguity [31].

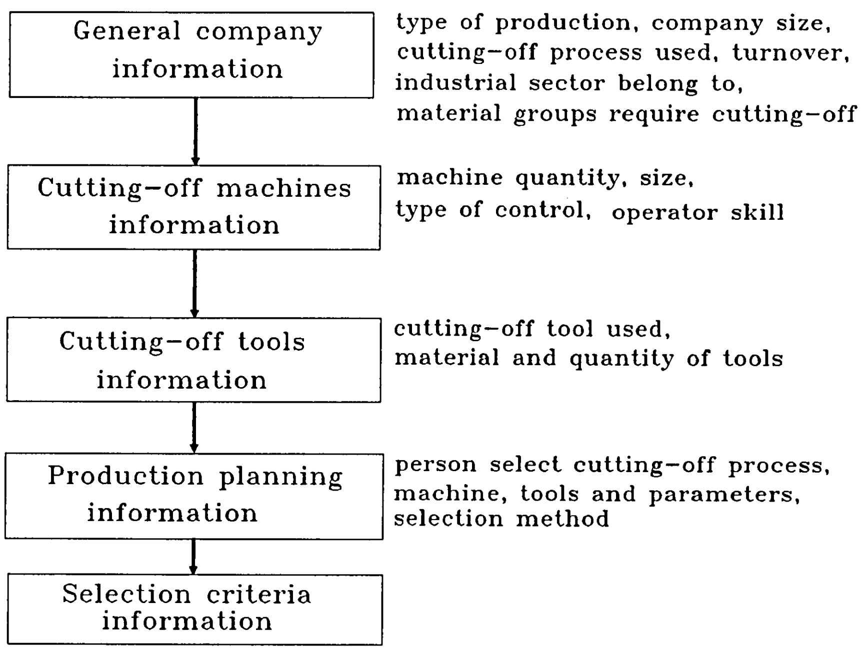

Figure 3.1 Cutting-off process user questionnaire layout

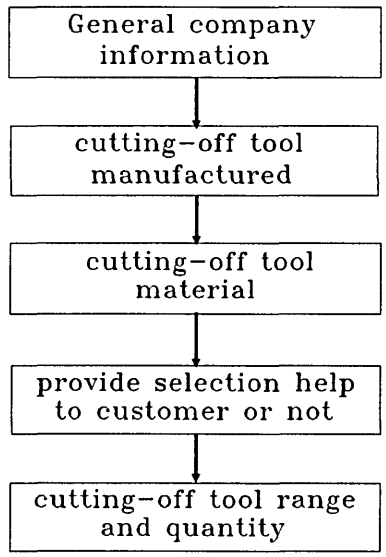

Figure 3.2 Cutting-off tool manufacturer questionnaire layout

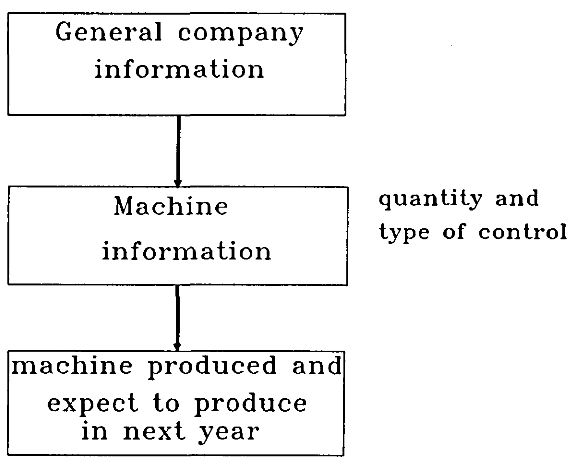

Figure 3.3 Cutting-off machine manufacturer questionnaire layout

The questionnaire designed for process users is divided into the following sections: (All three types of mail questionnaires are attached in appendix 3)

Section 1 for collecting general company information. Section 2 for collecting information regarding the cutting-off machine tools. Section 3 is asking about the information regarding the cutting-off tools. Section 4 is asking about the methods used and the people who undertake the selection of cutting-off processes, cutting-off tools, machines and their parameters. Section 5 covers the selection criteria.

From the answers, the methods of selection used for the cutting-off processes, machines, cutting tools and parameters can be collated. Computer assistance or manual approaches and what the major cutting-off processes used in manufacturing industry can also be determined.

The questionnaire designed for cutting-off tool manufacturers is divided into the following sections:
Section 1 asks about the general company information. Section 2 is about their cutting-off tool information.

From this, it is possible to identify the major cutting-off tools used in the industry. Are coated tools extensively used by the cutting-off industry or are they still using H.S.S. cutting tools as their major cutting tool? This information could indicate the market trend in the use of cutting tools.

The questionnaire designed for machine tool manufacturer is divided into the following sections:
Section 1 relates to general company information. Section 2 relates to the cutting-off machine tool information.

From the quantities of cutting-off machine production data in last financial year (1992 - 1993) and the expected production quantity in the next financial year (1993 - 1994), it is possible to determine the trend in the demand for cutting-off machines and also the trends in the use of cutting-off processes. It can provide the useful information for cutting-off tool and machine manufacturers.

These questions were simple but there were several possible answers, each of which required further information, so a series of questions was necessary. At each deeper level of questioning, the possible number of answers increases dramatically, and all these possibilities must be included in the questionnaire [31]. A list of the most common answers was given to the respondent, with opportunity to specify a different response if necessary. For example, "How does your company select cutting-off machine tools? The possible answers include "manual, use of computer, use of external expert advise, other methods". If the response was "Use of computer", then the next question was "Please give the name of the package."

Since the questionnaires was divided into three categories, each of these set out to draw information from different group of respondents. The first categories was the process user, as this is the major part of the survey. This is because the manufacturing engineer is faced with the dilemma of specifying the manufacturing process and the cutting tools from an increasingly large number of available alternatives for part manufacturers. The manufacturing engineer is also faced with many different process specifications and a variety of alternative combinations of parts and cutting-off processes.

3.6 Survey data analysis

The data was transferred to a tabular format and then presented in graphical form. The statistical data is easy to present and quite straightforward. A frequency distribution table of the answers to each question was constructed. The frequency distribution table was input into a Lotus 123 spreadsheet [32] and then transferred to the Harvard Graphics package [33] to present the data in graphical form. The data was represented in percentages rather than frequencies. The purpose of using percentages is to make comparisons easier. It is important, therefore, to see exactly what their use implies so that they will not be misused. Firstly, it can serve to put qualitative characteristics into numerical form. Thus, it is possible to compare several cutting-off processes on the basis of use by saying that 16.7% use power hacksawing, 10.7% use abrasive cutting, etc. Secondly, percentages reduce two frequency distributions to a common base, thus making comparisons much simpler.

3.7 Survey results

The names of companies were obtained from the "Sell's Products and Services Directory" [34]. The reason for choosing this directory was that it was easy to access and it contained all types of industry in the U.K.. The postal questionnaire are presented in appendix 3.

Paul L. Erdos suggests that [35] no mail survey can be considered reliable unless it has a response rate of at least 50%. Therefore it can be claimed that the response cannot represent the whole U.K. industry practice. However it shows the current situation of those responded respondents, and is still valuable information. Mail surveys with a response of as low as 10% are not known, while rates of 90% have been reported on a number of occasions. It used to be thought that if the sample was of the general population, rather than of a special groups, strenuous efforts would be needed to bring the response rate above about 30 to 40 % [29].

All the graphs show the percentages of the responses in each answer categories, as a proportion of the total number. These are fully explained in each of the three categories of companies and the associated questionnaires in the next sections of this chapter.

3.7.1 Cutting-off Process user company

A total of one hundred and eighty four letters were mailed out for process users and twenty eight replies were received and seven responses did not meet the selection criteria such as they are not cutting ferrous or non ferrous steel, or were using lathe, cutter, drills, reamers for cutting, etc.. The response rate for process users was 15.2%.

Figure3.4 shows the distribution of the number of employees in the companies who responded. The graph shows that most of the companies who responded employed fewer than 50 people. Figure 3.5 shows the distribution of industry sectors of the survey respondents. Figure 3.6 shows the types of production of the survey respondents. These product types are (i) job (38%), (ii) batch (13%), job and (iii) batch and customer dedicated (6%), (iv) job and commission and restoration (6%), (v) job and batch (38%).

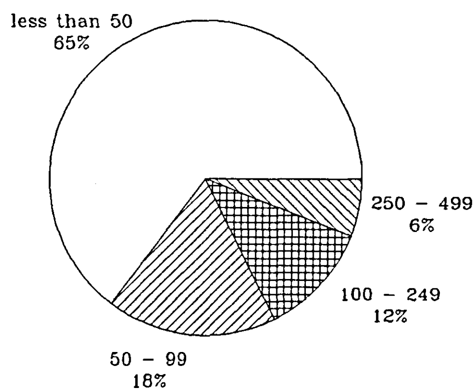

Figure 3.4 Number of employees employed in the cutting-off process user companies

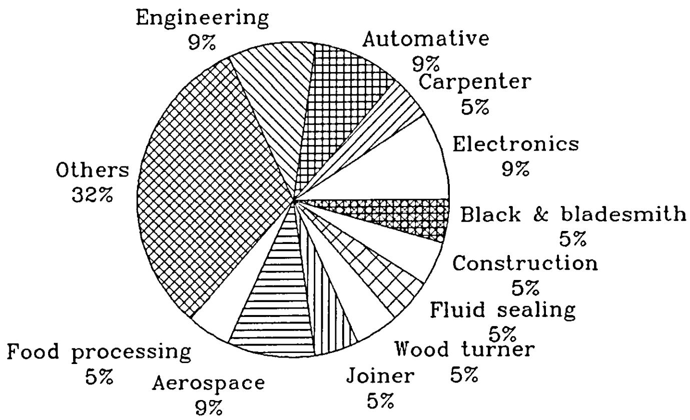

Figure 3.5 Industry sector of the survey respondents

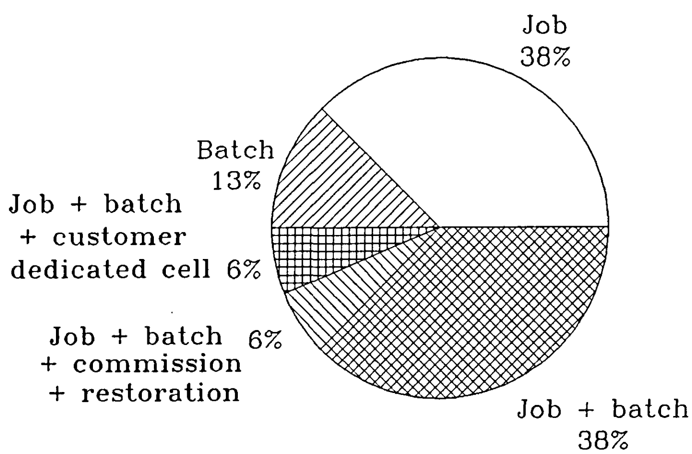

Figure 3.6 Production type of survey respondents

Figure 3.7 shows the types of personnel responsible for the selection of the cutting-off processes and Figure 3.8 shows the types of personnel responsible for for the selection of the cutting-off machines.

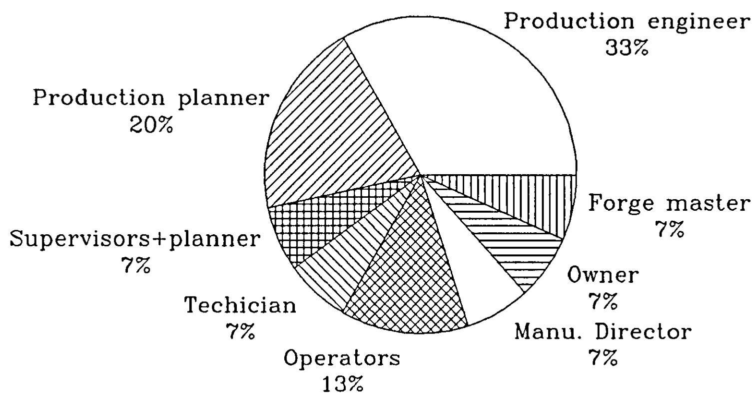

Figure 3.7 Personal responsible for selecting cutting-off processes

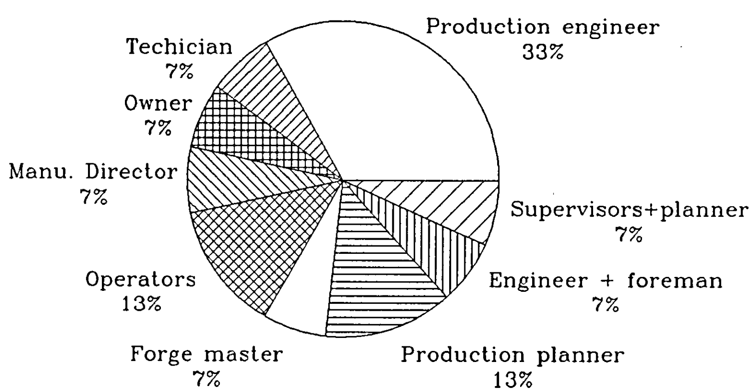

Figure 3.8 Personal responsible for selecting cutting-off machines

Figure 3.9 shows the types of personnel responsible for the selection of the cutting-off tools and Figure 3.10 shows the types of personnel responsible for for the selection of the cutting-off parameters.

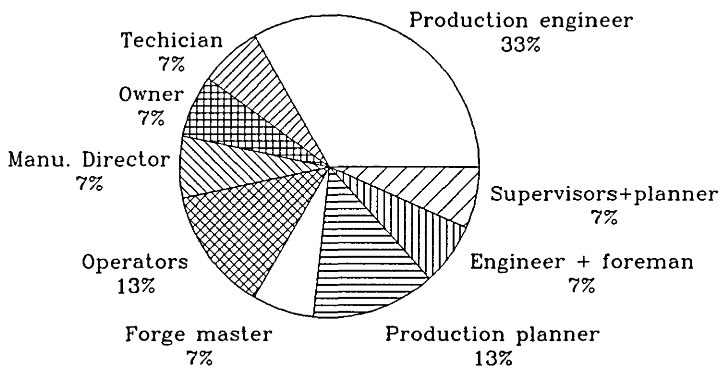

Figure 3.9 Personal responsible for selecting cutting-off tools

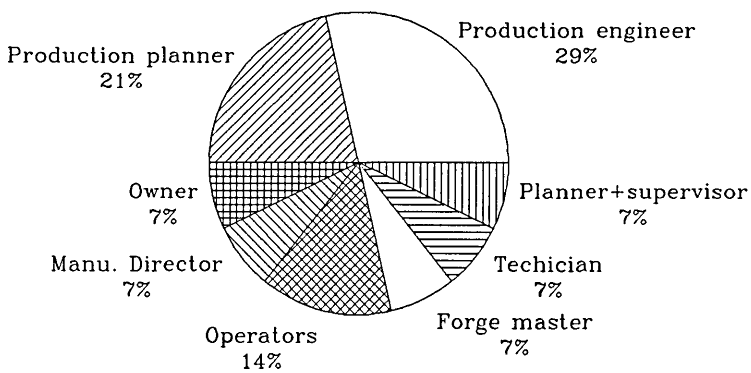

Figure 3.10 Personal responsible for selecting cutting-off parameters

The largest percentage of people involved in the selection were production engineers. A total of 33% of cutting-off machine and cutting-off tool selection decision were made by production engineers and 29% of cutting-off parameters were selected by production engineers. It seems that the selection decision were made by people with a technical background. No company selected the cutting-off processes, machines or cutting-off tools using a computer based program. Most of them selected cutting-off machine by in house personnel (manually) (82%), and only 18% by external expert advice and in house manually together (figure 3.11). The cutting-off tools were selected by in house personnel 83%, external expert advice and in house manually together accounted for 17% (figure 3.12).

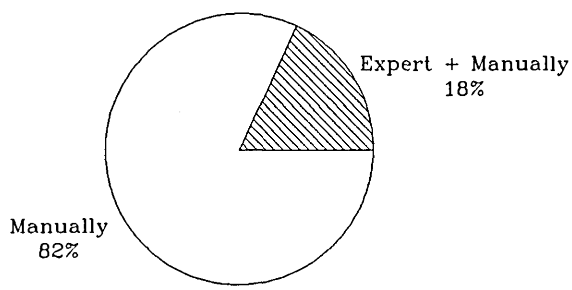

Figure 3.11 Resources used to select cutting-off machine

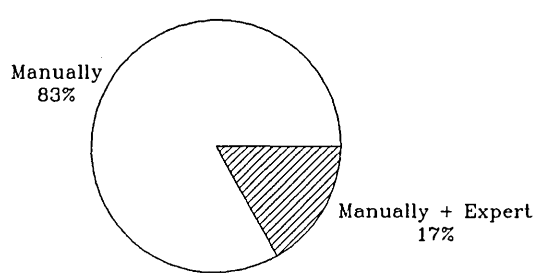

Figure 3.12 Resources used to select cutting-off tool

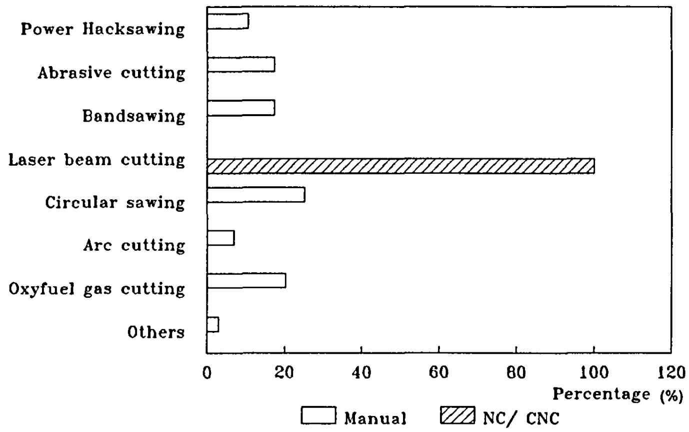

Figure 3.13 Types of cutting-off machine tools used by the respondents

Figure 3.13 shows the number of different cutting-off machines used by the various companies. The most widely used cutting-off machines are the circular sawing machine (25%), the oxyfuel gas cutting machine (20.2%), the bandsawing machine (17.3%) and the abrasive cutting machine (17.3%). Power hacksawing was only used by 10.6% of respondents.

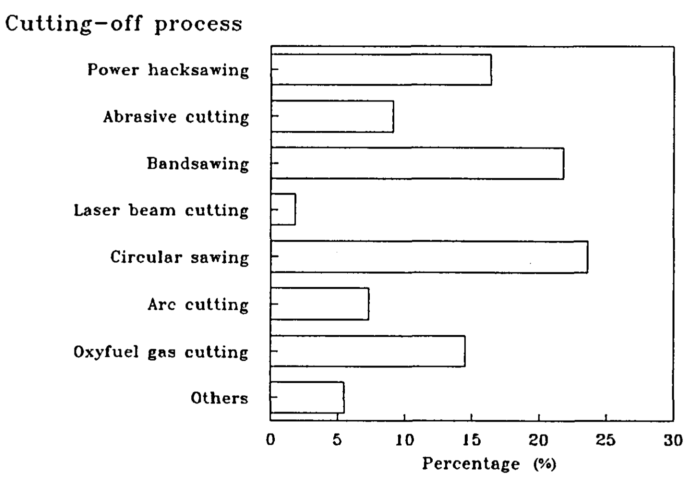

Figure 3.14 Cutting-off process employed by users

Figure 3.14 shows the proportions of each type of cutting-off processes used by the different companies. Circular sawing (23.6%), bandsawing (21.8%) and power hacksawing (16.4%) were the major processes used by cutting-off process companies.

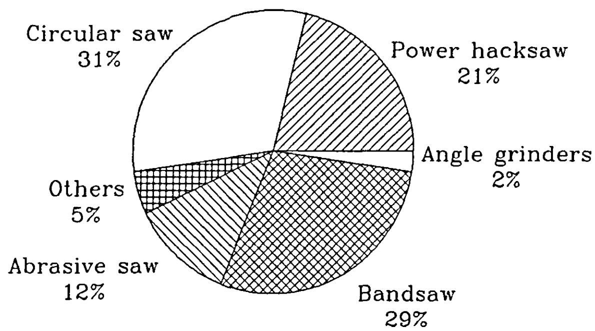

Figure 3.15 Cutting-off tools used by survey respondents

The cutting-off tools used by cutting-off companies were circular saws (31%), bandsaw blades (29%), power hacksaw blades (21%), abrasive disks (12%), angle grinders (2%) and others (5%). These are presented in Figure 3.15. From these sets of data, it can be see that industry applies circular sawing and bandsawing operation more extensively than power hacksawing.

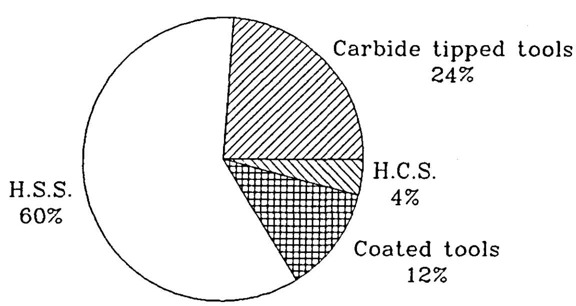

Figure 3.16 Cutting-off tool materials used by users

The materials for the cutting tools used by users companies (figure 3.16) were high speed steel (H.S.S.) (60%), carbide tipped tools (24%), coated tools (12%) and high carbon steel (H.C.S.) (4%).

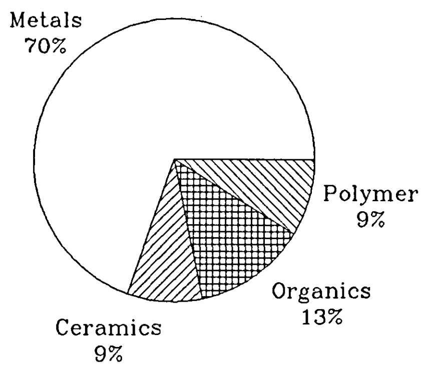

Figure 3.17 Types of materials cut by survey respondents

The materials cut by users companies represented by figure 3.17 were metals (70%), organic (13%), ceramics (9%) and polymer (9%).

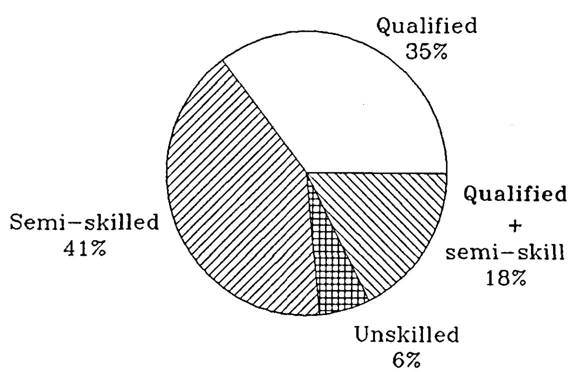

Figure 3.18 Cutting-off machine operator skill levels

Nearly half of the cutting-off process companies used semi-skilled (on job training) operators to run the machines (41%) and 35% companies used skilled (trained) operators to run a cutting-off machine and 18% companies use both skilled and semi-skilled operator together to run a machine. A few companies used unskilled (non trained) operators to run a cutting-off machine (6%) (figure 3.18). Most of the cutting-off process companies use one operator for their cutting-off machines (59%) but some are operated by 2 (12%), 3 (18%), owner (6%) and operators which can operate several machines (6%).

3.7.2 Cutting-off tool manufacturer

A total of seventy questionnaires were mailed out for cutting-off tool manufacturers, thirty three responses were received and twenty two responses did not meet the selection criteria The response rate of cutting-off tool manufacturers was 47%.

Figure 3.19 shows the company sizes of cutting-off tool manufacturer companies. The graph showed that most of the companies in U.K. (64%) employed fewer than 50 people in their company.

