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THE UTILIZATION OF NUMERICALLY CONTROLLED MACHINE TOOLS

by

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Department of Industrial Engineering
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Halifax

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PREFACE

The subject of machine tool utilization is one which receives little attention in either Engineering Degree programs or continuing education. Most often, students and practising engineers, must glean what they can from a wide variety of sources in the literature and learn from their own or colleague's experiences. In the majority of cases, an initial exposure to machine tools is acquired through a course in manufacturing processes or, in the case of numerically controlled machine tools, through courses in automatic control. Neither of these approaches give any real insight into the practical problems involved in the use of machine tools.

It should be noted, in passing, that the current situation within our educational system allows most mechanical and industrial engineering students to graduate with little or no exposure to the major aspects of manufacturing process capability and cost, let alone the practical problems involved in specifying and utilizing modern equipment. This problem is compounded by the ever increasing sophistication of both basic machine tools and support aids to both design and manufacturing. In the author's view one must have a good basic knowledge of both design and manufacturing before progressing to a consideration of the newer, seemingly more glamorous areas such as CAD/CAM or Integrated Manufacturing Systems. This latter opinion, however, is not shared by many in the academic community as witnessed by the proliferation of new courses in such areas, with it would seem, no attempt to improve student understanding of the underlying basic disciplines.

In this monograph, the author gives a personal overview of the major areas of interest and concern to users of numerically controlled machine tools. Because of the wide range of basic topics which are involved in such a subject, the author, by his own admission, has not attempted to be rigorous in his treatment of areas such as economics and metalcutting. The main emphasis is to provide a concise appreciation of major problem areas and to give guidelines to possible methods of solution. It is hoped that this format will encourage readers to examine the literature in the various areas and to this end a comprehensive bibliography is included.

Despite the fact that the view portrayed is a very personal one, the author owes a debt of gratitude to many former colleagues who have influenced his thinking on machine tool related topics. In particular the author would mention his colleagues at the University of Manchester Institute of Science and Technology, (UMIST), and at McMaster University who encouraged his research interest. Several informative years were also spent at Westinghouse Canada where the author learned much about the practicalities of machine tool utilization from a knowledgeable group of practising engineers. The author also thanks Mr. J.E. Crozier the editor of this series of monographs and Mrs. Kay Lawrence who performed the arduous task of preparing the manuscript, both of the Canadian Institute of Metalworking. Lastly the author thanks his family for their support and encouragement throughout the year which was spent in preparing the monograph.

CHAPTER (I)

ECONOMICS OF APPLICATION

1.1. INTRODUCTION

Numerically controlled machine tools are widely used in many sectors of industry. The current generation of these machines offer dramatic improvements in cost effectiveness when compared to the initial production machines installed some two decades ago. In the achievement of this goal significant improvements have been made in the design of structures, way systems, feed and spindle drives and perhaps most significantly in flexibility of control and reliability.

Unfortunately, whilst the presence of numerically controlled machine tools on the production floor is now commonplace, many companies have still not adapted their manufacturing techniques and product design to extract the full potential of these tools.

The aim of this monograph is to make the reader aware of the possibilities afforded by numerical control and the manner in which these possibilities are best exploited. Since the majority of machines are still used in metal cutting then the author will demonstrate, in some detail, the important role which an understanding of these processes plays in the economics of application. It is also necessary to examine overall production planning and the links between this process and part geometry. Unfortunately, in a monograph, it is not possible to integrate these topics with a discussion of closely related subjects such as machine tool performance, accuracy and programming. It is however likely that later monographs on these subjects will be forthcoming.

1.2. THE BASIC MACHINES - AN INTRODUCTION

Numerical control, that is the use of coded instructions to control machine or process behaviour, has been applied to a variety of fields. In this monograph the machines discussed are primarily metal cutting machine tools. It should be remembered, however, that the fundamental underlying technology has been applied to a wide range of production equipment. Most notably the author would mention turret presses, tube benders, inspection machines and assembly devices or robots.