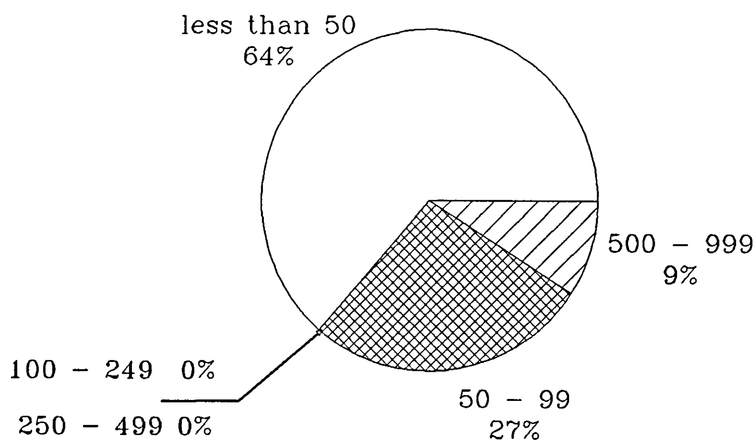

Figure 3.19 Number of employees employed in cutting-off tool manufacturer companies

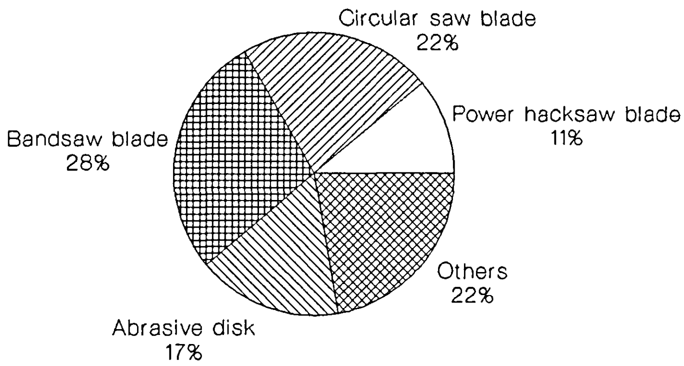

Figure 3.20 Types of cutting-off tool manufactured by cutting-off tool companies

Figure 3.20 Shows the types of cutting-off tools manufactured by cutting-off process companies. These include bandsaw blades (28%), circular saw blades (22%), abrasive disk (17%), power hacksaw blades (11%) and others (22%). The use of circular saw blades and bandsaw blades were both higher than the power hacksaw blades, this figure confirms the previous sections findings that most widely used processes were the circular and bandsawing (figures 3.13 and 3.14).

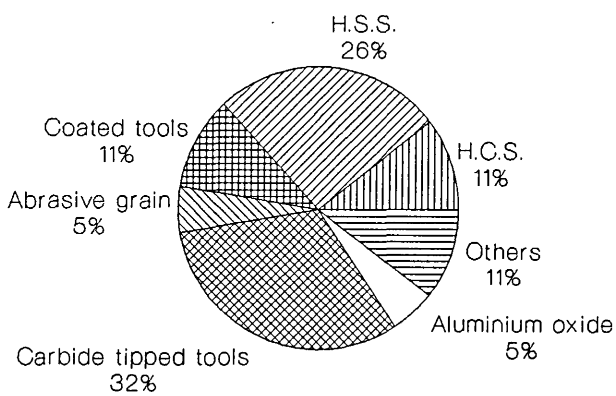

Figure 3.21 Cutting tool materials produced by cutting-off tool companies

Figure 3.21 shows distribution of the materials used for the cutting-off tools. These include carbide tipped tools (28%), H.S.S. tools (28%), H.C.S. tools (12%), coated tools (12%), abrasive grain (5%), aluminium oxide (5%), others (11%).

A total of 82% of cutting-off tool manufacturers provided cutting-off parameter data and tables for their customers which were based on their products.

3.7.3 Cutting-off machine manufacturer

A total of one hundred and thirty five questionnaires were mailed out for cutting-off machine manufacturers and thirty five responses received and twenty two responses did not meet the selection criteria. The response rate of cutting-off machine manufacturers was 26%.

Figure 3.22 shows sizes of the different cutting-off machine manufacturers. The graph showed that most of these companies in the U.K. (75%) employed fewer than 50 people.

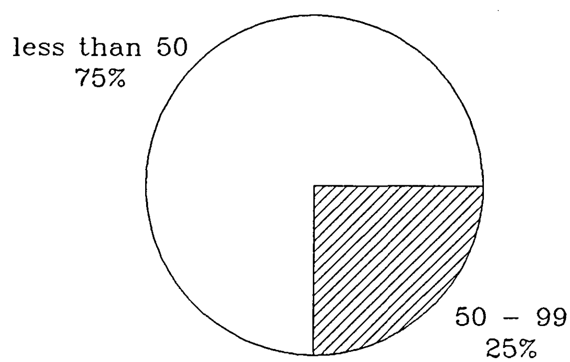

Figure 3.22 Number of employees employed in the cutting-off machine manufacturer companies

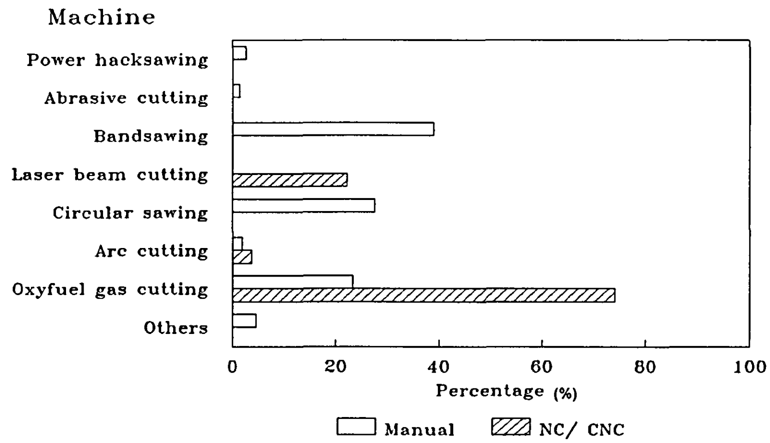

Figure 3.23 Types of cutting-off machine produced by machine manufacturers

Figure 3.23 shows the number of cutting-off machines and the types of controls for the machines produced in the last financial year by various cutting-off machine manufacturers. They produced a large quantity amount of bandsaws (301) and circular saws (213). Again this confirm both the findings of the wider use of circular and bandsawing processes by industry (figure 3.14), use of circular and bandsawing machine tools by industry (figure 3.13) and the cutting tools for these processes (figure 3.20) in previous sections.

3.8. Discussions

The response rate for three parts of the survey are not very high, especially the cutting-off process user and cutting-off machine manufacturer; this might be for several reasons. Firstly, some of the companies had moved or closed down. Secondly, a reminder letter had not been sent out to keep trace of the respondents and thirdly, some of the respondents had no interest in making any contribution to this survey.

It was noted that more than 50% of the respondents from the three categories were small companies (figures 3.4, 3.19, 3.22) especially the user companies. It is deduced that most of their production is job production. The data (figure 3.6) supports this assumption, and the percentage of companies employing more than 100 people was very small. There is only 18 % in cutting-off process user, 9 % in cutting-off tool manufacturer and 0 % in cutting-off machine manufacturer.

The selection of cutting-off processes and the machines, tools and cutting parameters involved is usually performed by experts with the relevant knowledge, such as production engineers. The responses show that, in some firms, technicians or operators are involved with making these decisions. Adequate knowledge and experience is required for this task.

Power hacksawing was once the most commonly used method for cutting off workpieces. However, this has recently been superseded by the process of bandsawing and circular sawing. New technology has enabled these methods to provide superior surface finishes, dimensional tolerances, production rates, kerf losses and squareness of cuts; compared with power hacksawing. The survey data from the users (figures 3.13 and 3.14) shows that bandsawing and circular sawing are now the preferred methods for cutting-off. The data for the types and quantities of cutting off machines produced (figure 3.23) supports this conclusion.

No companies used NC/ CNC sawing machine to perform their cutting-off processes. The only type of NC/ CNC machine used was the laser beam cutting machine. This was because it can conduct profile cutting which is more accurate than the manual operation.

Most of the respondent companies still use H.S.S. tools as their cutting-off tool material (figure 3.16). This is possibly because it is cheap, suitable for general cutting-off and it can be reground repeatedly before being discarded. Carbide tipped tools and coated tools are suitable for special purpose and hard material (i.e. Vickers hardness > 400) which can not be machined by H.S.S. tools.

The analysis of the result was limited, due to the small number of returned questionnaires from the respondents, but in spite of that, some interesting conclusions have been found. The three types of questionnaires had an extremely high degree of positive cross-checking and consistency indicating a high degree of accuracy of the survey findings.

From the survey, it has been established that the cutting-off companies do not use NC/ CNC cutting-off machine for their production. This might be because a programmer has to be employed to operate the NC/ CNC machine and the batch size had to large enough to cover the operating cost. It is also know that most of the companies were small concerned with batch production (figure 3.6), and they might change their product daily or only run a job for only a few hours so the NC/ CNC cutting-off machine were not used. However such machines may be kept in the laboratory for performing experimental works.

From the survey, it is found that most companies select the cutting-off machine (figure 3.11) and cutting-off tool (figure 3.12) manually (in house personal). When this person leave the company, it can cause a loss of knowledge.

From the survey, it is found that no companies used any computer based program to select the cutting-off process, the cutting-off tool or the machine or parameters. This is not surprising no such programs or systems exists for this task. Companies store the cutting-off process, machine, tool and parameters selection information in engineer's brain. As time goes by, this information will fade. A computer based selection system would therefore be very useful for these companies since it would prevent knowledge being "lost" when experts depart.

Chapter 4

Knowledge engineering for cutting-off process selection

4.1 Review of knowledge engineering

Knowledge engineering is the process of eliciting knowledge from human expert and then expressing this knowledge in the expert system format. The activity of knowledge engineering has been defined by Feigenbaum and McCorduck [29] as ,"The art of bringing the principles and tools of AI research to bear on difficult applications problems requiring experts' knowledge for their solutions." The technical issues of acquiring this knowledge, representing it, and using it appropriately to construct and explain lines-of-reasoning are important problems in the design of knowledge based systems. The art of constructing intelligent agents is both part of and an extension of the programming art. It is the art of building complex computer programs that represent and reason with knowledge of the world.

The aims and activities of the knowledge engineering can be summarised based upon references [26, 32, 37, 38].

A. Knowledge acquisition

Knowledge acquisition involves the acquisition of knowledge. It can be obtained from many sources such as books, reports, data, human experts or computer files. The knowledge may be specific to the problem domain and the problem solving procedures, general knowledge, or it may be the information about how experts use their knowledge to solve problems. Knowledge acquisition will discuss further detail in the next section.

B. Knowledge representation

This stage is where the system is actually being constructed with detailed knowledge elicited from the expert, encoded into the knowledge base.

C. Knowledge validation

The content of the knowledge base is validated and verified until its quality is acceptable.

D. Inference

This activity involves the design of software that will enable the computer to make inferences based on the knowledge, and then provide advice to the user on specific issues.

E. Testing and justification

This stage, is when the system is being considered for actual delivery to the users. For evaluation of the system, it is necessary to get other experts to go through hypothetical runs and criticise the performance.

F. Implementation and maintenance

The system is maintained and upgraded to correct the inevitable errors and satisfy users who are demanding changes and enhancement during use.

4.2 Knowledge elicitation

Knowledge elicitation is the process of extracting expertise from human beings with a view to constructing an expert system. It plays an important role in expert systems, where the process of seeking out the knowledge required by an expert system is referred to as knowledge acquisition. A computer based "expert" system, which simulates the decision making processes of human experts, requires a knowledge base. This knowledge can be obtained from a variety of sources including literature's, case studies, empirical data, existing data bases and personal experience [26]. The domain knowledge in the system knowledge base represents human expertise obtained by the knowledge engineer. This knowledge is transferred either directly from the expert, or through some type of learning process involving the observation of examples and distillation of knowledge.

Expert systems rely heavily on knowledge where the quality of knowledge often determines the success of such a system. Thus the ratio of effort expanded to results achieved for the expert system as a whole is often decided by the knowledge acquisition process, and the level of success achieved there.

A number of approaches to knowledge elicitation have been suggested. This project employed interviews to elicit knowledge from an expert. The interview technique is going to be discussed in the following paragraphs.

In this approach a knowledge engineer obtains knowledge from an expert through a series of interviews and encodes it in the expert system. Here the knowledge engineer plays a central role in the knowledge acquisition process, and the quality of the expert system greatly depends on the skills of the knowledge engineer and the knowledge of the expert.

This project involves the elicitation of knowledge verbally from experts. An interview technique known as verbal protocol analysis is used [27]. Carefully designed, unambiguous questions are asked specific information which can then be analysed. The questions are phrased so as to avoid the need for explanations of terms or other distractions. The required knowledge is therefore obtained in a comprehensible form.

The interview is used and allow experts to explain their knowledge of a particular problem and, in order to obtain a full record of the interview, a tape recorder and video recorder can be used. It is essential that no single word or action is missed. A tape must be transcribed and a video logged and, then the large volumes of material are analysed for useful information.

After the interview, the comments can be checked back with the expert allowing the expert to query or modify the interpreted data. If anything has been missed during the interview, it can amended. This part of the procedure is very important as it can make the interview more productive and effective

4.3 Results of the knowledge elicitation

From the interviews, the important details of the experts' cutting-off process selection methods have been obtained. Figure 4.1 shows the selection steps used by first expert and figure 4.2 shows the selection steps used by second expert .

From their selection steps, it is possible to draw the following conclusions of the experts' cutting-off process selection method. Although their selection methods are not identical, some aspects of parts are similar. When a job is received, both considered the material and hardness of the workpiece as the first priority. Hardness and material can affect the selection of cutting-off process and the tools used for this job. This is because H.S.S. saw blade can only cut material of less than 400 vickers hardness. Material characteristics such as elasticity, ductility can be compensated by selecting appropriate feed and cutting speed.

The second aspect considered is the accuracy of the cut. This factor will affect the selection of the cutting-off parameters.

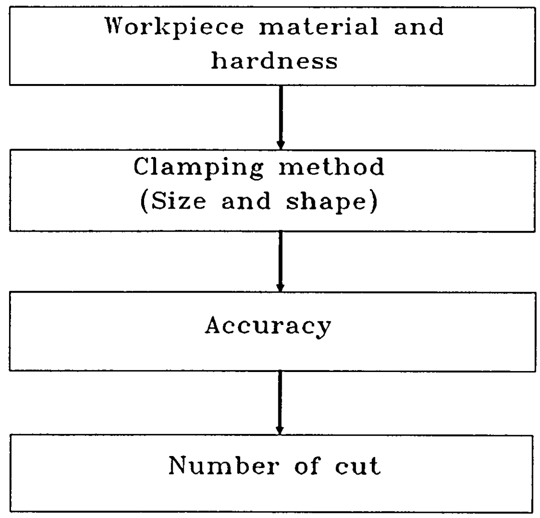

Figure 4.1 The first expert's selection procedure

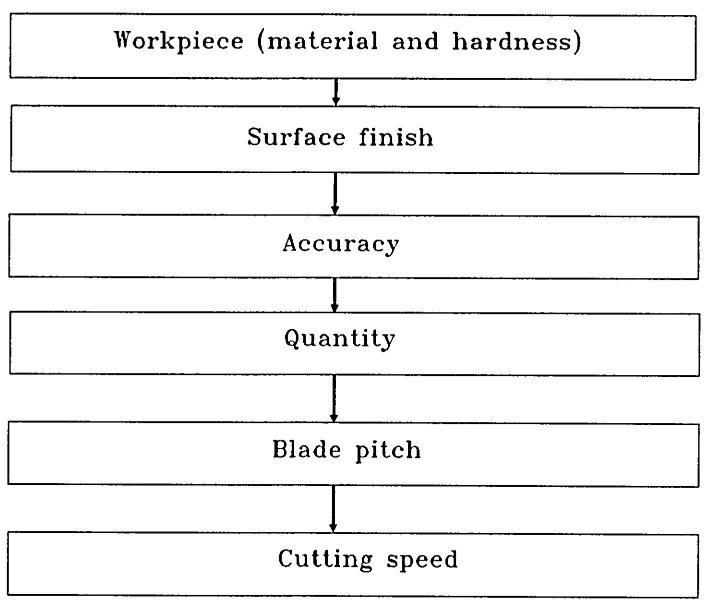

Figure 4.2 The second expert's selection procedure

4.4 Development of selection methodology

The results of the interview indicated how experts select cutting-off processes. After comparing the experts' selection method with the prototype system's assumed selection method, a combined cutting-off process selection method was developed. It is comprised of the following selection criteria:

a. Hardness
b. Material
c. Tolerance
c. Surface finish
e. Kerf loss
f. Cross section

Experts consider each constraint not necessarily sequentially without omitting any of them. This sequence provides a guideline for building the prototype system. The system will focus on each question individually in sequential order.

4.4.1 Selection methodology

The national survey data provided some valuable informations for constructing the prototype system before elicit the selection method from some experts. In appendix 3, A.3.1 it provided the idea of different kinds of cutting-off process selection criteria, without this information, the prototype system cannot be set up. The selection criteria has been defined at section 4.4.

Different cutting-off processes have different characteristics such as tolerance, surface finish, kerf loss, etc. If these characteristics can be captured in a knowledge base, then a suitable cutting-off process and its parameters can be selected by using the expert system. The system is designed as a hierarchical structure to approach this selection problem.

The process selection system contains six levels (figure 4.3) and seven knowledge bases. Each knowledge base contains one cutting-off process and its characteristics. Each characteristic is arranged in six different levels according to its selection priority as given in the sequence. The national survey provided the idea of the priority of the selection criteria.

Each level requires the user to input certain value to match any one conclusion of the rules. Each level asks for the desired value of each characteristics. If the input value satisfies one of the rules, it will go down to the next relevant level and start the consultation. At each level, various control rules and expert process selection knowledge is used to guide the user in an informed manner. After going through the six levels at a given knowledge base, it will go to the next knowledge base to continue the consultation process. The system keeps records of all the input data for consultation so the same data will not have to be input repeatedly.

If the input value does not match any one of the rules in any level, it will go to the next knowledge base to continue its consultation process. For example, if the input value satisfies the hardness level but the tolerance input value does not satisfy any one of the rules in this level. In this case the present knowledge base's consultation will end, and the consultation will start at the next knowledge base. All of the cutting-off processes in the knowledge base are accessed for consultation.

The knowledge bases for the cutting-off process are arranged in sequence. When one knowledge base finishes its consultation or is forced to end the consultation, the next knowledge base is loaded. It can not be diverted to the other knowledge bases. The detailed selection method is discussed in chapter 5.

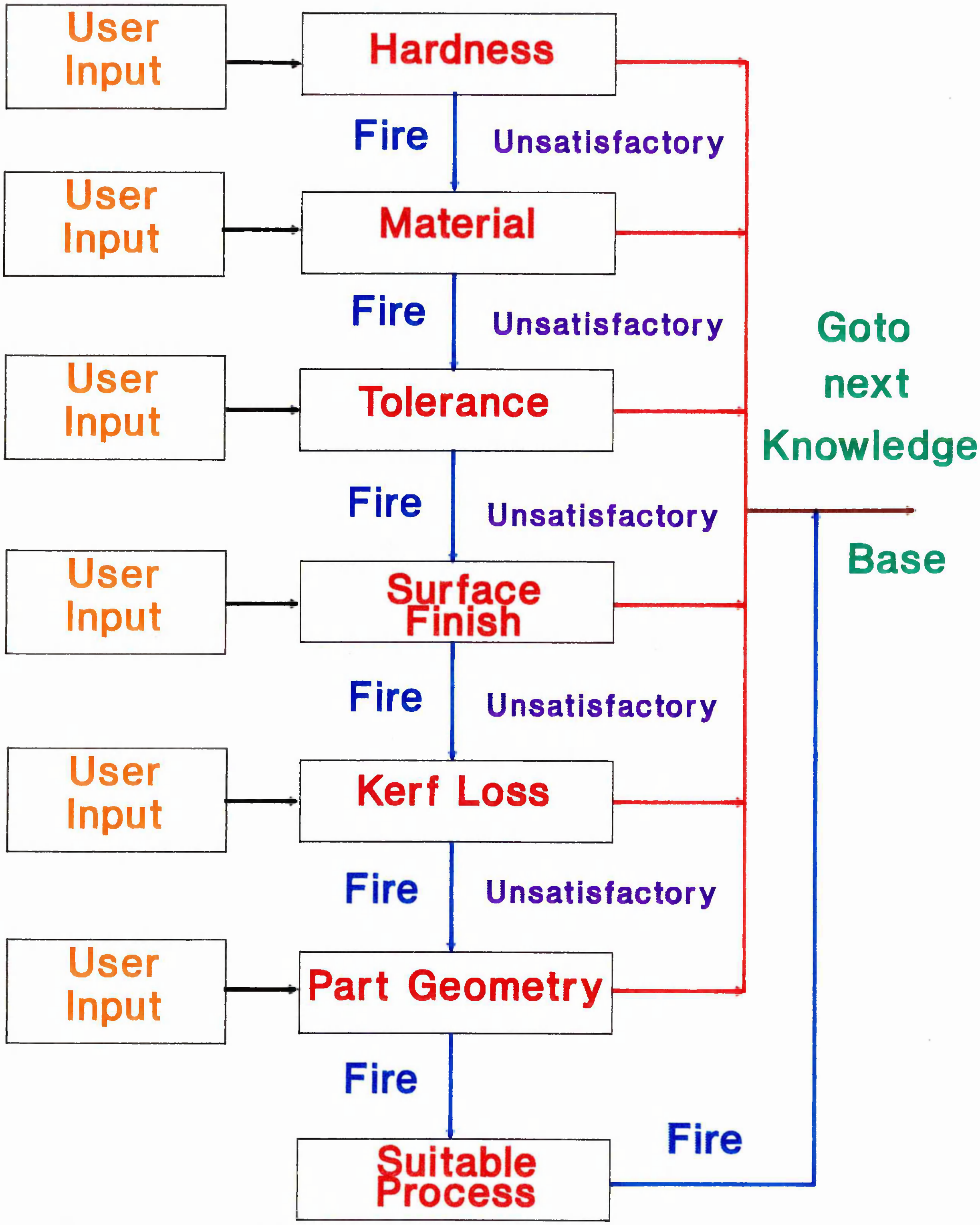

Figure 4.3 Cutting-off process selection system

Chapter 5

Development of cutting-off process selection expert system

5.1 Introduction

There are five distinct stages that need to be undertaken prior to developing an expert system, these are [26]:

5.1.1 Identification of problem

Identifying the right problem is perhaps the most critical part of the entire development effort [36]. At this stage, the appropriate problems are identified which the expert system will work on, in which order, and to what depth. The knowledge engineer needs to find someone to contribute expertise, and analyse the cost and benefits of the proposed system.

5.1.2 Task analysis

Task analysis is a detailed look at exactly what the expert does, with an eye to define the precise portion of the task that will be useful to encode in an expert system. Task analysis begins with a detailed look at how the task is currently performed. For example, someone approaches an expert and asks for help then the expert tells someone what to do. Before the expert made the decision, he analyse the data and then apply rules until he reaches a recommendation [26, 37].

5.1.3 Information processing

This project used a national postal questionnaire and structured interviews to acquire information and knowledge from industrial experts. From the interviews, several selection constraints were identified. These constraints included tolerance, surface finish, kerf loss, hardness, material and cross section, etc..

After the knowledge elicited, knowledge engineer must convert the acquired knowledge into a form that enables a computer program to use it. In this project, each knowledge base contains one cutting-off process only. This is to simplify the knowledge base and make it easy to understand and maintain. The cutting-off process parameters are stored as spreadsheet data and are called upon the knowledge base when necessary. The selection process itself is explained in detail in the next section.

The reason for using expert system approach is to minimise the major portion of the non-machining time in production of a component [20]. Arezoo and Ridgway [38, 39] suggest that conventional programming was inflexible and inadequate for automatic process planning. Conventional programmes mix data and logic in one programme and hence are hard to understand and extremely difficult to modify and maintain, similar reasons are valid for the cutting-off process selection.

5.1.4 Prototype development

A small system is developed to implement a small part of the total task [26]. This can demonstrate the overall feasibility of the proposed system and assumptions can be tested about how to encode the facts, relationships and inference strategies. It can also test the ability of the system in meeting the selection criteria and whether it can solve the problem in hand or not.

The knowledge engineers need to become familiar with the problem domain before discussion and interviews with the expert. They should speak the language of the expert and has knowledge of the problem domain so that it is possible to concentrate on the task without interruption. In order to learn about the expert problem solving techniques, the knowledge engineers need to ask the experts to explain the reasoning behind each decision made in the selection process.