In discussing metal cutting machine tools the prime functions to be controlled and desirable operating modes are the following:

a) Closed loop position and velocity control of major working axes. Most modern machines will be capable of linear interpolation in two or three axes, with circular interpolation in any two and, in the case of machining centers, helical interpolation.

b) The control of miscellaneous functions such as spindle rotation, turret or table index, coolant, part load/unload, tool change and axis clamping.

c) The capability of working from manual data input, tape or control memory with the possibility of editing the machine tool control tape. (The author, in this monograph will avoid, as much as possible, the use of terms such as CNC, DNC, etc. although, of course, the above requirements would dictate a computer based controller).

2

The axes on a numerically controlled machine tool are usually depicted as a right handed cartesian set as shown in figure (1.1). In addition to the primary axes X, Y, Z many machines use additional axes U, V and W which are parallel to the primary set. Angular axes A, B and C are labelled according to the axis about which the rotation takes place, thus an 'A' rotation is about the X axis, etc. The positive direction of rotation is clockwise when viewed in the positive direction of the corresponding linear axis. Typical examples of the basic machines and axis labelling are shown in figures (1.2), (1.3), (1.4), (1.5) and (1.6). The reader should take care to consult the programming manual of each specific machine tool before making any assumptions about axis labelling. It should also be borne in mind that if a particular axis moves the work rather than the tool, then the sense of that axis is reversed.

The remainder of this chapter is devoted to an examination of the economics of N.C. Further details of the machines themselves are to be found in Chapter 3. Readers who are interested in the problems of N.C. machine design, performance and accuracy are referred to the bibliography.