Sometimes the prototype system is designed by the knowledge engineer and expert together [26]. In this case, it offers the opportunity to make decisions about the appropriate software and hardware chosen for the target application. Finally, once the prototype is up and running, it becomes the model for the expert system when complete. Normally at this stage adjustments are made to the performance and capabilities of the proposed system. This small version of the whole expert system can allow problems which may occur with full scale development to be and resolved efficiently.

5.1.5 System development and test

During this stage, all the required data is input into the system. The user interface is tailor made to meet specified requirements, and the system's performance is monitored and compared with the original requirements. Under most circumstances, although the prototype is successful, the initial representation of the rules and facts may need some alternations. The rules that embody the human expert's knowledge are refined by combining and reorganising the knowledge contained in the knowledge base [40].

After the system has been established, it is necessary to modify or refine the user interface. This is the interface the end user will use to interact with the system. It is essential that the interface is "user friendly". Clear menu instructions must be given at all stages for each function. Explanations should also be provided, indicating how each part of the system operates. The system should make it easy for a user to inquire about any details that may need clarification.

5.2 The cutting-off process selection system

This prototype system contains one knowledge base for hardness consultation, seven knowledge bases for selecting cutting-off process, for tools and parameters, and eighty eight knowledge bases for calculating the cost of the cutting-off processes.

This prototype system contains more than one thousand rules. Each knowledge base contains six levels and considers one cutting-off processes only. Each level considers one characteristics of the cutting-off process. The consultation process starts from the first level and continues to the bottom level as the conditions have been satisfied. If an input value does not satisfy any of conditions specified in the knowledge base at a particular level, the consultation in this knowledge base will cease at this level. The system will proceed to the following knowledge base and resume the consultation. As well as making the selections, data are created to be carried forward into the next stage [24]. The details of the cutting-off process selection knowledge base and different aspect of knowledge bases are discussed in the following sections.

As discussed in Chapter 2, this project uses an expert system shell "Xi Plus" to build the selection system. This software can run on any personal computer such as 286 or more advanced machine and it can download to network and accessed by any nework computer. It makes the investment in computer very low.

Figure 5.1 shows the flow diagram of the prototype system. The consultation follows the defined path shown. it shows the knowledge base contain seven cutting-off process. Each cutting-off process contains six level of consultation. All level of consultation will discuss from section 5.2.1 to 5.2.6. The whole system will discuss in detail in the next sections.

5.2.1 First level: Hardness

The first level asks about the workpiece hardness. Hardness values change with different materials and conditions. Most cutting-off process users consider this as their first cutting-off process selection factor. Some cutting-off processes and saw blade's material can cut materials up to a limited hardness value. The following example shows how the knowledge is coded into sets of rules, which enable the system to operate.

Power hacksawing with an H.S.S. saw blade can cut a workpiece of up to 400 Vickers hardness.

A circular saw with carbide coated saw tips is suitable for workpieces of greater than 400 Vickers hardness.

This knowledge is formulated into the following sets of rules:-

The selection rule is therefore very simple. If the hardness value is less than or equal to 400 then it includes all the processes; otherwise power hacksawing is ignored.

The following are the rules which have been extracted from the knowledge base for the above selection knowledge.

if hardness > 400 RULE 1
then command load abrasive

if hardness =< 400 RULE 2
then command load power

The first set of rules implies that the hardness value is greater than 400, then the workpiece is not suitable for power hacksawing. The consultation begins from abrasive cutting.

The second set of rules implies that the input hardness value is less than or equal to 400 then the conditions are satisfied. The consultation starts from power hacksawing.

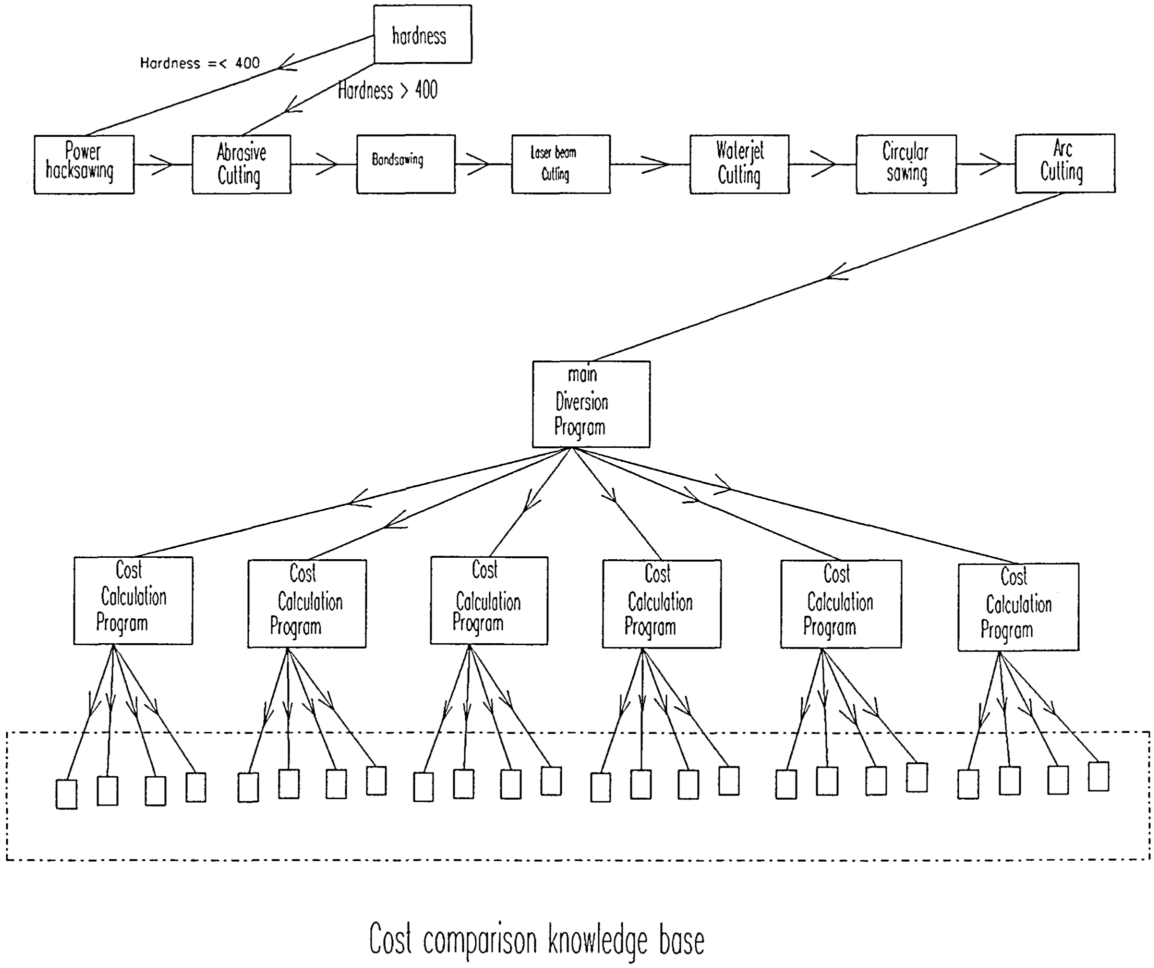

Figure 5.1 Prototype system flow diagram

5.2.2 Second level: Material

The second consultation level address the selection criteria involving workpiece material. Sometimes the workpiece material can determine the cutting-off process. The system contains several materials for the user to select, as the physical properties of the material to be cut have a major effect on the tooling, feeds and speeds used, and also on the capacity of the machine required. Their influence on the type of machine is generally minimal.

If the system cannot find the input material in the specified knowledge base, it will quit this knowledge and load the next knowledge base and restart the consultation from the beginning. If the rule is satisfied, it will progress to the next level and continue the consultation.

The following are the rules extracted from the knowledge base of abrasive cutting.

if component material is ABS RULE 1
then cross section2 is nothing
and command load bandsaw

if component material is mild steel RULE 2
then component material is abrasive cutting

Rule 1 stated that if the material is ABS then it is not suitable for abrasive cutting. It will load the knowledge base of bandsawing and start the consultation.

Rule 2 states that if the material is mild steel then the conditions are satisfied. It can go to the next level.

5.2.3 Third level: Tolerance

The third level asks about the tolerance criteria for selection, this is the accuracy of the cut workpiece. The user needs to input a value greater than zero, then the system will find the processes as that satisfies the requirements. Dimensional tolerance is an important aspect of manufacturing. It will have an effect on the subsequent assembly operations, proper operation of various machines and instruments.

If the input tolerance value is less than the lower limit of the present knowledge base's tolerance value, it will exit the present knowledge base. The system will load the next knowledge base and start the consultation from the beginning. If the input tolerance value is greater than, or equal to the lower limit of the present knowledge base's tolerance value, it satisfies this rule and it will go to the next level and continue the consultation process.

The following are the rules extracted from the knowledge base of abrasive cutting.

if component material is abrasive cutting RULE 1
and component tolerance < 0.1 mm
then cross section2 is nothing
and command load bandsaw

if component material is abrasive cutting RULE 2
and component tolerance >= 0.1mm
then component tolerance is abrasive cutting

Rule 1 states that if the tolerance value is smaller than 0.1 mm then it is not suitable for abrasive cutting. It will load the knowledge base of bandsawing and start the consultation.

Rule 2 states that if the tolerance value is greater than or equal to 0.1 mm then the conditions are satisfied. It can go to the next level.

5.2.4 Fourth level: Surface Finish

The fourth level address the surface finish criteria. This is the workpiece surface finish required after the cutting operation. A smooth surface is often required on finished components. Hence further operations are sometimes necessary after cutting-off. If further operations are to be avoided, a smooth finish must be produced by the cutting off process. The roughness of the finish required is specified by the user as the arithmetic average roughness (Ra) value. According to the American National Standard ANSI B46. 1 - 1978 [41], the standard measure of surface finish roughness adopted by the United States and approximately 25 other countries around the world is the arithmetic average roughness (Ra) [41] and the British Standard is BS1134 part 1 and 2, 1990 [42].

The system also checks against the lower limit of the specified cutting-off process's surface finish value. If the input value satisfies the rule (greater than or equal to the specified value) then it will go to the next level and continue the consultation. If the input value does not satisfy the rule then it will load the next knowledge base and start the consultation again.

The following are the rules extracted from the knowledge base for abrasive cutting. The numeric value is represented as the Ra value.

if component tolerance is abrasive cutting
and component surface finish < 1.5 µm (Ra) RULE 1
then cross section2 is nothing
and command load bandsaw

if component tolerance is abrasive cutting RULE 2
and component surface finish >= 1.5 µm (Ra)
then component surface finish is abrasive cutting

Rule 1 states that if the surface finish value is smaller than 1.5 μm (Ra) then it is not suitable for abrasive cutting. It will load the knowledge base of bandsawing and start the consultation

Rule 2 states that if the surface finish value is greater than or equal to 1.5 μm (Ra) then the conditions are satisfied. It can go to the next level.

5.2.5 Fifth level: Kerf Loss

The fifth level is the kerf loss, this considers the amount of material loss in the form of chips. Stated another way, more slugs or workpieces can be produced from any given amount of stock if material loss is minimised. Different cutting-off processes produce varying amount of wasted material from the workpiece. Therefore this factor becomes increasingly significant with more expensive materials, so to choose a cutting-off process with a small amount of kerf loss is beneficial as material costs rise.

The system also checks against the lower limit of the specified cutting-off process's kerf loss value. If the input value satisfies the rule then it will go to the next level and continue the consultation. If the input value does not satisfy the rule then it will load the next knowledge base and start the consultation again.

The following are the rules extracted from the knowledge base of abrasive cutting.

```
if component surface finish is abrasive cutting          RULE 1
 and component kerf loss < 0.127 mm
then cross section2 is nothing
 and command load bandsaw

if component surface finish is abrasive cutting          RULE 2
 and component kerf loss >= 0.127 mm
then component kerf loss is abrasive cutting
```

Rule 1 defines the rule, if the kerf loss value is smaller than 0.127 mm then it is not suitable for abrasive cutting. It will load the knowledge base for bandsawing and start the consultation.

Rule 2 defines the rule, if the surface finish value is greater than or equal to 0.127 mm then the conditions are satisfied. It can go to the next level.

5.2.6 Sixth level: Cross Section

The sixth level is the cross section of the workpiece to be cut. This will effect the selection process, i.e. the machine capability, type of cutting-off machine to be used, and the clamping method. For example, a round bar cannot be cut on a horizontal bandsawing machine because the bar can rotate during the cutting-off process.

If the system cannot find the input cross section shape in the specified knowledge base, it will quit this knowledge and load the next knowledge base and start the consultation from the beginning. If the rule is satisfied, it will go to the next level and continue the consultation.

The following rules are extracted from the knowledge base of abrasive cutting.

```
if component kerf loss is abrasive cutting        RULE 1
 and section is thin sheet
then cross section2 is nothing
 and command load bandsaw

if component kerf loss is abrasive cutting        RULE 2
 and section is round bar stock
then cross section2 is abrasive cutting
```

Rule 1 states that if the material is ABS then it is not suitable for abrasive cutting. It will load the knowledge base of bandsawing and start the consultation

Rule 2 states that if the material is mild steel then the conditions are satisfied. It can go to the next level.

5.3 Cutting parameter selection system

After passing through the seven knowledge bases, the cutting-off process selection system provides one or several cutting-off processes which are suitable based on the input values. The next step of the prototype system is to go to the cutting-off process parameter selection system. The system also uses process and cutting parameter data from a spreadsheet program. The spreadsheet package used is the Lotus 123 by inference [33]. Figure 5.2 shows the structure of the cutting parameter selection procedure. This procedure takes the list of feasible solutions and calculates optimal cutting conditions based on the part shape, material, cutting tool and the cutting-off process which is input by the user and inferenced by the cutting-off process selection system.

Different materials and workpiece sizes have different cutting-off parameters such as feed rates, speeds, tooth pitch, etc.. Therefore the ranges of the spreadsheet data corresponding to the material and size of the workpiece are specified in the knowledge bases. When the cutting-off processes are selected, the knowledge base will elicit data from the specified ranges and store the data in the system's memory for future use.

The following are the rules extracted from the knowledge base for abrasive cutting.

i.
```
if  cross section2 is abrasive cutting
 and workpiece is rotational
 and material is "Al and its based alloy"
 and component thickness > 0
 and component thickness <= 80
then row is 5
 and y2 reference is given
```

ii.
```
if  y2 reference is given
then start column is b
 and end column is g
 and x2 reference is given
```

iii.
```
if  x2 reference is given
 and y2 reference is given
then cell is concatenate ( start column , row , "." , end column , row )
 and do program read wks using ( "c:\chow\xip24\speed2.wk1" , cell ) giving ( cutter size ,
 abrasive type , grain , grade , bond , tool cost2 )
 and command reset start column
 and command reset end column
 and command reset cell
 and command reset row
 and program2 is finish
 and command load kb bandsaw
```

These rules will upon successful firing elicit the data from Lotus spreadsheet at the first cell address row 5 (see rule i. line 6), column b (see rule ii. line 2) of a rectangular area of the file and second cell address refers to the bottom right hand corner of the area row 5 (see rule i. line 6), column g (see rule ii. line 3) [28]. These rules contain specific commands which call an external program, and allows the program to accept values from Xi Plus and return a range of values which are then assigned to identifiers within the knowledge base. Different material starts from different row. The command reset is used to set all the identifiers ready to accept a new value.

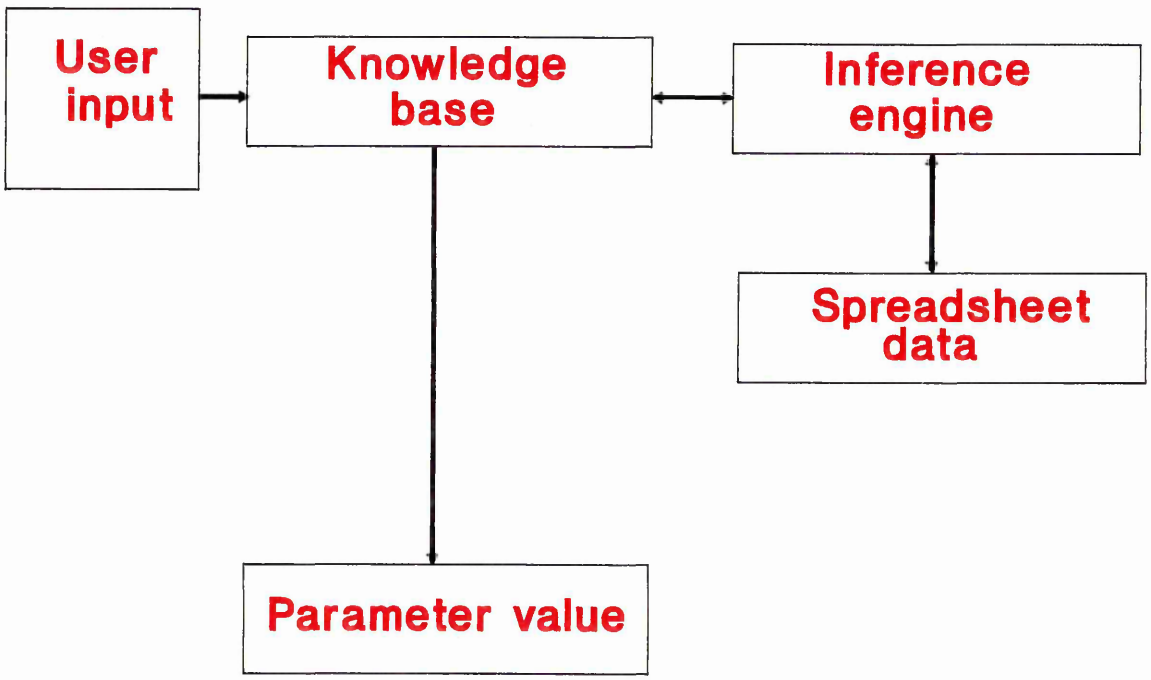

Figure 5.2 Cutting-off process parameter selection system

5.4 Cost analysis system

After undergoing the cutting-off process parameter selection process, the prototype system will arrive at the cost analysis system. The aims of this cost analysis system is to provide information for the user. It can provide a help for user in selecting the most economic cutting-off process. This part will ask for the cost information regarding the selected cutting-off process. These data include the machine overhead costs, labour costs, cutting tool costs, regrinding costs, etc.. The system provides a comprehensive cost ranges of cutting-off process for the user to select and the selected cutting-off process is suitable for the job.

In industry, company calculates the manufacturing costs either by standard formula or pre-determined unit costs. Either the formula or the unit costs are confidential to companies. In the interview with experts, one company used standard formula and the other one used pre-determined unit costs to calculate their manufacturing cost. Many variables can effect the manufacturing costs such as maximum production rate, machining costs, tool costs, tool changing costs and handling costs. This will be discussed in appendix 6.

The prototype system has several sets of rules to compare the cost values of different types of cutting-off processes. It arranges the costs in ascending order. The output provides a list of suitable cutting-off process's unit cost from the cheapest to the most expensive so that the user can choose the process they desire.

The cost analysis starts from the main diversion program and then proceeds to the cost calculation program (see figure 5.1). From this cost calculation program it will appoint the selected cutting-off process to the suitable knowledge base for cost comparison.

5.5 Report

This is the last part of this prototype system. All of the results presented to the user, shown on the screen, are also stored in report file. The report contains the suitable cutting-off processes, unit costs and the specified cutting-off parameters, which are grouped together under its specified cutting-off processes. All the data is inferred by the cutting-off process selection system, cutting-off process parameter system and cost analysis system. A hard copy of the report can be provided if it is required by the user. The company specific constructs such as availability of the process in house are not considered. As the full report gives all feasibilities process, the final decision on the most appropriate process for the company can be made with full consideration of above and other company specific criterion.

Chapter 6

System testing

6.1 Introduction

Ronald R. Yager and Henry L. Larsen [43] state that the knowledge base must be validated to enable the system to fully replicate the decision making of human experts. A first line of defence against inconsistency in a knowledge base is a careful 'visual' look at the knowledge base by the knowledge engineer, and the expert. A second line of defence is to use the system to check for these potential conflicts automatically.

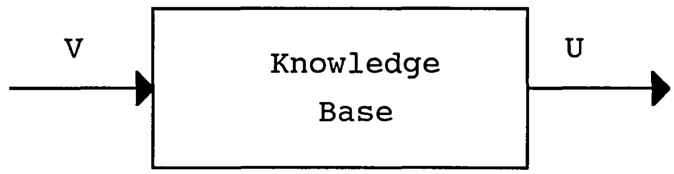

Fig. 6.1 A knowledge base portion of an expert system

Suppose V and U can be multiples (figure 6.1), V and U are an input and output to a knowledge base respectively. It should be noted that in constructing such a system both the input variable V and output variable U have domains. In particular, the output variable U has the set of possible conclusions. The domain D of the input consists of the set of acceptable input values for V. If this expert system is run backwards, in this case rather than inputting a value for V and asking for U, the user is not inputting a value for U and asking for the value of V. The user can call this process reflection on the input. Normally, one would expect that this mode of operation to provides the user with no information other than the fact that V can be any value in its acceptable domain. Thus this type of inference operation will tell the user that V can be any element in D. The system is prepared for any value in the acceptable input domain. The characteristics response to potential inconsistencies occurs using numerous different uncertainty calculi as well as in the standard propostional logic [43]. (When knowledge base contains potential conflicts a different output occurs. In particular, the inferred value of V in this reflection mode rather than being the whole domain of V, D, is a subset of this D. Effectively the user end up with D-A as the possible values for V, where A are those inputs that would lead to conflicts. Essentially the systems is telling the user only put in values in D-A for V, otherwise the system will choke, because of inconsistency.)

Ronald R. Yager and Henry L. Larsen contention that an automated approach to the discovery of potential conflicts can be developed based upon these results. (see paper in Appendix 4 full detail.) After the prototype system has been developed, it must undergo several testing stages before use. This is called system verification. Knowledge base verification becomes increasingly important as expert systems are used more frequently and their conclusions become trusted. During the construction of knowledge bases in expert systems, many changes and additions to the rule set occur. In order to help knowledge engineers develop expert systems rapidly and accurately, problems in the knowledge bases must be identified and corrected. This is because users of expert systems expect answers to be unfailingly consistent and correct. In general, a training course may be provided to instruct users. After the system has been used for a long period (e.g., every six or twelve months), it may require maintenance to be conducted and data to be updated [25].

An industrial validation test and a system validation test were undertaken to verify this system. Two test forms were designed one for human expert and the other prototype system. These two forms were used to undertake consultations for the same workpiece. The human experts' answers were used to check the consistency of the prototype system's answers. Different respondents were selected to perform this validation test. Respondents with expert knowledge of cutting-off process selection were used to perform this validation test. However the system was initially tested against its own results to check for possible missing information in the rules or lack of consistency and errors in the knowledge bases and operation.

6.2 Testing procedure

One of the most important components of an expert system is its knowledge base, which contains the knowledge about the domain of expertise. Knowledge base verification is a part of the validation process in the development of expert system, and includes checking the knowledge base for completeness and consistency. This is to guard against a variety of errors that can arise during the process of transferring expertise from a human expert to a computer [44].

If the system undergoes a full testing method (100% testing), it can ensure zero defects, but this is expensive and takes a long time and also may be infeasible. Therefore a sample testing method was devised to perform the system testing. Any value outside the systems limits (for example, material or cross section which is not in the display list) was not tested for.

The sampling test attempts to make sure that the system is free from errors without having incur massive time penalties of 100% testing. The user responses also control the path of the search through the knowledge-base, and hence no unnecessary line of questioning is followed, minimising the total user inputs required for the consultation [45]. Most of the ranges between several values are quite close together and some data are similar so the optimum sample values are selected carefully to minimise the test size. This is because some of the redundant or duplicated work can be omitted.

The approach to the system testing was divided into three Phases. The phase 1 section 1 was data checking. This included the checking of typing errors, knowledge data, error of input operating. The phase 1 section 2 is to test the system operation. The purpose of this part is to check whether any rules or knowledge is missing, and why particular rules are fired or not fired [46]. The phase 2 test involves using some examples of process selection, for which the results are already known, to check the system's ability to produce the correct answers. When the system operation test is complete, the system was then tested for performance. This was industrial validation testing and this is the third part of the testing. At this stage, industrial engineers are invited to complete test forms. They selected workpiece or worked example and noted all the relevant data (e.g. tolerance, surface finish, etc.) that was used to select a particular cutting-off process. These data are passed on to the system tester and will input into the system without the knowledge of the experts recommendations. The system output was then checked with the industrial engineer's results. Therefore any inconsistencies can be revealed and a quantitative measure of the system performance were obtained.

6.3 Phase testing

6.3.1 Phase 1

6.3.1.1 Phase 1 section 1

This software package used for system development allows the knowledge base to be saved as a text document so that it can imported into any word processing package in order to check the spelling. The input values were checked manually so that any errors can be corrected at this stage.

Five spelling errors and ten incorrect parameter unit specifications were identified in this section. These were caused by typing errors, which occur easily when inputting a large quantity of text. This type of error creates a new identifier or a new variable, which can cause the inference engine to stop working during the consultation process. Incorrect cutting parameter units could also confuse the user.

6.3.1.2 Phase 1 section 2

For both of the phases, we need to comment on the performance on all of the knowledge base and to do the sampling test. No typing errors should exist in the knowledge bases after phase 1 section

1 testing. For the hardness values, there are only two different ranges; these are below 400 Vickers and above 400 Vickers. The values for doing this test being 250 and 500 Vickers.

The following suffixes will be used in the following tables.

Power = Power hacksawing

Abrasive = Abrasive cutting

Bandsaw = Bandsawing

Laser = Laser beam cutting

Water = Waterjet cutting

Circular = circular sawing

Arc = Arc cutting

For the materials knowledge base table 6.1 shows processes which can be employed to cut various materials, letter 'y' means it can cut by this cutting-off process, in this case, the material can cut by six different cutting-off process (e.g. Al and its alloys, Cu and it's alloys, etc.) are taken out to undertake this testing. This is because most of the cutting-off processes can cut these materials, it will not cause a critical point for the next stage. The reason for not choosing the material to be cut by one or two processes is to try to widen the process selection and testing process. The testing sample size is 8.2% of the total system.

Table 6.1 Processes which can be employed to cut various materials.

Material	Power	Abrasive	Bandsaw	Laser	Water	Circular	Arc	Frequency
ABS				y				1
Asbestos board					y			1
Acetyl				y				1
Cotton gauze				y				1
Corrugated board					y			1
Epoxy laminate					y			1
Finished leather					y			1
Formica					y			1
Glass					y			1
Glass insulation					y			1
Glass laminate					y			1
Graphite laminate					y			1
Acrylic			y	y				2
Polyester				y	y			2
Waspaloy		y				y		2
H.S.S.	y		y	y		y		3
Hastelloy	y	y				y		3
Polypropylene			y	y	y			3
Cast iron	y	y	y			y		4

continued from previous page

Tool steel	y	y	y			y		4
Inconel	y	y		y		y	y	5
Carbon steel	y	y	y			y	y	5
Al and its alloy	y	y	y	y		y	y	6
Cu and its alloy	y	y	y	y		y	y	6
Ni and its alloy	y	y	y	y		y	y	6
Stainless steel	y	y	y	y		y	y	6
Ti and its alloy	y	y	y			y	y	5
Mild steel	y	y	y			y	y	5
Mg and its alloy	y		y			y	y	4
Mo and its alloy	y		y			y	y	4
Monel alloy	y	y				y	y	4
Incoloy	y	y				y		3
Mn and its alloy	y		y	y				3
Nylon			y	y				2
Nimonic		y				y		2
Polyethylene			y	y				2
Polycarbonate				y	y			2
Granola				y				1
Insulation board					y			1
Kidney filter					y			1
Mylar				y				1
Paper				y				1
Polyvinyl chloride					y			1
Printed circuit board					y			1
Rubber tile					y			1
Silicon steel			y					1
Tungsten							y	1
Tungsten carbide				y				1
Uraneeth					y			1

In table 6.2, the tolerance range is divided into 5 sections. These are arranged in ascending order of values. It can be seen that there are two large distinct ranges between rows 3 and 4 (0.373 mm) and row 5, when compared to the difference between other rows. Two values from these two ranges have taken out to undertake this test. The values are 0.15 and 0.6 mm. The reason for selecting these two values is that the tolerance range between 0.0127 mm and 0.127 mm is very small (the difference between 0.05 mm and 0.0127 mm is 0.0373 mm, the difference between 0.127 mm and 0.05 mm is 0.077 mm, and the difference between 0.5 mm and 0.127 mm is 0.373 mm). In order to eliminate the redundant work, 0.15 mm was selected. The reason for selecting the value of 0.6 mm is to allow all of the cutting-off process to be involved in the selection process. The sample size is 40% of the total system.

Table 6.2. Tolerance range group of cutting-off processes.

Tolerance (t) (mm)	Process (within specific tolerance range)
t< 0.0127	Power, Bandsaw, Circular
t < 0.05	Power, Bandsaw, Circular, Laser
t < 0.127	Power, Bandsaw, Circular, Laser, Abrasive
t < 0.5	Power, Bandsaw, Circular, Laser, Abrasive, Water
t >= 0.5	Power, Bandsaw, Circular, Laser, Abrasive, Water, Arc

Table 6.3 shows the surface finish range. It has six sections. The range difference between section 4 and 5 is very large (247.46). Therefore a value between section 4 and 5 has been selected, and another value 300 which is at the range of section 6 has been selected to undertake this test. The values for performing this test are 2.87 and 300. The purpose of selecting 300 is to cover all the cutting-off process in the testing. The sample size is 33.33% of the total system.

Table 6.3. Surface finish range group of different cutting-off processes.

Surface Finish (sf) (Ra)	Process (within specific surface finish range)
0.635 < sf < 0.8	Arc
sf < 1.27	Laser, Arc
sf < 1.5	Laser, Arc, Water
sf < 2.54	Laser, Arc, Water, Abrasive
sf < 250	Bandsaw, Laser, Arc, Water, Abrasive
sf > = 250	Bandsaw, Laser, Arc, Water, Abrasive, Power

Table 6.4 shows the kerf loss range. It has 7 sections. It can be seen that there are 3 larger distinct ranges between rows 3 and 4 (1.0 mm); rows 5 and 6 (1.2 mm), and rows 6 and 7 when compared to rows 1 and 2, and rows 2 and 3. Therefore in each part, the maximum value has been taken out to do this test. The numbers are 0.5, 2.7 and 3.0 mm. The aim of choosing these three values is to reduce the redundant work in using any value within each part for doing the test and each part can cover the previous one's cutting-off processes so all the cutting-off process can be tested.

Table 6.4. Kerf loss range group of cutting-off processes.

Kerf Loss (kl) (mm)	Process (within specific kerf loss range)
0.1 < kl =< 0.127	Water
kl =< 0.13	Abrasive, Water
kl =< 0.5	Abrasive, Water, Laser
kl =< 1.5	Abrasive, Water, Laser, Power
kl =< 1.6	Abrasive, Water, Laser, Power, Arc
kl =< 2.8	Abrasive, Water, Laser, Power, Arc, Bandsaw
kl > 2.8	Abrasive, Water, Laser, Power, Arc, Bandsaw, Circular

Table 6.5 shows the cross section of a workpiece that can be machined using different cutting-off processes. The letter 'y' indicates that it can be cut by this process. As from table 5, we can find out all the cutting-off processes which can cut thin strip, hollow, round bar stock, hexagonal bar stock and short end stock. Therefore round bar stock and short end stock have been selected for doing this test. The reason for selecting these two values is to try to widen the process selection, not in one particular process, and testing the system process. It has selected two cross section sample from ten cross section variables so the sample size is 20% of the total.

Table 6.5. Processes which can be employed to cut various cross sections.

Cross section	Power	Abrasive	Bandsaw	Laser	Water	Circular	Arc
Thin strip	y	y	y	y	y	y	y
Hollow	y	y	y	y	y	y	y
Short end stock	y	y	y	y	y	y	y
Hex. bar stock	y	y	y	y	y	y	y
Round bar stock	y	y	y	y	y	y	y
Angles/ channel structural shape	y	y	y	y			y
Wire		y		y	y		y
Coil		y		y			y
Thin sheet			y	y	y		y
Web				y	y		

After all the values selected for the test, the next step is to design a testing procedure. The test will check all the combination of the samples so all the relevant data will be checked to confirm the accuracy of the system.

Although the sample size of the variables in each of the size levels was large, only a small percentage of the possible combinations were sampled.

For any set A and B

$$n(A \times B) = n(A) * n(B)$$

Multiply the number of elements in A and the number of elements in B to obtain the number of combinations in A and B [47].

Therefore the number of combinations in full test is;

= 2 * 49 * 5 * 6 * 7 * 10

= 2058000

The number of combinations in sampling is;

= 2 * 4 * 2 * 2 * 3 * 2

= 192

Therefore the percentage of sampling test is;

= (2 * 4 * 2 * 2 * 3 * 2) / (2 * 49 * 5 * 6 * 7 * 10)

= 0.1%

It has only 0.1% of the full system test (100%) As mentioned previously, most of the ranges between several values are quite close together. Some data are similar so optimum sample values are selected carefully to minimise the test so that most of the redundant work is omitted. The test is not critical in any one process or in any one of the variables. The other reason is the object of the test is to test all the processes not for any particular process or processes. Therefore the percentage of the sampling test in the full test is low.

Five control rules were discovered missing from the knowledge base by this phase of the test. They are as follows:

```
Rule 1 when cross section1 is power hacksawing
        and cross section2 is abrasive cutting
        and cross section3 is bandsawing
        and cross section4 is laser beam cutting
        and cross section7 is arc cutting
        and cross section5 is nothing
        and cross section6 is nothing
       then programs is end43
        and command load kb cost5
```

Rule 2 when cross section2 is abrasive cutting
and cross section3 is bandsawing
and cross section4 is laser beam cutting
and cross section7 is arc cutting
and cross section1 is nothing
and cross section5 is nothing
and cross section6 is nothing
then programs is end44
and command load kb cost5

Rule 3 when cross section2 is abrasive cutting
and cross section4 is laser beam cutting
and cross section6 is circular sawing
and cross section1 is nothing
and cross section3 is nothing
and cross section5 is nothing
and cross section7 is nothing
then programs is end46
and command load kb cost5

Rule 4 when cross section1 is power hacksawing
and cross section3 is bandsawing
and cross section4 is laser beam cutting
and cross section6 is circular sawing
and cross section2 is nothing
and cross section5 is nothing
and cross section7 is nothing
then programs is end65
and command load kb cost5

Rule 5 when cross section1 is power hacksawing
and cross section2 is abrasive cutting
and cross section3 is bandsawing
and cross section4 is laser beam cutting
and cross section5 is waterjet cutting
and cross section6 is circular sawing
and cross section7 is nothing
then programs is end79
and command load kb cost5

These errors are overlooked by the programmer. These missed control rules directed the selected cutting-off process to the suitable cost calculation knowledge base. The other possible cause of these rules being omitted was error during the input of the combination data due to its large quantity .

6.3.2 Phase 2 test

The phase 2 test is to set up some hypothetical examples. The solutions of the cutting-off process selection are already known. The examples input all the six variables in the system, the result of the system will be compared with the known solutions and to check correlation between them.

This can help to check if the inference mechanism is functioning correctly. The use of cutting-off process selection examples, for which the results are already known, facilitates the checking for missing information in the knowledge bases, and evaluation of the system's performance. Ten examples were selected to undertake this test. (Test examples are at Appendix 5.1)

This test was worked from reverse manner. The results and selection criteria of the examples were known. After inputting all of these selection criteria into the system, the output of the prototype system was shown to be the same as the result. This test is like an internal test. It tests whether the prototype system can provide all the pre-defined output, or part of it, or none of it.

6.3.3 Phase 3 test

Traditionally the prototype system is tested by the user or expert and modified until the performance meets their requirements over a period of time and use [26]. It is tested in many different ways, and it is tested against the user interface and problem areas. (Test examples are at Appendix 5 A.5.2) Hence the reasoning techniques and data structures must be finely tuned at this stage so the knowledge base can better represent the correct knowledge.

The phase 3 test involves line industrial trials. Industrial experts were invited to complete test forms which collected all the necessary data and results for the process selection. Details of the workpieces involved and the experts' decisions are obtained (see Appendix 5 A.5.2 for all the test parts). The system outputs can then be checked with the expert's opinions, revealing any errors.

The following table (table 6.6) is the test samples from the expert.

Table 6.6. Results of selected examples from expert.

Specimen no.	Process	Cutting speed	Machine
1	Bandsawing	65 m/ min.	Amada HA 250
	Circular sawing	50 m/ min.	ADIGC CM 501
2	Bandsawing	70 m/ min.	Biamea 315
	Bandsawing	70 m/ min.	Mitre m/c
3	Abrasive cutting	3400 rpm	RGA Commoslave 300
5	Bandsawing	30 - 35 m/ min.	Vertical bandsaw powered table

The following table (table 6.7) is the results of prototype system.

Table 6.7. Results of prototype system.

<table>
<tr><th>Specimen no.</th><th>Process</th><th>Cutting-off parameter</th></tr>
<tr><td rowspan="4">1</td><td>Abrasive cutting</td><td>Wheel size = 200 mm
Abrasive type = A
Grain size = 30
Grade = T, Bond = B</td></tr>
<tr><td>Bandsawing</td><td>Pitch = 8 - 10 (teeth/ inch)
Tooth form = Precision
Band speed = 74 m/ min.</td></tr>
<tr><td>Arc cutting</td><td></td></tr>
<tr><td>Power hacksawing</td><td>Pitch = 6 (teeth/ inch)
Feed = 0.23 (inch/ stroke)
Speed = 120 (stroke/ min.)</td></tr>
<tr><td rowspan="3">2</td><td>Power hacksawing</td><td>Pitch = 4 (teeth/ inch)
Feed = 0.23 (inch/ stroke)
Speed = 170 (stroke/ min.)</td></tr>
<tr><td>Abrasive cutting</td><td>Wheel size = 300 mm
Abrasive type = A
Grain size = 30
Grade = R, Bond = B</td></tr>
<tr><td>Bandsawing</td><td>Band speed = 69 m/ min.
Tooth form = Precision
Pitch = 3 - 4 (teeth/ inch)</td></tr>
<tr><td>3</td><td>Abrasive cutting</td><td>Wheel size = 200 mm
Abrasive type = A
Grain size = 46
Grade = Q, Bond = B</td></tr>
<tr><td>5</td><td>Power hacksawing</td><td>Pitch = 4 (teeth/ inch)
Feed = 0.006 (inch/ stroke)
Speed = 180 (stroke/ min.)</td></tr>
</table>

continued from previous page

5	Abrasive cutting	Wheel size = 300 mm Abrasive type = A Grain size = 30 Grade = T, Bond = B
	Bandsawing	Band speed = 180 m/ min. Tooth form = Precision Pitch = 6 (teeth/ inch)
	Circular sawing	Cutting speed = 400 (fpm) Feed = 15 - 30 (ipm) Pitch = 0.6 - 0.95 (inches)

For specimen 1, the prototype system suggested three more processes other than the expert. The data and the cutting-off process selection criteria, shows that all of these three processes can cut-off this specimen. The reason that the expert did not select these three processes might that be they had no available equipment to perform this operation, or that it is not economic in production. There may be another knowledge gap in the prototype system. The prototype system did not select circular sawing for cut-off this specimen. This is because the input data failed in one of the selection criteria. This is because the kerf loss value does not suitable for the knowledge base selection criteria.

For specimen 2, the prototype system suggested two more processes other than the expert. The data and the cutting-off process selection criteria, show that all of these three processes can cut-off this specimen. Therefore the expert did not select these two processes might be they had no available equipment to perform this operation or it is not economic in production. There may be another knowledge gap in the prototype system.

For specimen 3, the prototype system and the expert both select the same process. Giving a 100% correlation for this part.

For specimen 5, the prototype system suggested three more processes other than the expert. The data and the cutting-off process criteria, shows that all of these three processes can cut-off this specimen. Again the reason that the human expert did not select these three processes might be they had no available equipment to perform this operation or it is not economic in production. Again there may be a knowledge gap between in the prototype system.

For specimen 5, the prototype system contains one kind of Al alloy only. The specimen for doing this test is Aluminium Lithium. Coolants and lubricants cannot be applied to this material. A low cutting speed is used to reduce the heat generated by the process, and avoid overheating the workpiece.

6.4 Discussion of results

The content analysis technique [31] was used to compare the system outputs with the expert's decisions. This involves bringing together the two sets of results and coding the output to enable a definite conclusion to be reached [31]. The consistent and opposed results are counted separately and compared with each other. It was intended to compare the results for three parameters namely the cutting-off process, the cutting-off tools and the cutting off parameters. However the company provided information on the cutting speed only, so the results for the other parameters cannot be compared.

The prototype system may suggest more possible processes for any one job than the human expert. These additional processes may be technically feasible, but not considered by the company on economic ground, or due to unavailability of the process equipment. If, the prototype system suggests fewer process solutions than the human expert, it is possible that the knowledge base is not comprehensive. Further investigation of the knowledge base is then required. Reasons for the differences between the human expert and the prototype system conclusions need be analysed after the comparisons have been made.

6.5 Analysis and correlation

6.5.1 Cutting-off process

Table 6.8. Comparison of human expert and expert system result of cutting-off processes.

Specimen	Expert	Expert System	No. of match Expert/ Expert System	No. of difference between Expert/ Expert System
1	2	4	1	4
2	1	3	1	2
3	1	1	1	0
5	1	4	1	3

Table 6.8 shows the comparison of Expert and Expert System result. The numbers in the column under Expert are the processes selected by expert. The numbers in the column under the Expert System are the processes selected by expert system. The numbers in the column under Expert and Expert System are the processes selected by them respectively. The numbers in the column of the number of matches between Expert/ Expert System is the number occurrences of same process being selected by the Human Expert and Expert System for the same specimen. The number of difference between Expert and Expert System are the number of different processes selected by the Human Expert and Expert System for the same specimen.

6.5.2 Cutting-off parameter

The company participating in this project suggested cutting speed only so the comparison is on the cutting speed of the same process only (table 6.9).

Table 6.9. Comparison of human expert and expert system result of cutting-off process parameters.

Specimen	Expert	Expert System	No. of match between Expert/ Expert System	No. of difference between Expert/ Expert System
1	1	1	1	0
2	1	1	1	0
3	1	0	N / A	N/ A
5	1	1	0	1

The numbers in the column under Expert are the parameters selected by human expert. The numbers in the column under the Expert System are the parameters selected by expert system. The numbers in the columns under Expert and Expert System are the parameters selected by them respectively. The numbers in the column of the number of matches between Expert/ Expert System is the number of occurrences of the same parameter being selected by the Expert and Expert system for the same specimen. The number of difference between Expert and Expert System are the number of different parameters selected by the Expert and Expert System for the same specimen.

There is no comparison for example 3. This is because the prototype system cannot suggest the cutting speed so therefore only the three examples can be compared.

The company submitted five specimen for conducting this test but only four of them were tested. This is because material for specimen 4 did not exist in the prototype system. The cutting parameters of some non ferrous metals and plastics are not available in published machining data handbooks. These data are only known by the experts. Therefore there is a knowledge gap between the expert and the prototype system. This needs more experts to take part in importing their knowledge into this prototype system.

For the cutting-off processes, human expert suggested five cutting-off processes and the prototype system suggested 12 cutting-off processes. One of these results must be identified as the truth. In this case expert result is selected as the truth. Table 6.10 and 6.11 shows the result of the accuracy of the prototype system for selecting cutting-off processes and cutting-off parameters respectively.
In specimen 1, the correlation of the prototype system (table 6.8)
= (number of match between expert and expert system)/ (expert)
= 1 / 2 = 50 %

The worst case is
= (number of match between expert and expert system)/ (expert system)
= 1 / 4 = 25%

Table 6.10. Correlation of prototype system in selecting cutting-off processes

Specimen	Accuracy	Worst case
1	50 %	25 %
2	100 %	33.33 %
3	100 %	100%
5	100 %	25 %

Average correlation = (50 + 100 + 100 + 100)/ 4
= 87.5 %

Table 6.11. Correlation of prototype system in selecting cutting-off process parameters.

Specimen	Accuracy	Worst case
1	100 %	100 %
2	100 %	100 %
5	0	0

Average correlation = (100 + 100+ 0)/ 3
= 66.67 %

Chapter 7

Discussions and future work

Many manufacturing processes start with cutting-off operations. Each cutting-off process has different characteristics. Some of these can be found in text books or machine data handbooks. Some special machines have unique characteristics, details of which can be found in the manufacturers manuals.

Many machine data handbooks or cutting-tool manufacturers provide cutting-off parameters to assist the user to do their job. Most user's select the cutting-off parameters, cutting-off machines and the cutting-off tools based upon the economics of cutting or on other economic considerations.

After completing of the national survey of industrial practise for cutting-off process selection, it was established that company using a computer based program to select the cutting-off process and its parameters were non existent. Most of them left this selection for people of varying competency. Some of them were working in the company or as an external consultants, these cases have been documented in the record. If the engineer leaves the company, his/ her knowledge is lost. Therefore when a repeat job arrives at the company, they need to select the cutting-off process, and suitable tools, machines and parameters again. It would be of considerable benefit to these companies to capture the expert's knowledge, past experience, and a computer based system to solve this problem.

Due to time and financial limitations, the author could not visit all of the companies and interview more experts. Therefore a questionnaire was posted to all of the companies. However fewer than 50 % of the questionnaires were returned (15.2% in cutting-off process user, 47% for cutting-off tool manufacturer, 26% for cutting-off machine manufacturer), although some cutting-off tool manufacturers provided product information for this project. Two formal interviews have undertaken to elicit information from experts. The author has done four informal interviews with industrial experts, university technical staffs and lecturers and consult their method in selecting cutting-off process, all of them are similar to the experts' selection methods.

The prototype system knowledge base contains all of the selection criteria required to select the cutting-off process. In a general case the system can identify one or more cutting-off processes which are matched with the values of the input variables. However the selection may not be matched to a specialised cutting off tool or machine. Unfortunately the technical information required to incorporate these capabilities into the prototype system was not supplied by the cutting-off tool or machine companies.

The cutting-off parameter knowledge bases and spreadsheets contain data for general purpose materials only. When it is required to select the cutting-off processes and parameters for a specialised workpiece material, system errors will occur. For example a workpiece material with a high Lithium (Li) content requires a slower cutting speed than ordinary Aluminium (Al) alloy. The spreadsheets only contain normal Al alloy data so an error would be produced.

It has not been possible to combine all of the cost calculation and companion knowledge bases into a single program. A hardware and software 'platform' with a sufficiently large RAM to accommodate the shell was not available. "Xi Plus" is a DOS version software, the maximum RAM it can access is 640 KB only. Window Version "Xi Plus" or any other Window version expert system tool can solve this problem but they are not available in the university. This project do not have any funding from industrial so it is impossible to pay for the expensive Window version software patent. Hence several smaller knowledge bases are therefore used. A main diversion knowledge base is constructed to direct the selected cutting-off process information to the appropriate cost calculation knowledge base.

The variables affecting the economics of a machining operation are the tool material, the machine tool capacity and the numerous machine conditions. These include the cutting speed, feed, depth of cut and tool geometry. Since these variables are readily accessible on the machine tool, their selection has been considered part of the machine operators' duties. However, the economical selection of the cutting conditions involves technical and cost data not readily available to the operator, so that an optimum selection can seldom be achieved by this approach. The situation is further complicated by the fact that in general most manufacturing machine tools are used for more than one type of component, and these may give different economic returns.

The size and shape of the workpiece will also affect the selection of cutting-off process. The ideal case is to clamp as much as possible of the workpiece in the jaw but sometimes the size and shape will not allow this. Some cutting-off processes such as laser beam cutting, and waterjet cutting, have workpiece thickness limitations. This thickness limitation is also included in the prototype system.

Knowledge elicitation is an important stage in building an expert system. It should include as much as possible of the experts' knowledge in the knowledge base. Most of the knowledge in this prototype system came from two experts. Their knowledge was used to guide the selection procedure, but the cutting parameter data came from experience. This data might not be agreed by the expert. It is better to elicit this data and selection method from further experts if possible.

This expert's cutting-off process selection knowledge was drawn out by several practical examples. These examples made the expert start his selection process from the decision. Different experts had different selection criteria priorities. Although they were different, they still had some similar priorities. For example, the two experts participating in this project see figure 4.1 and 4.2 page 42. By comparing their selection priorities, a suitable set of cutting-off process selection priorities was established. This selection priority was the structure of the prototype system. It guided the system's working and reasoning procedures. It reflected an expert working out a problem.

There was an important aspect which could not be elicited from the expert. It was the cost and method of calculating the total manufacturing cost. This information was classified as a company confidential matter. Therefore some assumptions had to be made to calculate the manufacturing cost.

The cost figures used to calculate the different cutting-off processes are based on the programmer's assumptions. These figures may not represent the actual cost for a particular cutting-off process but can provide an estimate of the cost of the different cutting-off processes in performing the operation.

Conclusions

Many production process starts from cutting-off. From the result of national survey and interviews with experts, the current cutting-off process selection based on expert's experience, cutting-off tool or machine tool manufacturer's recommendation and machine data handbook. There is little documented information and systematic approach in selection of cutting-off process, tool and parameters.

The national survey provides some valuable informations for doing this research. Although the response rate is not too good, it can represent the response companies situation and provides the current situation information of the industry. The information provides a foundation for constructing the prototype system.

From the result of the national survey, it shows that the cutting-off process, tool, machine and parameters are selected by experts with the relevant knowledge, such as production engineers. In some companies, technicians or operators are involved with making these decisions. Therefore people involved in making decisions must have adequate knowledge and experience.

The survey made explicit that no companies used any computer based program to select the cutting-off process, the cutting-off tool or the machine or parameters. The selection is based on human expert's knowledge and experience and stored in expert's brain. Therefore it is very useful for companies use a computer based program to store this selection information, it can prevent knowledge being lost when experts depart.

The approach of using a knowledge based system to select a cutting-off process and its parameters has been tested and verified and a prototype system has been built to demonstrate this approach. From the results, this approach was shown to be a feasible solution to the selection problem and after answering all the questions asked by the prototype system, it would list all the possible cutting-off processes for doing the job. With the help of this prototype system, the selection of cutting-off process and its parameters can be left to people without any technical background. Experts can be reserved to do high level work.

The cutting-off selection methodology provides a clear defined path for any programmer to modify or update the knowledge base. Each knowledge base deal with one cutting-off process, by changing one or all of the selection criterias' variables in a knowledge base can change the limitation of a cutting-off process's selection criteria.

The cost analysis system cannot be combined into a single knowledge base. This is because Xi Plus is a DOS version software, the maximum RAM can be assessed only 640 KB. It cannot process any data larger than this amount. The alternative way is to split the whole system into several small knowledge base. Further modification require a programmer to look for the relevant knowledge base. A window base expert system software can solve this problem. This is because the maximum RAM can be assessed depends on the hardware not only on the software itself.

Testing is an important stage before delivering the system to the user. This project used three testing phases. Phase 1 can be divided into two sections. Section 1 is to check the spelling and other input errors. Section 2 is to check the performance of the system. Different values are input into the system to verify the system performance. This test is only 0.1% of the full system test (100%). This is because some data are similar so optimum sample values are selected carefully to minimise the test so that most of the redundant work is omitted. The optimum sample values allow the testing of different aspects of the system, therefore the performance of the system can be fully verified by only a few tests.

Phase 2 test is used to set up some hypothetical examples. The solutions of the cutting-off process selection are already known. The result of the system will be compared with the known solutions and the correlation between them checked. The aim is to find out if the inference mechanism is functioning correctly.

The Phase 3 test requires information to be provided by each industrial expert. This will involve the completion of a test form to give essential information relating to cutting-off process and parameter selection. The system outputs can then be checked with the expert's opinion, revealing any errors.

In this project, the average correlation of cutting-off process selection is 87.5%. The accuracy is very high. As mentioned before, the correlation is the match between human expert and expert system. The human expert's selection depends on the cutting-off machines availability. The expert system's selection depends on the selection criteria. Therefore it can says that the prototype system can perform the cutting-off process selection.

In this project, the average correlation of cutting-off parameter selection is 66.67 %. The accuracy is not very high. This specialise material (Al- Li) is not included in the knowledge base, the author selected Al alloy instead of it. As previously stated, coolant or lubricants cannot be applied to this material for cooling down the high temperature produced during cutting between the cutting tool and workpiece. Therefore in this case a low cutting speed is used for cutting-off the workpiece to reduce the heat produced during cutting. Therefore the error came out. A conclusion can be made, if it is not a specialise material, the prototype system can be used to select the cutting-off process.

Although the prototype system can select cutting-off process and its parameters, the prototype system still requires more knowledge from human experts to enhance its knowledge. More information on areas such as cross section and material is needed. A given alloy may contain many compositions. This information can be added into the knowledge base to make it cover all the materials and compositions. Different compositions in the workpiece can cause changes in the characteristics such as hardness. The hardness value is a one criteria for selecting a cutting-off process.
This prototype system can provide all the possible solutions for a particular problem, being based on selection criteria. Different cutting-off process have different criteria and these can be changed in the knowledge base.

The cutting parameter data is prototype system. Data could be amended in the spreadsheet and the knowledge base together. This data was obtained from the Machining Data Handbook, published papers, etc..

Future work

It is suggested that the present work provides a basis and the following steps of work can enhance the investigations:

1. Obtain more expert's knowledge (by using interviews) to build an improved knowledge base.
2. This project's survey data obtained two years ago, a new national survey must undertake to find out the actual situation.
3. If possible obtain further machine tool product information, such as size of cutter, cost and kerf loss, from the tool or machine manufacturers. This information can provide the new election criterias for the knowledge bases.
4. Find out the most appropriate method and figures for calculating the cost of cutting-off process.
5. Establish a database or spreadsheet which covers all the compositions of materials for the cutting-off process selection system which can be accessed by the expert system.

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Appendices

Appendix 1

Sawing Process

Sawing is a process of cutting a workpiece with a power driven saw. Power driven saws can be classified according to the kind of motion used in the cutting action [1]:

1 Power hacksaw

2. Circular saw

3. Bandsaw

In either case, sawing is a parting off operation, so that the body of the saw is kept as thin as is practical to avoid wasting material in the cut-off operation.

A.1.1 POWER HACKSAW

Hacksawing is characterised by the reciprocating motion of a relatively short, straight blade that is drawn back and forth over the workpiece [1]. Power hacksawing is different from bandsawing in that the blade makes a discontinuous cut [2]. It is usually possible to position the stock so that multiple pieces may be cut simultaneously. Action may be vertical or horizontal reciprocating with a closed frame or an open frame. Heavy pressure required to obtain a cutting action in each tooth throughout the length of the cut.

The power hacksaw frame is loaded by various mechanisms [3], applying force on the workpiece to improve the cutting rate. The depth of feed is usually regulated by spring loading or by weights clamped to the frame. The essential features of a power hacksaw machine are the swing arm assembly, which carries the saw blade and its bow, a mechanical drive to produce the reciprocating motion of the blade and a device for developing thrust load between the blade and the workpiece.

The amount of feed depends on the magnitude of resistance the saw meets [4]. The reciprocating motion produces a discontinuous cut, only the forward motion cuts into the workpiece, with the blade lifting on the return stroke.

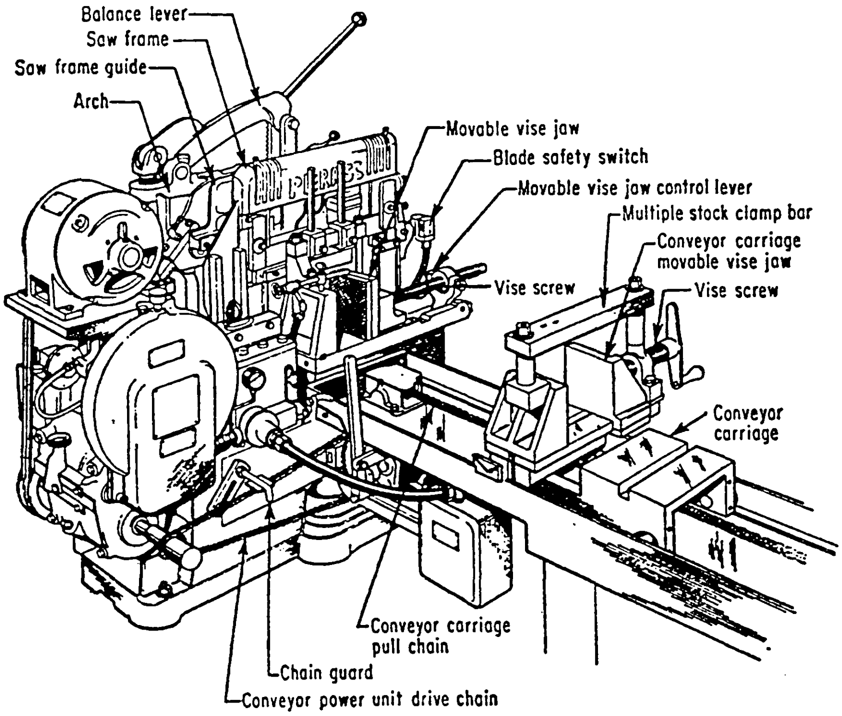


Figure A1. Power hacksaw

The operator can control the cutting performance by choosing the correct blade, a suitable thrust load and the number of cutting strokes performed per minute. Power hacksaw machines are exclusively used for cutting-off processes [2].

While the basic operating motion of the hacksaw is different from that of other sawing machines, hacksaw teeth can readily be compared to those on a bandsaw blade. Hacksaw blades are constructed of materials similar to those used for bandsaw blades. Power hacksawing is usually done with high speed steel blades. Although high speed steel blades provide the best overall cutting characteristics, they do have a safety drawback. Should a solid high speed steel blade fully tensioned in the clamping arrangement [7], break during cutting, the blade itself will have a tendency to shatter in sharp pieces. The welded edge hacksaw blade has largely overcome this dangerous problem. In a welded edge blade, a strip of high speed steel is first welded to the cutting edge of a blade body made of steel alloy. Cutting teeth are then milled into the high speed steel edge. With such bi-metal blades, both heavier feed pressures and higher blade speeds can be used [7]. Bandsaw blades are also available with welded high speed steel cutting edges [7].

When cutting, the hacksaw blade actually curves away from the workpiece because of the heavy thrust forces exerted between the saw blade and the workpiece [2]. Some manufacturers design their blades with a pin hole closer to the cutting edge, that is, below the vertical centre of the blade [2]. Tension is greater near the teeth and the rest of the blade absorbs these bowing forces better. Like the bandsaw, the hacksaw blade obtains its inherent stability through high blade tension. In spite of this tension, the feed force causes a slight cambering of the saw blade. Thus, fewer teeth are simultaneously in contact with the workpiece. Blades are held in the saw frame by pins through holes; if the pin diameter is much smaller than the hole diameter the ends of the blade may break off. Proper matching of the blade to the machine is very important.

Gravity feed machines

This type of machine develops the thrust load by virtue of the gravity force acting on a massive blade bow and swing arm assembly [6]. In some machines an adjustable mass is provided on the swing arm assembly so that the gravity force can be adjusted. While these machines are mechanically simple they are limited in respect of the magnitude of the thrust load which can be generated and therefore are light duty machines. The magnitude of the thrust load is not constant during the cutting stroke due to the reciprocating movement of the blade bow and the action of the lift-off mechanism.

Hydraulic machines

The thrust load developed by this type of machine is produced by the action of a hydraulic device [6], the most common of which may be said to operate on a restricted back flow principle [6]. In this type of machine the saw bow is carried in a slideway housed in the swing-arm assembly. This assembly rotates about a fulcrum. The slideway in the swing arm assembly and the blade clamps on the saw bow are arranged so that a small taper exists between the cutting edge of the blade and the swing arm slideway. The effect of this taper is such that during the cutting stroke the blade and the swing arm assembly ride over the workpiece to rotate about the pivot point. This rocking motion is transmitted via mechanical linkage to the piston of a hydraulic cylinder, causing the piston to displace oil through a flow control valve. The back pressure thus created develops pressure in the hydraulic cylinder and causes a torque to develop about the pivot point of the swing arm assembly [6]. This torque produces the thrust load between the blade and the workpiece. The magnitude of this load is governed by the flow valve setting, deflection of the blade, the cutting performance achieved, and the cutting speed. As the operator only has control over the flow valve setting and the cutting speed, the system is subject to much variation beyond his control. Also the magnitude of the thrust load varies throughout the cutting stroke, reaching a peck value at approximately mid-stroke position. However this system is common and is capable of developing a large thrust load; hence the use of hydraulic machines for heavy duty applications.

Positive displacement machines

A few machines are available in which the feed rate of the blade is directly controlled by a mechanical screw device [2]. In this type of machine the blade is indexed into the workpiece by a fixed amount per cutting stroke. Such direct control of the cutting rate is unique to this type of machine. In the machines already described the feed rate is only indirectly controlled by adjustment of the thrust load. The magnitude of the thrust load depends on the rate of blade feed, the metal cut, the geometry of the workpiece and the condition of the blade teeth. Once the teeth become worn the thrust load developed by a given feed rate increases and can increase to such an extent that the blade fractures. The lack of control over the thrust load and the resultant tendency to break blades are the main disadvantage of the positive displacement machine.

Application

Power hacksaw cuts metal into any size provided that the vice can hold the work. It is a relatively low capital investment and can handle a wide range of stock size within the machine capacities and it may cut multiple pieces simultaneously. It is used in low volume production.

Advantage

1. It is possible to cut multiple pieces at the same time.
2. Low capital investment.

Limitation

1. Rough finish left on the cut surface. Surface finish is 250 -- 1000 μmm (10 -- 40 μinch).[6]
2. Tolerances as small as +/- 0.15 mm (+/- 0.005 inch) are practical [6].
3. The discontinuous cutting motion makes it less efficient than other types of power driven sawing machine.
4. Its function is limited to cut-off operation.
5. Lack of flexibility.

Economic

1. Machine is not expensive.
2. Easy to operate and maintain.
3. Easy to change from job to job.
4. Operating cost is cheaper than other power driven sawing machine.

A.1.2 CIRCULAR SAWING

Circular sawing involves the use of a rotating cutting blade [1] with many teeth which can rotate through a large range of speeds. The cutting blade fed horizontally, vertically or inclined at an angle into the material. With vertical feed, the rotating blade travels downward in a straight line to engage the workpiece. Blade feed motion is assisted by gravity, and the workpiece can be positioned directly beneath the centre line of the saw blade for optimum cutting accuracy and minimum vibration.

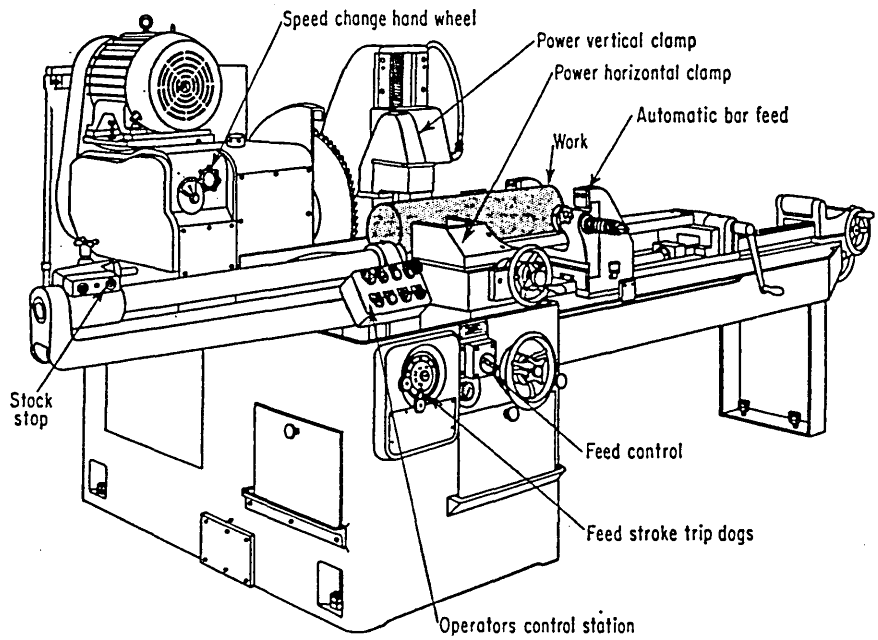


Figure A2. Circular sawing machine

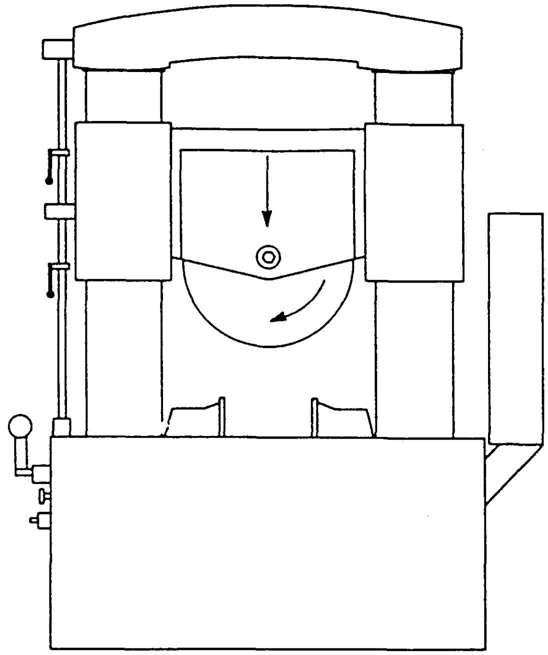


Figure A3. Vertical feed circular sawing machine

In the case of horizontal feed machine, the blade is pushed into the workpiece from the side. Variations on basic horizontal feed units include specialised plate cutting saws which traverse the blade along the length of the plate. A third basic feeding configuration is fed through an arc from a pivot point like a chopping motion. The pivot feed motion can sometimes be manually fed, but air or hydraulic feed is used on almost all other machines [41].

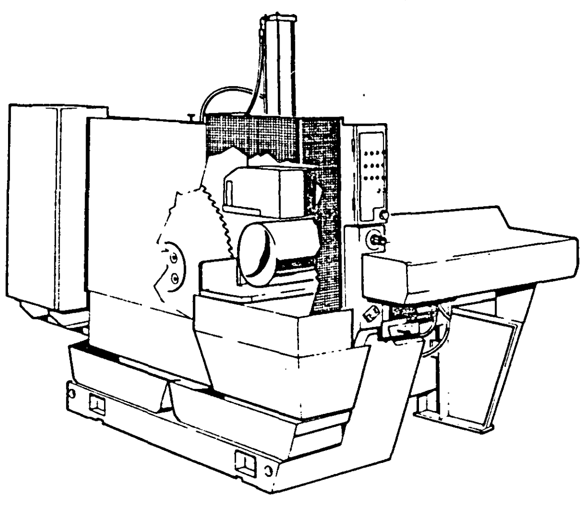


Figure A4. Horizontal feed circular sawing machine

When a saw blade penetrates deeper and deeper into the workpiece, its tendency to jam increases. Teeth in a circular blade get their rigidity from the entire blade and in many operations, most of the blade body follows the teeth into the cut. This means that a circular blade must cut a wider slot into the workpiece than other types of blades to prevent jamming [2].

Two different types of tooth patterns are common in large circular saws: straight tooth design and high-low patterns [2]. Straight tooth design, the teeth are not bevelled and they are all the same height. Tooth gullets allow chips to curl. The tooth gullets temporarily store the chips so that the teeth can continuously remove material from the workpiece.

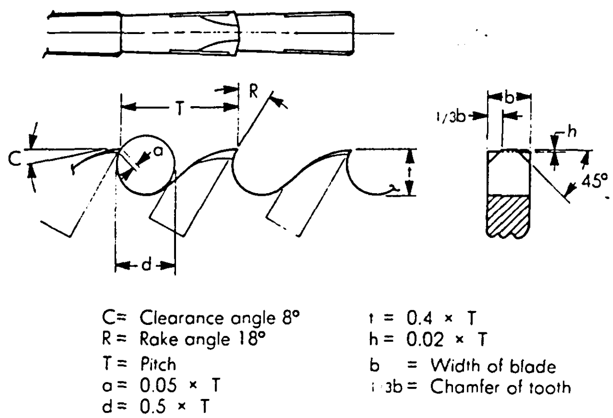


Figure A5. High-low pattern tooth geometry

In the high-low pattern, the first tooth is high and chamfered (usually 45 degree angle) on both sides. This tooth removes material from the centre section of the cut. The following tooth is lower than first and it opens up the cut removing material from both sides of the slot made by the preceding tooth. Each pair of teeth produces three cutting chips: for this reason the pattern is alternatively known as the 'triple chip' method. This type of geometry breaks up the chips and splits the chip load between each pair of teeth, allowing faster material removal. The height difference in each pair of teeth is the major determining fact for the blade feed rate into the workpiece.

Compared to bandsaws and hacksaws, the circular saw has a disadvantage; that is the body of the saw blade has to be sturdy enough to prevent lateral buckling as a result of the feeding force and its diameter.[13] Therefore, with increased diameter of the saw blade, the blade thickness also increases to ensure stability. This, of course, has an effect on the width of the cut [2].

Since circular sawing is done at the fixed periphery of the wheel, machine design is affected. Surface speed at the blades cutting edge varies directly with wheel radius. Cutting speed can thus be changed without an elaborate motor transmission by designing the machine to accept different blade sizes [13].

Nevertheless, most circular sawing machines do offer several spindle speeds, even if they are not designed with the special high speed gearing needed for abrasive disc and friction cutting-off applications.

There are two circular saw blade. One used in cold sawing is a toothed circular disc. It is used principally for relatively minor cut-off operations. It is a continuous and fast method for cutting off and leaves a smooth and accurate surface on the work with few or no burrs [41]. This may save work in subsequent operations.

Second type may have either individually inserted teeth or detachable segments that may contain several teeth. It can be used for sawing large section of metal. A cutting fluid is recommended when cutting all metals except cast iron.

Circular saws use more carbide than any of the other major sawing methods; carbon tool steel and high speed steel are also commonly used. Requirements for a circular saw material include resistance to thermal shock, high hardness and toughness and the ability to maintain these properties at cutting temperatures. Carbon steel is generally acceptable but hardness drops at high cutting temperatures. Elevated temperatures are better handled with high speed steel combined with proper use of coolant. Tungsten carbide has the highest hardness and is less sensitive to heat: it is however sensitive to mechanical shock.

Cooling the circular saw blade and workpiece interface is similar to the cooling used with other sawing methods. It depends largely on cutting speed and type of material being cut. Cooling with oil or water soluble fluids is most often used but some applications need special methods.

Application

Circular sawing process is fast and used for work requiring good surface finish and accurate dimensions and no subsequent operation. In general, it is used for high production rate sawing of large cross sections, such as products from rolling mills.

Advantage

1. The disc for inserted teeth circular saw can be made of a less expensive metal.
2. It is a fast cutting method.
3. Surface finish is 1.5 -- 3.2 μm (60 -- 125 μinch) [13].

Limitation

1. The accuracy of cut is generally +/- 0.001 inch (+/- 0.03 mm) per inch (25.4 mm) in the direction of the blade travel [13].
2. Generally the harder the material the smoother the finish.

Economic

1. Machine is expensive.
2. Operation cost is the highest compared to other power driven sawing machines.

A.1.3 FRICTION CUTTING

The cutting action is produced by friction of metal disc. The metal disc is a large diameter circular blade rotating at high speed or a bandsaw moving at anywhere between 20 - 76 m/s, to create friction instead of chips. The frictional energy is converted into heat, it heats the workpiece to a temperature between red heat and its melting point and rapidly soften a narrow zone in the workpiece [7]. With the material in this condition, the weakened surface can no longer resist the sliding action of the blade and the material is literally wiped away [47]. The disc which is provided with teeth or notches, pulls and ejects the soften metal from the cutting zone. A path or cut is formed by the wiping action of the rotating disc.

The melting point and structural characteristics of the workpiece material is critically important. Oxygen carried in the gullets between the blade teeth causes the blade to burn its way through the work. The resulting action is similar to that of a cutting torch. Coolant is required to prevent excessive heat build up at the rotating disk. Many materials that cannot be flame cut may be friction cut.

In bandsaw friction cutting, it is suitable for sawing plastics, wood and non-ferrous metals. Even though friction sawing generates tremendous heat, it is confined to an area immediately ahead of the saw, and only to a very small extent to the sides of the kerf [13]. The resulting heat penetration is very shallow, seldom more than 0.05 mm deep [13]. In contrast with the temperature at the point of cut, the saw band remains relatively cool. The reason is that the band is long and tooth or the high speed band is only in momentary contact with the workpiece [41]. In its long journey around the saw band carrier wheels each tooth has ample time to cool before it again engages the work.

A limiting factor to the process is workpiece thickness. This is because high pressures between the saw band and the work must be maintained to generate the heat required, friction sawing is practical for any workpiece not more than 25 mm in thickness.

Because friction sawing softens and removes material just ahead of the saw band by creating frictional heat, tooth sharpness is not a critical factor as it is in conventional sawing. In fact, the heavy feeding pressure and fast band speed required to produce the frictional heat require dull teeth. This dullness actually makes the teeth more efficient heat generators because a blunt surface produces greater friction than a sharp one. A low carbon flexible friction cutting blade is better than a very hard one since it is less likely to crack from flexing over the drive wheels. Because the blade is moving fast, coarser tooth pitches can be used on thin materials than in conventional sawing, with little danger of tearing out teeth.

Blade life is determined more by set or blade waviness than by tooth sharpness. When the set has been worn off, the blade will still friction cut but it is difficult to guide it accurately. Special friction cutting bandsaw blades are available with increased set to minimise this problem.

Friction cutting can also be done on circular sawing machines as long as the surface speed is fast enough [7]. Most circular friction machines, however, are specialised pieces of equipment and have very high power, accurate speed control and a high pressure water pump for blade cooling. Although convention air currents set up by the blade rotation do help in cooling the blade, this often is not enough. Compared with a friction cutting bandsaw blade, a circular blade has much more metal and therefore retains heat better [13].

The circular blades operates at sufficiently high uniform velocity and under sufficient pressure to generate heat by friction on the contact surface of the section at a rate that is faster than the rate at which the surface can absorb heat. Heat increases directly as the length of contact between the workpiece and the blade increases. This contact arc can be controlled somewhat by the saw arrangement. When the work reaches a temperature at which it is red hot, its tensile strength is reduced rapidly. At some pint above red heat but below the melting point, the weakened surface can no longer resist the sliding action of the blade periphery and is cut away. A downstroke machine most often used for cutting bar, rod angle and similar stock, is set up for the most efficient friction cutting with the contact arc between the blade and the work nearly horizontal.

Application

It is used for rapid cutting action. This process is several times faster than ordinary circular sawing operations. The workpiece structure characteristics is not important for subsequent usage because heat will cause distortion in the workpiece structure. It is suitable for hard ferrous metals such as steel and iron, etc. and reinforced plastic. Some plastics, for example the thermosetting type filled with hard materials such as glass and mica, can be successfully friction cut, thermoplastics can lose sufficient strength without melting. It is not suitable for non-ferrous metals because they have a tendency to stick to the blade.

Advantage

1. It is the fastest cutting method than the other power driven saws.

Limitation

1. The process is fast but leaves a heavy burr which can be chipped off easily[1].
2. The cutting surface is less accurate than tooth cutting does.
3. It is not suitable for non ferrous metals because they have a tendency to stick to the blade [48].
4. Care must be taken with cast iron because the structure has a tendency to break down before the appropriate tensile-strength-breakdown temperature is reached [41].
5. Thermoplastics loss of strength when cut by friction sawing [41].

A.1.4 ABRASIVE DISC CUTTING

This process is used when a better surface finish and close limits of accuracy are required [49], advantageous for hard materials, even in large sections. The cutting pressure can be kept small and thin sections in hard or soft material can be cut without distortion. Most abrasive cutting machines are readily adaptable to both wet and dry cutting operation [13].

This type of operation is similar to a grinding process. An abrasive cut-off disc is a thin grinding wheel with thickness no more than 1/48 of the disc diameter. The process is extremely fast. Cutting time depends on wheel size, surface speed and machine horse power.

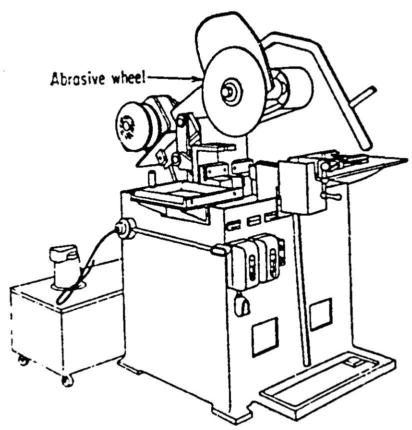
Normal grinding precautions are essential because the wheel speed of abrasive cut-off units is very high. Most wheels are marked by the manufacturer to indicate maximum operating revolutions per minute and this statistic should be taken very seriously [13]. At its recommended speed, a cut-off wheel has high radial strength, and there is a reasonable safety margin left to keep down the danger from shock and vibration induced wheel break up. If a wheel is run at a high speed, most or all of its strength may be taken up by centrifugal force, and even the least amount of shock incurred when the blade enters the workpiece could cause wheel shatter.

A considerable amount of cut-off work is done with small portable power machines, which are usually provided with reinforced resinoid bonded wheels for dry cutting. For high volume production, cutting-off is done on large machine with special coolant systems and complex material handling systems. For the large machine, water or water based emulsions are used as normal coolants and they are applied to both sides of the wheel through piping systems. Large machines may incorporate oscillators to help the abrasive wheel feed into the workpiece.

Machines with 37, 75 and 120 KW driving motors are not uncommon [1]. Replacement wheels are also a factor to consider. While the initial cost of an abrasive machine is often far less than that of a sawing unit with similar capacity, annual abrasive wheel costs can occasionally exceed the cost of the machine itself.

Wet cutting uses coolant to flood the wheel and work. The effectiveness of the wheel depends upon the abrasive action between the wheel and the work. The surface speed is very important, too high a speed will prevent the coolant from wetting the wheel. The cutting accuracy achieved with a wet wheel is within +/- 0.1 -- 0.3 mm for 25 mm stock (+/- 0.004 inch to 0.01 inch for 1 inch stock) [23].

Dry cutting is similar to friction sawing. Surface speed is also important, otherwise the heating effect will breakdown the structure of the metal being cut. Accuracy within 0.5 mm for 25 mm stock (+/- 0.02 inch for 1 inch stock) [23].



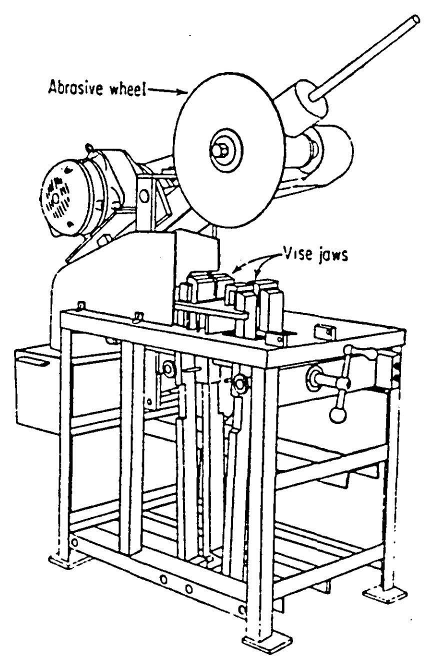


Figure A5. Hand operated dry abrasive cutting machine

Figure A6. Hand operated oscillating wet abrasive cutting machine

Advantage

1. Good surface finish can be achieved by this method.
2. This process can cut very hard material. It is good for hard material, even in large sections.
3. High accuracy can be achieved by this process(+/- 0.1 -- 0.5 mm, +/- 0.004 -- 0.02 inch).
4. Cutting process can be kept small thus thin section, hard or soft material can be cut easily without distortion.

Limitation

1. Surface speed is important for dry and wet cutting, especially important for dry cutting.
2. It need additional attention on the condition of the cutting wheel for both process.
3. Wheel balance to reduce flutter is very important in both process.
4. High temperature will cause break down the bond of the wheel rather than the structure of the material being cut.

Economic

1. The machine is expensive.
2. Operating cost is the highest among the other power driven sawing machine.
3. Additional cost to store the cutting disk such as Rubber bonded wheel must be kept in a dry cool place and on a flat surface [12].

A.1.5 BAND SAWING

This machine is considered more versatile than any sawing machine previously discussed. It combines the advantages of the circular saw with those of the hacksaw. It encompasses continuous cutting along straight and curved lines, like the circular saw, all the teeth on a bandsaw blade cut in a continuous action [2]. This involves a long endless saw band travelling in one direction over two or more wheels. The saw band must be long, flexible, thin enough to bend over driving and idler wheels and must have sufficient thickness and beam strength to withstand the pressures exerted during cutting. The blade length ensures that the teeth are adequately cooled as they progress around the band wheels between each contact with the workpiece. And, like the hacksaw, machines can be designed to handle large workpieces without incurring penalties of excessive tooling costs, machine cost or power consumption. Because the bandsaw's blade is the thinnest of all production cutting-off tools, power consumed is low and material waste is minimised [11]. With the more expensive materials, this latter characteristic is highly important.

During a cutting operation, the band is in continuous contact with the workpiece and the thrust load applied is normally constant. The operator can control the cutting performance by choice of the band, the band speed and the magnitude of the thrust load. A number of different machines are available and they may be classified according to the orientation of the band and the method used to develop the thrust load.

The feed force is transferred across the two band guides onto the cutting edges of the band saw blade. Since the band has to be thin for flexibility, there is a limit to the amount of feeding force that can be transferred [11].

The high cutting rates, therefore can only be achieved by increasing the band speed. For this reasons, the bimetal saw blades are heat treated to 69-70 Rc at the tips of the teeth. As a result, it is possible to use a cutting speed about three times that of the circular saw and power hacksaw processes, although with a lower chip load.

HORIZONTAL BAND SAW

This machine was designed to combine the flexibility of reciprocating power hacksaws and vertical band saw actions. This provides a convenient method for holding a long length of stock for a cutting off operation [41]. It has higher productivity than power hacksaws. In this type of machine the band is carried horizontally on a swing arm assembly, which is usually pivoted at one end and has means by which the thrust load can be developed and adjusted. The workpiece normally in the form of bar or tube is held stationary in a vice during cutting. Gravity fed machines exist for light duty work in which the thrust load is developed by virtue of the gravity force acting on the massive swing arm assembly. Other more heavy duty machines are available in which the thrust load is developed by a hydraulic device. Horizontal band machines, like power hacksaw machines are exclusively used for parting-off operations.

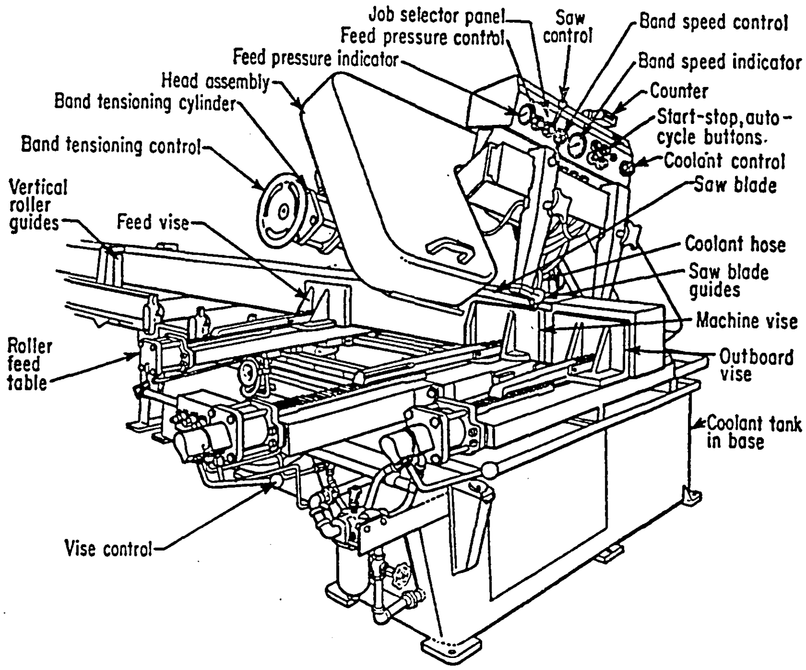


Figure A7. Horizontal bandsawing machine

VERTICAL BAND SAW

This machine is used for straight as well as contour cutting of flat sheets and other parts, which are supported on a horizontal table [1]. Standard metal cutting band saw are extremely versatile. There are a number of accessories to assist its operation. In this type of machine, the band is carried vertically whilst the workpiece is moved in the horizontal plane. The workpiece is fed over a fixed work table and manually controlled. With this arrangement the thrust load needed to achieve a cutting action is provided by the operator. More sophisticated machines exist in which the workpiece is carried on a power fed table, such machines are capable of automatic control and like the positive displacement power hacksaw machines the thrust load developed is governed by the feed rate of the blade. Whilst vertical bandsaw machines can be used for cutting-off operations their main use is for cutting intricate shapes in materials in the form of sheets and slab.

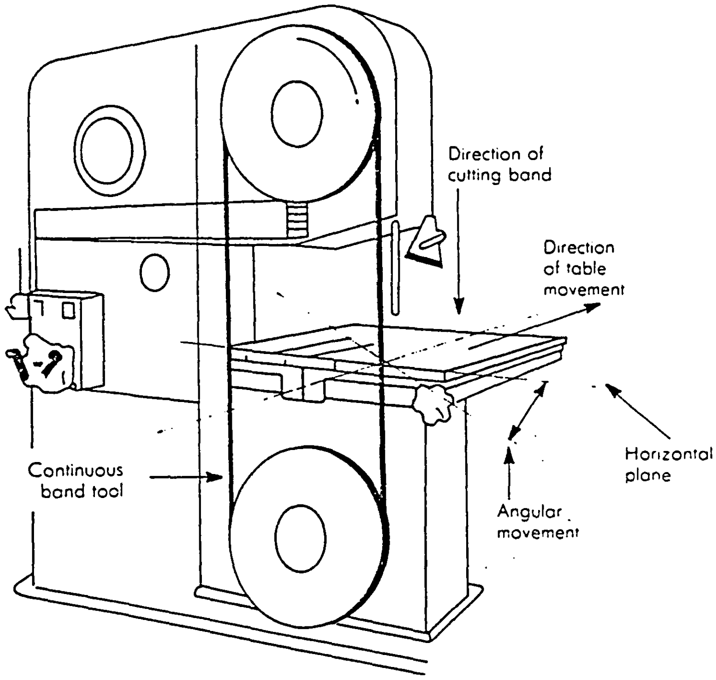


Figure A8. Vertical bandsawing machine

CONTOUR BAND SAW

This process is performed on a vertical band saw having a C - shaped yoke frame, clearance between the workpiece and the frames imposing a size limitation. It is possible to produce complex contour in one straight forward machining operation. For internal contour sawing, the ends of the saw band are welded together after the band has been inserted through a hole provided in the workpiece for this purpose [41].

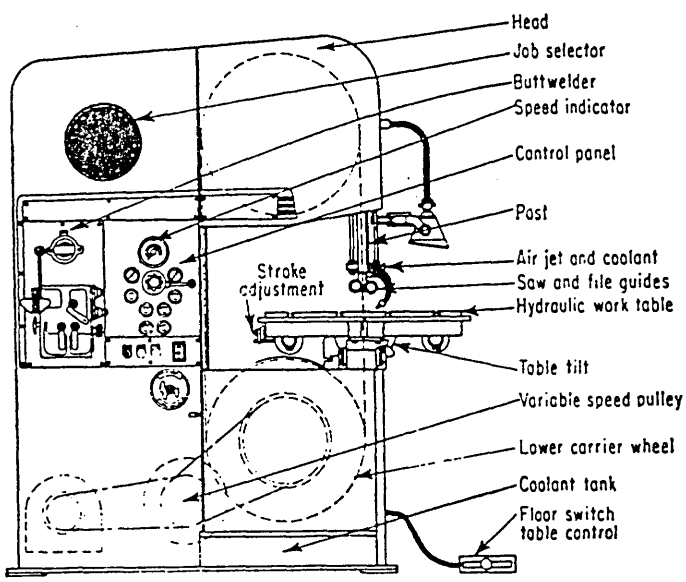


Figure A9. Contour bandsawing machine

VERTICAL BAND SAW FOR FRICTION

This machine provides straight, angular and contour cuts, not recommended for parts measuring greater than 1 inch in thickness. It is a chipless process and no coolant is used. When compared to a conventional band saw machine, this machine operates at a greatly increased speed and cuts through materials several times faster.

Application

Horizontal and vertical band saw are used for light to medium duty cutting. The cutting action allows the cutting edge to follow a contour path during cutting. Power band sawing is material, time, and energy efficient because it removes unwanted material primarily in section rather than in chips [11]. It therefore minimises the power required to change material from solid to chips. In vertical band sawing the downward cutting action holds work to the table, thus simplifying fixture design. It can be fitted with computer control to gain the capability of guiding the contour path automatically when equipped with appropriate bands. Vertical band saw machine may also be used for filing and polishing operation. The cutting accuracy is usually within 2 mm/ mm. Under ordinary production, surface roughness approximately 5.0 to 7.0 μm [41]. Friction band sawing is restricted solely to ferrous materials that are harder than 42 HRC or that work harden rapidly. It is especially adaptable to the cutting of certain difficult to machine metals, it has been found that increased hardness of materials actually enhances the cutting efficiency of this process. It is also used for the distortion free cutting of thin material and can produce complex contoured as well as straight cuts.

Advantage

1. It is more versatile than other sawing machines.
2. It can be used for cut-off or contouring operations.
3. A large number of assessories can be attached to the machine.
4. Material removed in stock instead of chips.
5. For contour band machining, this method offer several major advantages over other machining methods: rapid cutting to shape, safe and easy operation, raw material savings and relatively low cost.
6. Tolerance is +/- 0.05 mm (+/- 0.002 inch) [41].

Limitation

1. The power rating of the machine limit the cutting rate and the thickness and hardness of the material to be cut.
2. For friction sawing, the material near the cutting edge is harder than the bulk metal.
3. The blade may diverge from a true path in a heavy cut.

Economic

1. Machine is expensive.
2. Blades have long life for general purpose.
3. Operating cost is cheaper than circular saw.

A.1.6 OXYFUEL GAS CUTTING

This process uses heat to remove a narrow zone from a metal plate or sheet [41]. The process is particularly suitable for steels. Cutting occurs mainly by oxidation and burning of the steel with some melting taking place. This process generates a width of cut similar to that produced by sawing with a saw blade.

Application

Torches may be guided along various paths manually, mechanically or by automatic machines using programmable controllers and robots. Two or more layers of flat sheet can be cut by this process thus improving productivity and reducing the cutting cost. Cast iron and steel casting can also be cut by this method. The width of cut varies from 1.5 mm to 10.0 mm (from 0.06 inch to 0.4 inch) with reasonably good control of tolerances [41]. Most ferrous metals can be flame cut. It is used to cut-off structural shapes and bar stock, cutup steel scrap, cut-off rivet head. Rough flame cutting is done just to cut off pieces, precision flame cutting is used for producing fairly accurate shape.

Advantage

1. It is suitable for cutting off thick sections.
2. Cutting process is fast.

Limitation

1. The maximum thickness that can be cut depend on the gas used [41].
2. The flame leaves a drag line on the cut surface which is rougher than the surface produced by other power driven sawing machines [41].
3. Distortion caused by uneven temperature distribution can be a problem in this process [41].
4. High accuracy cannot be obtained by this process (+/- 0.4 -- 10.0 mm, +/- 0.015 -- 0.04 inch)[1].
5. Steel with high carbon content require preheating. The higher the carbon content of the steel, the higher the preheating temperature required.
6. For oxyacetylene gas the maximum thickness is about 300 -- 350 mm (12 -- 14 inch) [49].
7. For oxyhydrogen gas the maximum thickness is about 600 mm (24 inch) [49].

Economic

1. Relatively little power is required to operate the mechanism of mechanical flame cutting unit and to remove or cut the metal.
2. Cost is made up primarily of the cost of the gases used in cutting [1].
3. Initial investment and overall operating cost is relatively lower than power driven saw.
4. Speed of metal removal per unit volume is far greater than any other method [1].

A.1.7 ARC CUTTING (Plasma)

This process is so rapid, the heat effected zone is usually less than 2.4 mm and the original properties of the metal are generally modified only within 1.6 mm of the cut [41]. In the torch, an inert gas such as argon is passed through a small chamber in which an arc is maintained. Electrons flow from the cathode to the anode, this flow ionising the gas. The gas molecules than dissociate causing large amount of thermal energy to be liberated. The ionised gas and arc are forced through the nozzle of the torch.

There are two main types of plasma arc system.

1. The transferred arc

An arc is maintained between work and the torch electrode [1]. Work is anode and electrode is cathode. In this case, more of the electrical energy is transferred to the work, cause the work more heat.

2. Non-transferred arc

The arc is struck between two parts of the torch [1]. The torch case is the anode and the torch electrode is the cathode for the purpose of striking the arc. Heat is caused by the flame so the nozzle and electrode need water cooled.

Application

It can be used to cut non ferrous and stainless metal plate. The cutting productivity of this process is higher than OXYFUEL gas cutting. It produces good surface finish and narrow width of cut compared to OXYFUEL gas cutting [2]. It can be utilising programmable controls the cutting process.

Advantage

1. It can penetrate almost any material that conducts electricity.
2. It can used for those material difficult for flame cutting [41].
3. Surface finish is better than gas cutting. Surface finish can vary anywhere from helical ridges along the surface to a completely smooth surface with approximately 30 min. (0.76 mm) R_a surface finish, depending upon the feed into the work optimisation of the process [41].

Limitation

1. Surface finish is rough.
2. Uneven heat distribution cause distortion in the work.
3. Arc radiation is intense.
4. Accuracy is not good (+/- 0.5 -- 3.2 mm, +/- 0.02 -- 0.125 inch) [1].

Economic

1. Power demand is high.
2. Equipment is expensive.
3. The processing speed is 10 times as fast as gas cutting.

A.1.8 LASER BEAM CUTTING

Laser beam cutting uses intense heat from a laser beam to melt and/or evaporate the material being cut [50]. It is suitable for cutting a wide variety of material. For some non metallic materials the mechanism is purely evaporation, but for many metals a gas may be supplied, either inert gas to blow away the molten metal and provide a smooth, clean width of cut or oxygen to speed the process through oxidation [51].

Application

This process is used for very accurate cutting. The surface finish is better and the width of cut is narrower than that for other thermal cutting process. It can minimise the requirement for fixtures during the cutting operation. It is ideal for batch process, just in time or low to medium work volume production. Laser operation can be achieved by continuous wave (CW) or pulsed mode [52]. In co-operation with CO_2, CW laser is used for cutting thicker metal section. The pulse mode is used for thinner metal section. Pulsed high power laser are used for cutting thick section of superalloy metals. It is quite easily adapted to computer or tape control.

Advantage

1. Heat effected zone is smaller than thermal cutting.[41,52]
2. Higher cutting rate than other thermal cutting.
3. Tolerance is +/- 0.0127 -- 0.127 mm (+/- 0.0005 -- 0.005 inch).

Limitation

1. Proper safety precaution are important.
2. Machine is less efficient (about 15 - 20%) [52].
3. Thermal stress produced along the heat effected zone.

Economic

1. High equipment cost.
2. High cost of safety equipment [52].

A.1.9 WATER JET CUTTING

This process uses a high velocity stream of water as a cutting tool. The water jet acts like a saw and cut a narrow groove in material [2]. When a large power is required to cut harder and denser materials, fine abrasive particles are injected into the water stream. The cut can be started at any location. For internal cuts, no pre drilled holes required. No heat produced, no deflection of the rest of the workpiece takes place, little wetting of the workpiece takes place, and the burr is minimal.

Application

Wide variety of materials can be cut by this technique, including plastics, fabrics, rubber, wood products, paper, leather, insulating materials, brick, and composite material. It can cut material up to 25 mm (1 inch) thickness and higher [48]. Small width of cut can be obtained, when cut two or more layers of flat sheet, quality of all layers are the same. Tolerance is +/- 0.13 -- 0.254 mm (+/- 0.005 -- 0.01 inch) [14].

Limitation

High pressure up to 1400 MPa input to the system, the jet can only output pressure of 400 MPa for efficient operation. The process is used for cutting non metallic material [14].

Appendix 2

Expert System Building tools

A.2.1 ESE - Expert System Environment

This was IBM's first significant expert system tool [26]. In August 1987, ESE was written by PASCAL. The rule base is backward chaining. It has a strong structuring facility called Focus Control Blocks. The latest version was rewritten by C programming language.

The Focus Control Blocks can break down knowledge in tree structure of separate contexts. FCBs have some commands to control the processing of knowledge. All of them, except for the forward chaining invoker, can assign groups of objects to work on and most of them also have a range of function which can add additional control to the knowledge processing.

ESE has five basic structures [26]:

1. Parameters:	These are the domain facts in the knowledge base, it can have one or more than one value but it can not handle string value.
2. Rules:	It uses standard rules (IF...THEN), the inference engine can do forward and backward chaining, single or multiple fire demons.
3. Focus Control Blocks (FCB):	It is the primary structure mechanism, the focus control block also contains much of the control knowledge.
4. Groups:	This function can collect parameters, rules or FCBs in the knowledge base.
5. Screens:	It is a custom display screen.

The developer's interface has adequate mandatory menu driven editing environment. It can trace, rerun and save consultations as well as various cross-referencing and structuring aids, etc. The user interface has a similar competent functions to the developer's with some nice display features.

A.2.2 Knowledge Tool (KT)

Knowledge Tool is the third member of the IBM's expert system shell [26]. It was put on the market in April 1989. This release has a much better interface with windows and an interactive debug/ trace facility.

Knowledge Tool lends itself to including data types and calls to other functions. It has the ability to interface into other applications. It can call or be called by other programs written in PL/1, COBOL, FORTRAN, Assembler or Pascal. It has forward chaining inference engine only.

A.2.3 Adviser (ICL)

In order to use this software to develop a system, developer first build a rule base by using the editor to create a text file, the editor is meant to be user friendly but it is difficult to find a standard one[36]. The file is then used by another component called Builder which constructs a model which the Interpreter uses to conduct a dialogue with the user.

It has a good user interface which includes commands to undo previously asserted facts, ask for explanations and help at various levels. The developer interface is adequate such as tracing, logging and cross-referencing but occasionally seem to have been developed in an ad-hoc, un-integrated, fashion.

It has some quite sophisticated components whose ancestry undoubtedly lies more with conventional programming language design than AI theory but the inference mechanisms are restricted [36]; consisting of backward chaining to establish facts, demons and procedural evaluation of rules within the sub-units that the rule base is broken into. The system can develop by forward chaining but this is quite foolish to do it in this way compared to the shells mentioned before.

A.2.4 Knowledge Based Management System (KBMS)

There are three primary structures in KBMS [26]:

1. Objects — These are entities which are basically logical grouping of facts and rules. They have associated attributes which in turn can have rules. Features such as inheritance are included.
2. Rules — It is in the standard format (If...Then).
3. Packets — This is the function to separate knowledge base into blocks for control and inferencing.

The inference mechanism can be one of four varieties and appears to be both rich in function and relatively easy to use [26].

1. Backward chaining and
2. Forward chaining are the normal inference mechanism.
3. Hypothetical reasoning is a technique used to structure knowledge in a knowledge based system in a way that defines the contexts in which facts and rules apply.
4. Object oriented programming permeates the system. Rules can be attached at various levels and can be used automatically whenever the object or attribute is created, accessed, deleted, etc. There are also User Defined Objects (UDOs) which allow access to any file system at the record key level.

Through the UDOs, the KBMS can access a wide variety of database. The developer only need to define certain data manipulation parameters and the translation from rule to object to database record is handled automatically. It can support multiple simultaneous database calls.

A.2.5 Application Expert (AE)

AE is mainly written in COBOL with a small amount by Assembler and is a rule based system with forward and backward chaining [26]. The interface is simple to use, an experienced programmer should understand it without any difficulty by using the various EXEC calls. Communication is carried out via global cache common storage.

It has the ability to retrieve data from file. The shell can select, update, insert and delete records and by using multiple values for single attributes you can ask the number of records within a single file call. AE appears to provide good seamless interfaces to both application development environment and database files.

The developer's interface contains a good selection of tools including trace, debug and display facilities which include a graphical representation of the structure. The user interface allows the use of windows, forms, menus and answer abbreviation. It has interface to support voice response so that the user can conduct the whole session over a telephone using a touch-tone pad [26].

A.2.6 Knowledge Engineering System (KES)

It was written by "C" language [33]. It has three separate inferencing mechanisms [36]:

1. PS — It is the standard production rule with both forward and backward chaining and demons.
2. BAYES — Which performs statistical patterns using Bayes theorem.
3. HT — Hypothesise and test, the system generate a minimum set of hypotheses to explain the facts it has and search information to prove or disprove them, adjusting the list of possible hypotheses as required.

It also includes frame like description and classes with class inheritance and has some usual user commands such as Why, Explain and Help, the range of these commands varies depending on the style of inferencing being used, something which could be a little confusing for some users. It can link in other C programs, using a set of supplied sub-routines, or alternatively call the expert system from another program using a section of the knowledge base called the 'externals' for communication and data passing [26].

A.2.7 Xi Plus

Xi plus provide a complete development environment on micros. The user interface is rich of commands, you can ask why the system asks this question, volunteer information, temporary pause the consultation process to review the data. The developer interface can allow the rules delete, move or copy from the knowledge base, checker, advisers, tracing and cross referencing tools.

It uses standard rule "If...Then", the inference mechanism is forward and backward chaining as well as demons and some other quite complex control methods [28]. In Xi Plus, the knowledge base items such as facts, rules etc. are expressed in a form similar to simple natural language [28]. The knowledge base contains the domain expertise. It is also known as Rule Base, specially when expert system uses production rules (If ... then ...) to represent knowledge. Since knowledge base is independent of the inference engine, any number of expert systems can be developed by creating knowledge bases for each application [28]. When production rules are used they can be appended to the knowledge base in any order. This permits the modular development of knowledge bases.

In an application, it can contain more than one knowledge base. When build a knowledge base, developer can define and control the contents of each knowledge base. When querying a consultation, one knowledge base is held in memory at any one time but each knowledge base still communicate and share data to each other [28].

Xi plus can display graphical image, retrieve data from lotus 1-2-3 and have some program interface such as Assembler, C and Basic [28].

Xi Plus is an expert system shell which can be embedded in any other software system is also available and in most expert system shells, knowledge items can be expressed in English.

A.2.8 KAS

This software uses standard production rule (IF...THEN) and the antecedent of a rule can be the conjunction of disjunctions of other statements also the statements can be either logical or descriptive [54]. KAS uses inference rules with associated certainty factors together with a partitioned semantic network to encode its knowledge. Inferences are based on forward and backward chaining and the propagation of probabilities through the semantic net [36].

Its inference engine classification of objects to make useful deductive inferences about logical relations among the descriptive statements. It is no formal top level goal, but certain consequents are distinguished as top-level hypotheses, each consultation will make the possibility of the goal lower and lower. With further consultation, it can establish find out the truth or falsity of the most promising ones. When no conclusion has been reached, the system will identify the missing information that will be useful in debugging the valuable output of the program.

At any given time KAS is either trying to identify the best top level hypothesis to pursue or trying to identify the best question to ask the user to establish that hypothesis. The first mode will be called the goal selection mode and the second, the question asking mode [54].

In goal selection, the user supply information will direct the inference engine during the session. The user input any information relevant to the consultation. The inference engine will try to match against the descriptive statement in the knowledge base. Either it is partial or exact match the knowledge base, the system updates the score on each of the top level hypotheses that statement supports. The scoring function take into account the certainty of the evidence, the nature of the match, and by tracing through the rules whether the evidence is favourable or unfavourable for the hypothesis. While the best scoring hypothesis is typically identified, the user can cancel the goal hypothesis, H. Thus, mixed initiative control is supported.

When the goal hypothesis H has been selected, the program will go to question asking mode. All the statements one level below H will be inspected in order to find out the one that is expected to have the greatest effect on the probability of H. Let S denote that statement. If S is marked as askable and if the user was not asked about S previously, the system asks whether S is true, forward chains to propagate the consequences of the answer, and returns to the goal selection ,mode. If S is not askable, S becomes a new goal, and the same procedure is reapplied, resulting in "best-first" backward chaining.

KAS has a well built in environment for developing and debugging rules, semantic networks and taxonomic structures [54]. Its knowledge base editor has three special features: 1, it can operate directly on network structure, 2, it uses knowledge about representational formalisms to assist the knowledge base designer, 3, it facilitates development by allowing the designer to get immediate feedback on the consequences of changes to the knowledge base.

Structure editing can allow programmer use both text and structure editors for programming languages. KAS has many special properties of the networks. It can protect any common and potential errors. It can keep record of any unfinished work, providing reasonable default values wherever possible. Knowledge base editor can use at any time in the development cycle, it can be used in the middle of a run to modify the current knowledge base.

A.2.9 EXPERT

EXPERT is a general system for developing consultation models [26]. Its principal characteristics include a forward chaining control scheme designed for diagnosis or classification-type problems, mechanisms for handling certainty, and efficient and transportable code, which have a predetermined list of potential conclusions from which the program my choose [36].

The design of EXPERT has been deliberately streamlined to emphasise certain themes, including [54]:

1. Ease of model design. Prototype models should be capable of running in relatively brief periods of time.
2. Efficient system performance.
3. Predictable performance. Interaction among decision rules should be relatively easy to understand.
4. Empirical testing. A model's performance should be matched to a data base of stored cases, providing a degree of verification and consistency checking.

In EXPERT three representational components are used to design a consultation model: hypotheses, findings and decision rules. It has three types of production rules to describe logical relationships between findings and hypotheses: finding-to-finding rules (FF); finding-to-hypothesis rules (FH); and hypothesis-to-hypothesis rules (HH) [54].

The FF rules which specify truth values of finding that can be directly deduced from an already established findings, are used to establish local control over the sequence of questions. FH rules are logical combinations of findings that indicate confidence in the confirmation or denial of hypotheses. Programmer can specify inferences between hypotheses in HH rules.

The major issue of control in EXPERT goals are directed to the related goals of reaching accurate conclusions and asking reasonable questions that aid in interpretation [56]. EXPERT is a system applied to solve problems require reasoning, effort has been required to simplify the control strategies so additional knowledge is specified by the knowledge engineer. The production rules are in an ordered fashion that has been pre specified by the knowledge engineer. Since the production rules are in order and the relatively efficient implementation of Expert, revaluation of all rules can take place after each new response is received. EXPERT selects the rule with the maximum absolute value of confidence in that hypothesis. A bonus may be added to the score of a hypothesis that is supported by a relatively large number of findings, In most applications, however, scoring by maximum value has proven satisfactory, yielding highly predictable results.

A.2.10 AGE

AGE is a software tool that aids in the design, construction and testing of a variety of frameworks for knowledge based programs [25]. It provides an environment for user to choose or specify a variety of knowledge representation and processing methods. The AGE system provides the user with a set of predefined modules called components or building blocks. A component is a collection of LISP functions and variables that support conceptual, as well as concrete, entities [36]. For convenience, the component can be pre-programmed but it can be changed or modified by the user during the programming.

The components have been carefully selected, defined and modularity programmed to be usable in various combinations. The use of different combinations makes it possible to construct programs that have different problem solving behaviours. If users are not familiar with combining components, AGE provides predefined configurations of components. Each configuration is called a framework. A framework is conceptually similar to a prefabricated house - the basic design decisions have been made, but many of the final decisions have been left for individual requirements. Similarly the components of the framework can be rearranged or modified to suit the problem at hand.

Back chain framework is used for building a program that uses production rules as its primary knowledge representation and goal directed, backward chaining of rules as its inference method. Blackboard framework is useful primarily for building a program whose design is rooted in the blackboard model developed for the HEARSAY-II speech understanding system. The blackboard model uses the concepts of a globally accessible data structure called a blackboard and independent sources of knowledge that co-operate to form hypotheses incrementally on the blackboard [54]. This framework has been designed to provide flexibility for user in the representation, selection and utilisation of the domain knowledge [54].

AGE provides a user environment that facilitates the construction and detailed specification of each of the components. It is unable to help a novice knowledge engineer translate a problem into suitable framework so knowledge engineer must have knowledge in the use of various problem-solving methods. After a framework has chosen, AGE provides some help in designing its components.

The AGE system consists of four major subsystems [54]:

1. The users design and construction of an application program for a predefined framework has been guided by the design subsystem.
2. The various editors help the user enter detailed domain-specific information as well as control information for each of the components.
3. The interpreter executes the user program and provides a variety of debugging aids.
4. The complete trace of the execution of the user program is provided by the explainer.

A.2.11 EMYCIN

EMYCIN is an appropriate skeletal system for developing a consultation program that can request data about a case and provide an interpretation or analysis [36]. It is well-suited to deductive problems such as fault diagnosis, in which a large body of possibly unreliable input measurements is available and the solution space of possible diagnoses can be enumerated [54].

MYCIN inference engine can be applied to EMYCIN's problem domain and its problem-specific knowledge can be represented in the MYCIN rule language, providing all of MYCIN's features as well as a human-engineered system building environment [54]. It can give a great help in entering and debugging the knowledge base.

Most of EMYCIN's domain specific knowledge are represented by production rules. EMYCIN's inference engine is backward chaining, it tries to determine the value of a top level goal attribute and it is working on the goal of establishing the value of the attribute of some object. In order to achieve this, it retrieves rules which are bear on that goal and it systematically attempts to applies the rules until it either establish the value with complete certainty or exhausts the rule list. If no value can be deduced whether there are no rules or the rules are not satisfy the conditions, it resorts to asking the user for the value.

EMYCIN's explanation system allows user to examine a particular session's conclusion and the information in the static knowledge base. EMYCIN provide a programmer friendly environment for developing the knowledge base. Rules can be entered in Abbreviated Rule Language, a convenient formal representation that is more English-like than LISP and modified with a high level knowledge base editor that checks them for syntactic validity and sees that they do not contradict or subsume existing rules [54].

EMYCIN provides valuable tracing and debugging facilities. Libraries of test cases are maintained, and a debugger based on the one in the TEIRESIAS program is available to guide the designer through the program's reasoning process (Davis 1976). Such features greatly facilitate the development of a new system [54].

Appendix 3

Mail Questionnaires

A.3.1 Process user

Please put a tick in the appropriate box.

Section 0

General Company information

1. Name of company: ____________________
2. Name of respondent: ____________________
3. Telephone Number: ____________________ Ext,: ____________________
4. Position held in the company: ____________________

5. How many employees are there in your company?

✓

☐ under 50 ☐ 50 - 99 ☐ 100 - 249 ☐ 250 - 499

☐ 500 - 999 ☐ 1000 - 2499 ☐ over 2500

6. What is the annual turnover of your company?

✓

☐ under £ 100 k ☐ £100 k - £250 K ☐ £250 K - 500K

☐ £ 500 k - £1 M ☐ £1 m - £5 m ☐ £5 M - £ 25 M

☐ Others (please specify) ____________________

7. What kind of industrial sector does this company belong to?

✓

☐ aerospace ☐ electronics ☐ air conditioning ☐ pharmacy

☐ chemical processing ☐ automotive ☐ food processing ☐ plastics

☐ Others (please specify) ____________________

8. Which form of production is employed by your company?

✓

- ☐ job production
- ☐ batch production
- ☐ mass production
- ☐ others (please specify) ______________________________

9. Does your company use any of the following processes?

✓

- ☐ power hacksawing
- ☐ abrasive cutting
- ☐ bandsawing
- ☐ laser beam cutting
- ☐ waterjet cutting
- ☐ circular sawing
- ☐ arc cutting
- ☐ oxyfuel gas cutting
- ☐ others (please specify) ______________________________

10. Which material groups require cutting-off in your company?

✓

- ☐ power hacksawing
- ☐ abrasive cutting
- ☐ bandsawing
- ☐ others (please specify) ______________________________

Section 1

CUTTING-OFF MACHINES

1. Please indicate the type, make, quantity, size and age of all of the cutting-off machines in your company? (please put a tick in the box and fill the blank)

Machine type	Make (e.g. bridgeport)	Quantity (No. of)	Manual	NC/ CNC (please specify)	Size (capability cubic mm)	Age (years)
Power hacksawing						
Abrasive cutting						
Bandsawing						
Laser beam cutting						
Waterjet cutting						
Circular sawing						
Arc cutting						
Oxyfuel gas cutting						
Others (please specify)						

2. What is the skill level of people who operate cutting-off machines?

✓

☐ power hacksawing ☐ abrasive cutting ☐ bandsawing

3. How many cutting-off machine does each operator supervise?

✓

☐ power hacksawing ☐ abrasive cutting ☐ bandsawing

☐ more (greater than 3 please specify) ____________________

4. Do you regularly use special fixtures for cutting-off purposes?

✓

☐ yes ☐ no

Section 2

CUTTING TOOLS

1. What kind of cutting tools for cutting-off are used in your company?

✓

☐ circular saw

☐ bandsaws

☐ power hacksaws

☐ abrasive saws

☐ others (please specify) ______________________________

2. What type/ material are the cutting-off tools used in your company?

✓

☐ carbide tipped tools ☐ coated tools ☐ H.S.S.. ☐ H.C.S.

☐ others (please specify) ______________________________

3. How many cutting tools do you have in your company in total?

✓

☐ 0 - 100 ☐ 101 - 200 ☐ 201 - 350 ☐ 351 - 500 ☐ 501 - 1000

☐ others (please specify) ______________________________

4. Does your company regrind or check the cutting-off tools at fixed intervals?

✓

☐ yes

☐ no

☐ others (please specify) ______________________________

Section 3

Planning

1. Please indicate which person selects the cutting-off , machine tools, cutting tools and cutting off parameters? (please put a tick in the box or fill the blank)

	Production Engineer	Production Planner	Others (please specify)
Cutting-off process			
Cutting-off machine			
Cutting-off parameter			

2a. Does your company use a computer to help select cutting-off processes?

✓

☐ yes

☐ no (please go to question 3)

2b. Please give the name of the software package. (If delivered in house, please give the name of the programme.)

____

3a. Please indicate how your company selects the following: (please put a tick in the box or fill the blank)

	Use of computer (please complete 3b)	Manually	Use of external expert advice	Other methods (please specify)
Machine tool				
Cutting tool				

3b. If you use computer for machine/ cutting tool selection, please give name and company of the package. (If developed in house, please give the name of the programme.)

Programme of machine tool selection

Name of software ______________________________________

company name ______________________________________

Programme of cutting tool selection

Name of software ______________________________________

Company name ______________________________________

4. How much does your company spend on purchasing cutting-off machine tools per annual?

✓

☐ under £ 50 k ☐ £51 k - £200 K ☐ £201 K - 500K

☐ £ 501k - £1000 k ☐ £ over 1000 K

5. What are the stocking holding* cutting tools cost and regrinding cost* (per year)? (please put a tick in the box)

	Carrying cost	Regrinding cost
£ 0 - 50 K		
£ 51 K - £ 99K		
£ 100 K - £ 200 K		
£ 201 K - £ 500 K		
£ 501 K - £1000 K		
over £ 1000 K		

* If the cost is identifiable, please say so.

6. How does your company select cutting-off parameters (e.g. speeds, feeds, etc.)?

✓

- ☐ computer based system
- ☐ in company manually
- ☐ external expert advice
- ☐ standard formulae
- ☐ others (please specify) ______________________________

7. Please indicate which person does the following maintenance jobs: (please put a tick in the box or fill the blank)

	In house company personnel	Tool supplier (vendor)	Others (please specify)
Machine Maintenance			
Cutting tool maintenance			

Section 4

Selection criteria

1. In selecting cutting-off machine tool what do you consider to be important? (please specify in order of importance. 1 = most important, 7 = lease important)
Please list 1 - 7

	Machine availability
	Machine capability
	Job quantity
	Production rate
	Machining cost, labour cost
	Others (please specify)

2. In cutting-off parameter selection what do you consider important? (please specify in order of importance. 1 = most important, 7 = least important)
Please list 1 - 7

	Job specification
	Tool life
	Productivity
	Cutting rate
	Operation cost
	Others (please specify)

3. What do you think are the most important objectives when selecting the cutting parameters? (please specify in order of importance. 1 = most important, 7 = least important)

Please list 1 - 7

	Surface finish
	Maximum tool life
	Minimise cutting time
	Optimum cutting conditions
	Company standard
	Others (please specify)

4a. Do you predict cutting tool life at standard precedence in your company?

✓

☐ yes ☐ no (please go to question 5)

4b. Which method do you use for tool life prediction?

✓

☐ standard formulae ☐ operator knowledge/ experience

☐ external expert advice ☐ computer based system

☐ others (please specify) ____________________

5. Would you like to help us further in this survey by: allowing us to visit or to telephone your company

✓

☐ yes

☐ no

6. Would you like to have a copy of the final report a survey findings?

✓

☐ yes ☐ no

Thank you in advance for helping in this research.

A.3.2 Cutting-off machine tool manufacturers

Please put a tick in the appropriate box.

Section 0

General Company information

1. Name of company: ______________________________
2. Name of respondent: ______________________________
3. Telephone Number: ______________ Ext,: ______________
4. Position held in the company: ______________________________

5. How many employees are there in your company?

✓

☐ under 50 ☐ 50 - 99 ☐ 100 - 249 ☐ 250 - 499

☐ 500 - 999 ☐ 1000 - 2499 ☐ over 2500

6. What is the annual turnover of your company?

✓

☐ under £ 100 k ☐ £100 k - £250 K ☐ £250 K - 500K

☐ £ 500 k - £1 M ☐ £1 m - £5 m ☐ £5 M - £ 25 M

☐ Others (please specify) ______________________________

7. Which form of production is employed by your company?

✓

☐ job production

☐ batch production

☐ mass production

☐ others (please specify) ______________________________

Section 1

Please put a tick in the appropriate box

Machine Tool Information

1. What types of cutting-off machines and their quantities are produced by your company per annual?

(please put a tick in the box)

Machine type	Quantity (No. off)	Manual	NC/ CNC (please specify)
Power hacksawing			
Abrasive cutting			
Bandsawing			
Laser beam cutting			
Waterjet cutting			
Circular sawing			
Arc cutting			
Oxyfuel gas cutting			
Others (please specify)			

2. How many cutting-off machine tools were produced in the last financial year?

✓

☐ under 50 ☐ 50 - 99 ☐ 100 - 249 ☐ 250 - 499

☐ 500 - 999 ☐ 1000 - 2499 ☐ over 2500

3. How many cutting-off machine tools do you expect to produce in the next financial year?

✓

☐ under 50 ☐ 50 - 99 ☐ 100 - 249 ☐ 250 - 499

☐ 500 - 999 ☐ 1000 - 2499 ☐ over 2500

Could you please send technical information and brochures on the full range of your cutting-off machine tools.

Thank you in advance for helping in this research.

A.3.3 Cutting-off tool manufacturer

Please put a tick in the appropriate box.

Section 0

General Company information

1. Name of company: ______________________________
2. Name of respondent: ______________________________
3. Telephone Number: ____________________ Ext,: ____________
4. Position held in the company: ______________________________

5. How many employees are there in your company?

✓

☐ under 50 ☐ 50 - 99 ☐ 100 - 249 ☐ 250 - 499

☐ 500 - 999 ☐ 1000 - 2499 ☐ over 2500

6. What is the annual turnover of your company?

✓

☐ under £ 100 k

☐ £100 k - £250 K

☐ £250 K - 500K

☐ £ 500 k - £1 M

☐ £1 m - £5 m

☐ £5 M - £ 25 M

☐ Others (please specify) ______________________________

7. Which form of production is employed by your company?

✓

☐ job production

☐ batch production

☐ mass production

☐ others (please specify) ______________________________

Section 1

Please put a tick in the appropriate box.

Cutting-off tool information

1. What kind of cutting-off tools are manufactured by your company?

✓

☐ circular saws ☐ bandsaws

☐ power hacksaws ☐ abrasive saws

☐ others (please specify) ______________________________

2. In which material do you produce tools?

✓

☐ carbide tipped tools ☐ coated tools ☐ H.S.S.. ☐ H.C.S.

☐ others (please specify) ______________________________

3. Do you provide machining parameters selection help to your customers (e.g. speed, feed, etc.)?

✓

☐ yes ☐ no

4. How may cutting-off tools were produced by your company in last financial year? (please fill the blank)

Tool type	Range (size e.g. diameter in mm)	Quantity (no. off)
Power hacksawing		
Abrasive cutting		
Bandsawing		
Circular sawing		
Others (please specify)		

Could you please send technical information and brochures on the full range of your cutting-off tools.

Thank you in advance for helping in this research.

Appendix 4

Expert System Verification

Faruk Polat and H. Altay Guvenir [53] suggest an expert system cannot be tested, even on simple cases, until much of the knowledge base is encoded. An expert system must check for consistency and completeness.

Consistency checking includes testing whether or not the system produces similar answers to similar questions; inconsistencies in a knowledge base may appear as conflicts, redundancies or subsumptions. Two rules conflict with each other if they succeed in the same situation but produce contrary results. If two rules succeed in the same situations and result in the same conclusions then we have redundancy in the knowledge base. A rule is subsumed by another rule which has the same conclusions as the first rule, but only a portion of the antecedents of the first rule as its own antecedents. Redundancies and subsumptions may lead to inconsistencies in systems that use some type of scoring scheme. They might cause the same information to be accounted more than once, leading to erroneous increases in the weight of conclusions.[53]

Completeness checking includes testing whether the system answers all reasonable situations within its domain. Whenever such completeness can be obtained, everything derivable in the domain from the given data will be derived. This can be achieved by identifying knowledge gaps in the knowledge base, which may be caused by dead-end rules or circular rules.[53]

During the development of an expert system, it is necessary to decide on the knowledge representation scheme that is most suitable to the application. Rules in a knowledge base may be interrelated if they have common predicates. During the verification process, predicates are compared to each other to determine the relationships between them. These common predicates may be equivalent even though they are not exactly equal. The conjunctions of predicates must be compared to check whether one is a subset or superset of the other, or whether they are equivalent.

Polat and Guvenir [53] also suggest need to be determined the rules inferred by the knowledge base before going into the consistency and completeness tests. Finding the inferred rules is necessary because one inferred rule may contradict another, or may cause circular chains. Inferred rules can be found by computing the transitive closure of the rules in the knowledge base; however, computing all the inferred rules is unfeasible since there will be too many of them.

From Trevor Bench-Capon and Frans Coenen's idea [54], it is necessary to validate the knowledge base after maintenance has taken place. Validation can be carried out by analysing the rule base and determining what inference can be made or tracing how inference are made.

Graham F Forsyth, Michael D Larkin, Glen A Wellace [55] use the following approach to attain rule verification.

i. The knowledge engineer asking the experts for adequate causal explanation at the interview stage;

ii. If the computer based causal model is not yet available, try to compensate by looking for either physical or causal links between the conditions and the conclusions defined by the rule;

iii. Rigorously examine the explanations with the identified links;

iv. Look for holes in coverage, such as known links to items which have not been used anywhere either as conditions or conclusions.

They built a rule-set and explanation-set in parallel. The explanation-set forms the basis on which to develop a qualitative causal model and building such a causal model will be considered as part of the process for long term support for the rule set.

The aim for knowledge base verification work is some means of automated comparison of a set of heuristic rules and a causal model. Towards this end, they need to develop methods for comparing rules and the causal model output. They have experience with the manual comparison of rules and causal model output, they intend to develop a procedure to perform this task automatically, possibly using a knowledge base tool to encode their experience. This verification knowledge base contains the possible causes and symptoms for faults of the knowledge base will result. It is quite possible that during knowledge acquisition interviews, the experts and the knowledge engineer will become focused on a particular line of investigation and will not consider other possible scenarios.

Appendix 5

Testing examples

This appendix includes the examples used for Phase 2 and phase 3 test.

A.5.1 Phase 2 test examples

The following examples are taken out from Metals handbook [14]. The shaded portion is the cut-off. All dimensions in mm.

Example 1

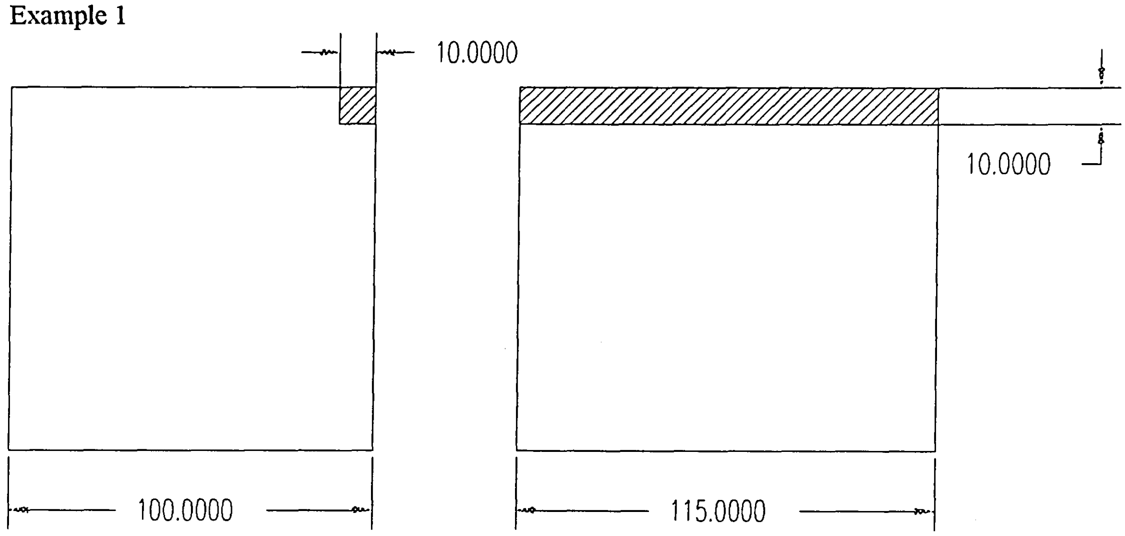


Figure A10

Hardness = 40 Vickers

Tolerance = +/- 0.1 mm

Kerf loss = 3.0 mm

Size = See figure A10

Material = Carbon steel

Surface finish = 10

Section = Short end stock

Example 2

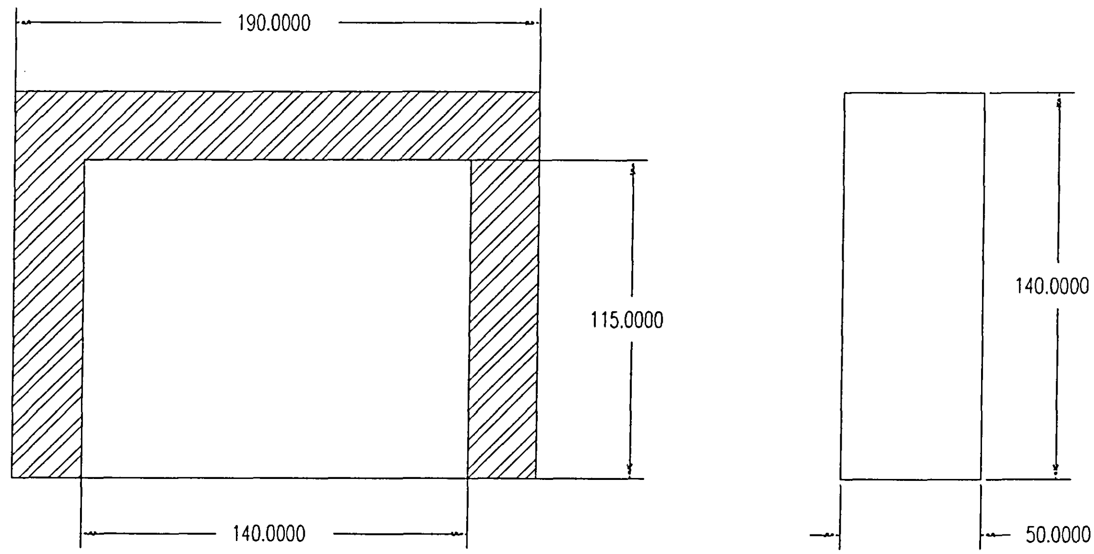


Figure A11

Hardness = 40 Vickers	Material = Carbon steel
Tolerance = +/- 0.2 mm	Surface finish = 8
Kerf loss = 5.0 mm	Section = Short end stock
Size = See figure A11	

Example 3

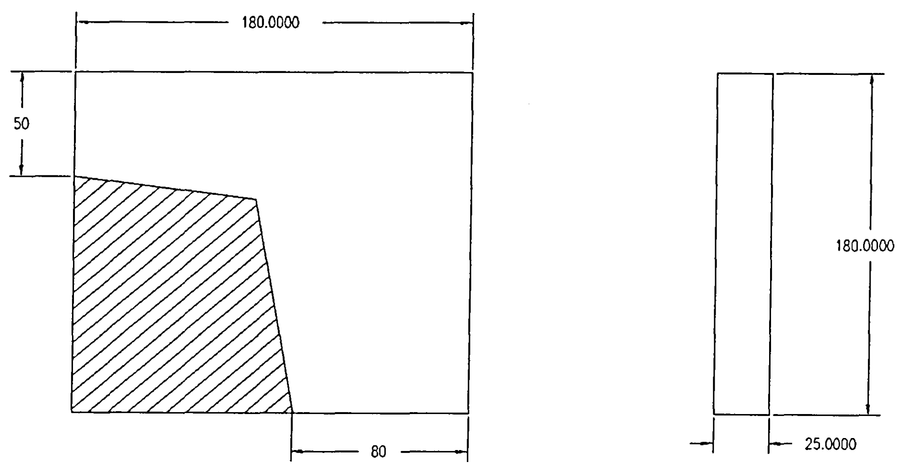


Figure A12

Hardness = 40 Vickers	Material = Carbon steel
Tolerance = +/- 0.1 mm	Surface finish = 6
Kerf loss = 2.0 mm	Section = Short end stock
Size = See figure A12	

Example 4

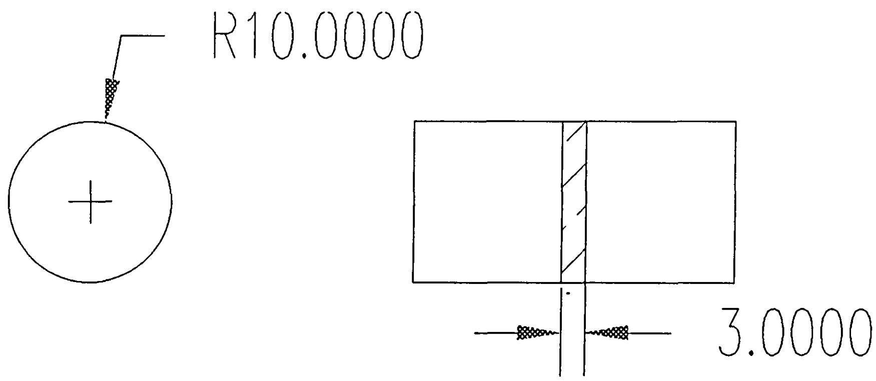


Figure A13

Hardness = 300 Vickers	Material = Cast iron
Tolerance = +/- 0.5 mm	Surface finish = 300
Kerf loss = 2.8 mm	Section = Round bar stock
Size = See figure A13	

Example 5

Hardness = 100 Vickers	Material = Al alloy
Tolerance = +/- 0.3 mm	Surface finish = 50
Kerf loss = 2.0 mm	Section = Round bar stock
Size = See figure A13	

Example 6

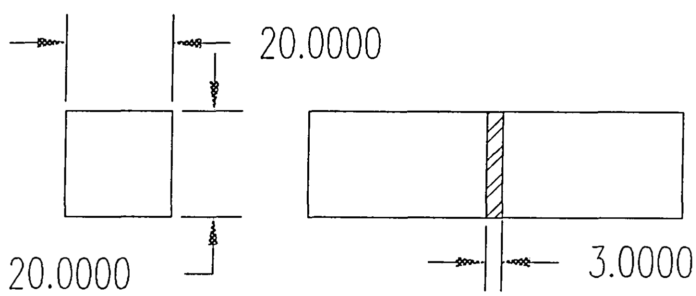


Figure A14

Hardness = 150 Vickers	Material = Stainless steel
Tolerance = +/- 0.5 mm	Surface finish = 10
Kerf loss = 0.8 mm	Section = Short end stock
Size = See figure A14	

Example 7

Hardness = 50 Vickers

Tolerance = +/- 1.0 mm

Kerf loss = 2.8 mm

Size = See figure A14

Material = Mild steel

Surface finish = 300

Section = Short end stock

Example 8

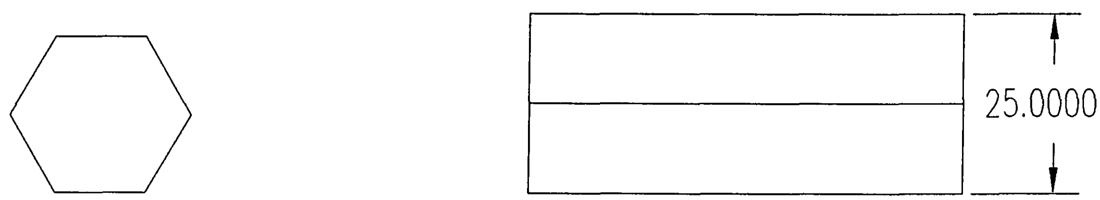


Figure A15

Hardness = 30 Vickers

Tolerance = +/- 0.7 mm

Kerf loss = 0.8 mm

Size = See figure A15

Material = Cu alloy

Surface finish = 30

Section = Hexagonal bar stock

Example 9

Hardness = 100 Vickers

Tolerance = +/- 0.3 mm

Kerf loss = 0.8 mm

Size = See figure A15

Material = Ni alloy

Surface finish = 30

Section = Hexagonal bar stock

Example 10

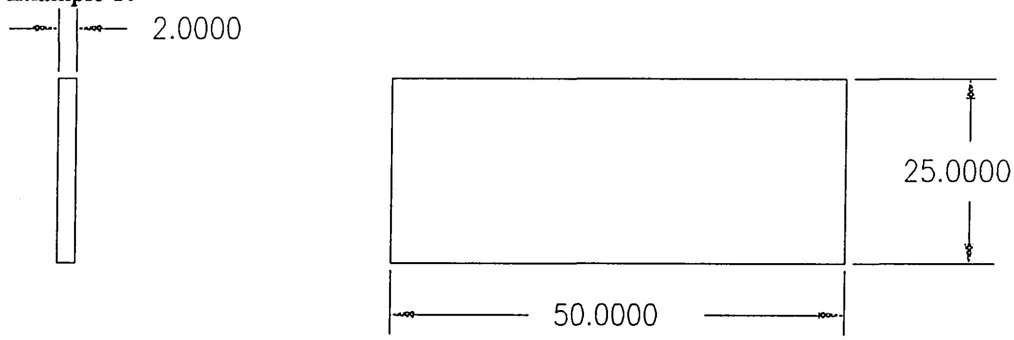


Figure A16

Hardness = 100 Vickers

Tolerance = +/- 0.1 mm

Kerf loss = 2.0 mm

Size = See figure A16

Material = Stainless steel

Surface finish = 100

Section = Thin sheet

A.5.2 Phase 3 tests - Industrial testing

Industry users cut many different shapes and materials product from day to day. Their working practice can provide valuable informations to verify the prototype system. The following examples are taken out from industry people's working practice. These informations input into the prototype system and the system output will check against the human expert's suggested solutions.

1. Seat belt clamp

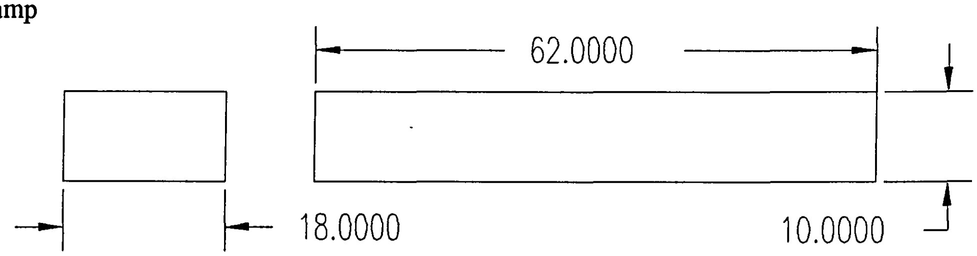


Figure A17

Hardness = 208 Vickers
Tolerance = +/- 0.5 mm
Kerf loss = 1.7 mm
Size = 18 * 10 mm (figure A17)

Material = Alloy steel
Surface finish > 300
Section = Rectangle strip

2. Box

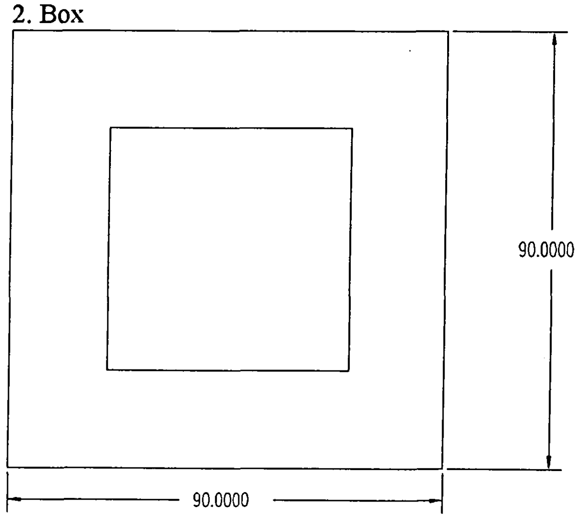


Figure A18

Hardness = 152 Vickers
Tolerance = +/- 1.0 mm
Kerf loss = 1.7 mm
Size = 90 * 90 mm (figure A18)

Material = Carbon steel
Surface finish = 500 (not important)
Section = Hollow section

3. Medical implant

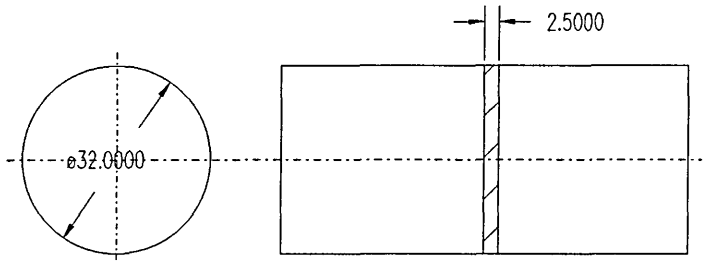


Figure A19

Hardness = 500Vickers

Material = Cobalt cone

Tolerance = +/- 0.5 mm

Surface finish = 5 (Very good finish)

Kerf loss = 2.5 mm

Section = Round bar stock

Size = 32.0 mm diameter (figure A19)

4. Electrode

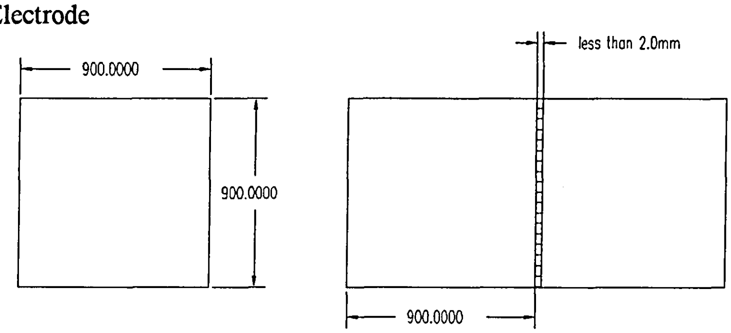


Figure A20

Hardness = unknown

Material = Graphite

Tolerance = +/- 2.0 mm

Surface finish = Good

Kerf loss > 2.0 mm

Section = Block

Size = 900 * 900 * 900 mm (figure A20)

5. Concast billet

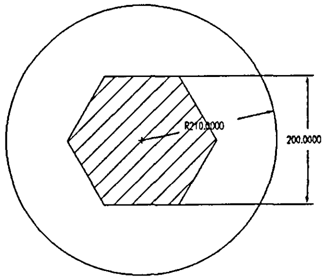


Figure A21

Hardness = 47 - 130 Vickers

Material = Al - lithium

Tolerance = +/- 3.0 mm

Surface finish = 500 (not important)

Kerf loss = 3.0 mm

Section = Round bar stock

Size = See figure A21 (shaded area is the required workpiece)

Appendix 6

Manufacturing Cost Calculations

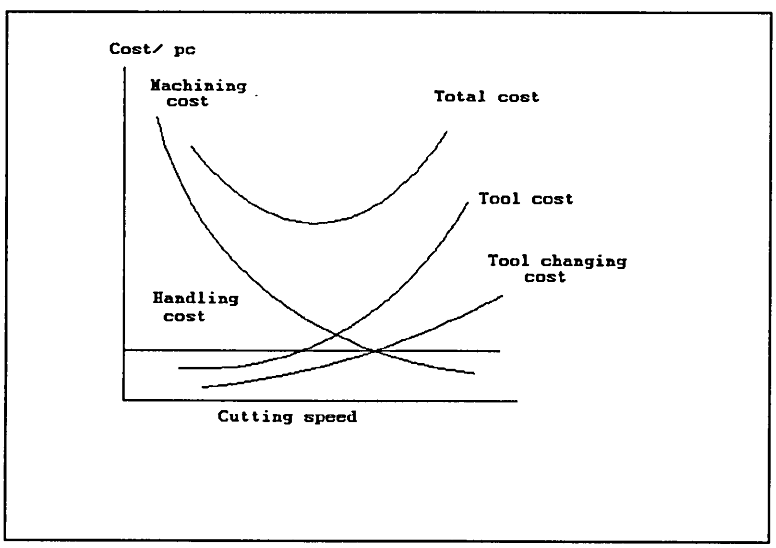
Two criteria frequently used in the optimisation of machining operations are the 'maximum production rate' [41] criterion and the 'minimum cost per component' criterion [41]. These two will always give a different cost and production rate. The minimum cost criterion will give a lower production rate, while the maximum production rate criterion will have a higher cost per component. The overall optimum situation will generally be fairly close to the conditions established by these criteria, which is usually somewhere between the two. These costs involve machining cost, tool cost, tool changing cost and handling cost. The sum of these costs are the total cost.(figure. A22)

Total cost = Machining cost + Tool cost + Tool changing cost + Handling cost

$[C = C_1 + C_2 + C_3 + C_4]$

In selecting economic operating conditions, machine tool capabilities must be accounted for. Often the desired condition may be unattainable on the machine tool proposed for a particular operation. It is then necessary to either change the operating conditions or review the machine tool selection. The change may involve purchase of a new machine, re-scheduling of another machine, or possibly modifying the existing machine. On the other hand, it may happen that the machine conditions selected on economic grounds are using the chosen machine tool far below its capacity (power, speed, feed etc.). In this case, the machine selection should be reviewed, to see if a machine with lower capacity can be used for this operation.

Figure A22. Total cost



The capacity limits of a machine tool, limiting the selection of machining conditions are listed as follows:

i. machine tool maximum feed.

ii. machine tool maximum speed.

iii. machine tool maximum power.

iv. maximum allowable cutting or thrust force.

v. feed and speed limits for the desired component surface finish.

vi. machine tool feed and speed increments.

Improved tool materials and tool geometry which give longer tool life values will reduce the number of tool replacements and hence lower the cost per component. Similarly, work materials giving less tool wear can reduce the cost per component. Overhead costs cannot normally be expected to drop, so that cost reductions will have to be based on improved techniques. The cost per component can also be lowered by decreasing machining time. Increasing the cutting speed or feed reduces the machining time but reduces the tool life at a faster rate.

The production rate is dependent on the cutting conditions and the tool life. Decreases in non-productive time and time required to change the cutting tool, will increase the production rate. Increases in cutting speed will reduce the machining time per component; a minimum time per component or maximum production rate will therefore result. Variations in cutting speed will optimum values of cost per component and production rate.

In general, the speed for maximum production rate will differ from the speed for minimum cost.