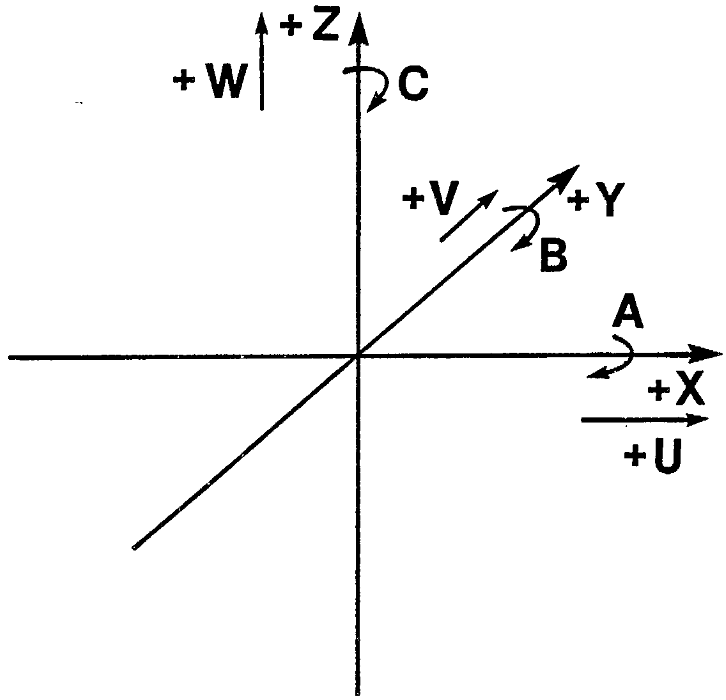


Figure 1.1. Right Handed Cartesian Set

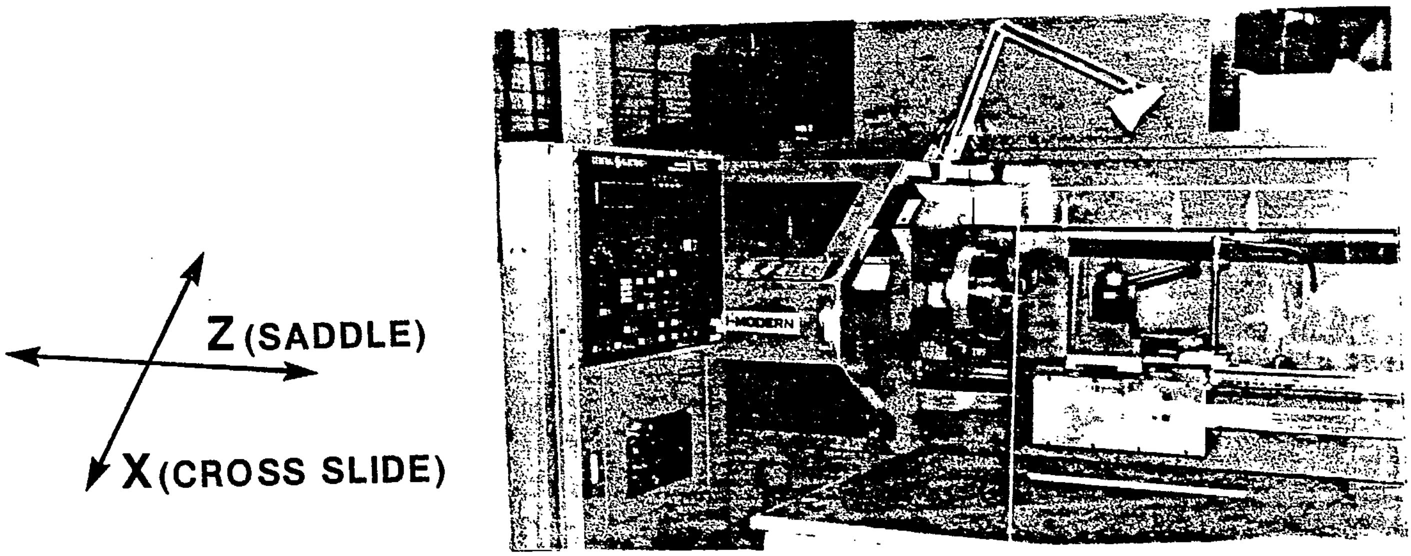


Fig. 1.2. Two Axis N.C. Lathe (Photograph Courtesy of Bristol Aerospace)

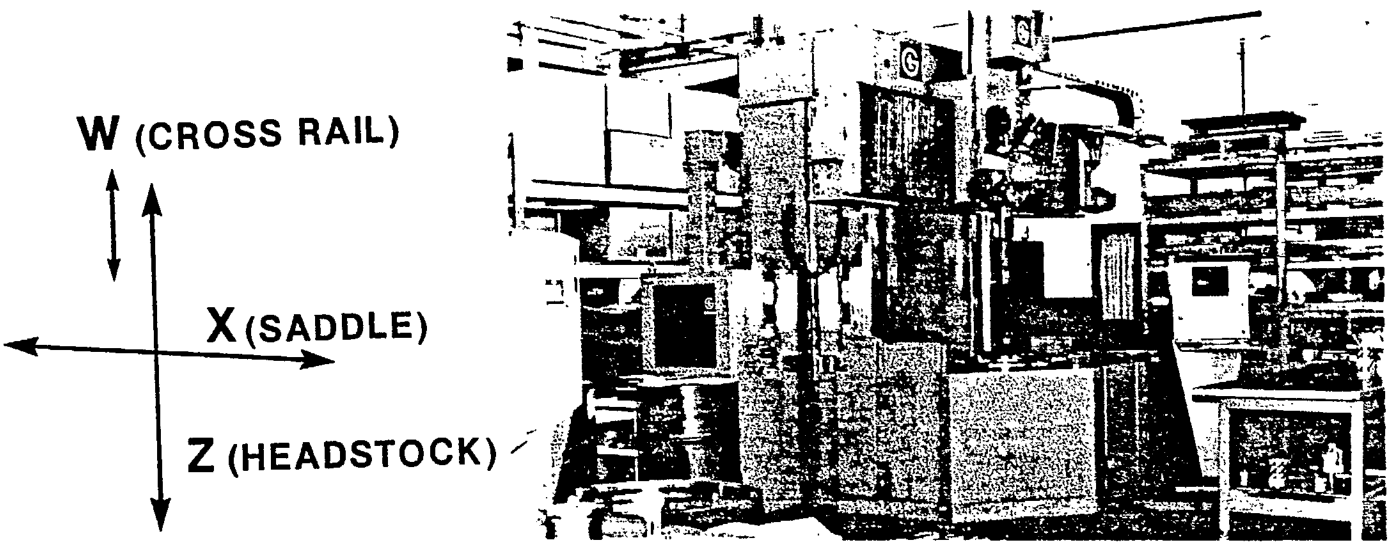


Fig. 1.3. Two Axis N.C. Vertical Turning Lathe, (with positioning cross rail). (Photograph courtesy of Bristol Aerospace)

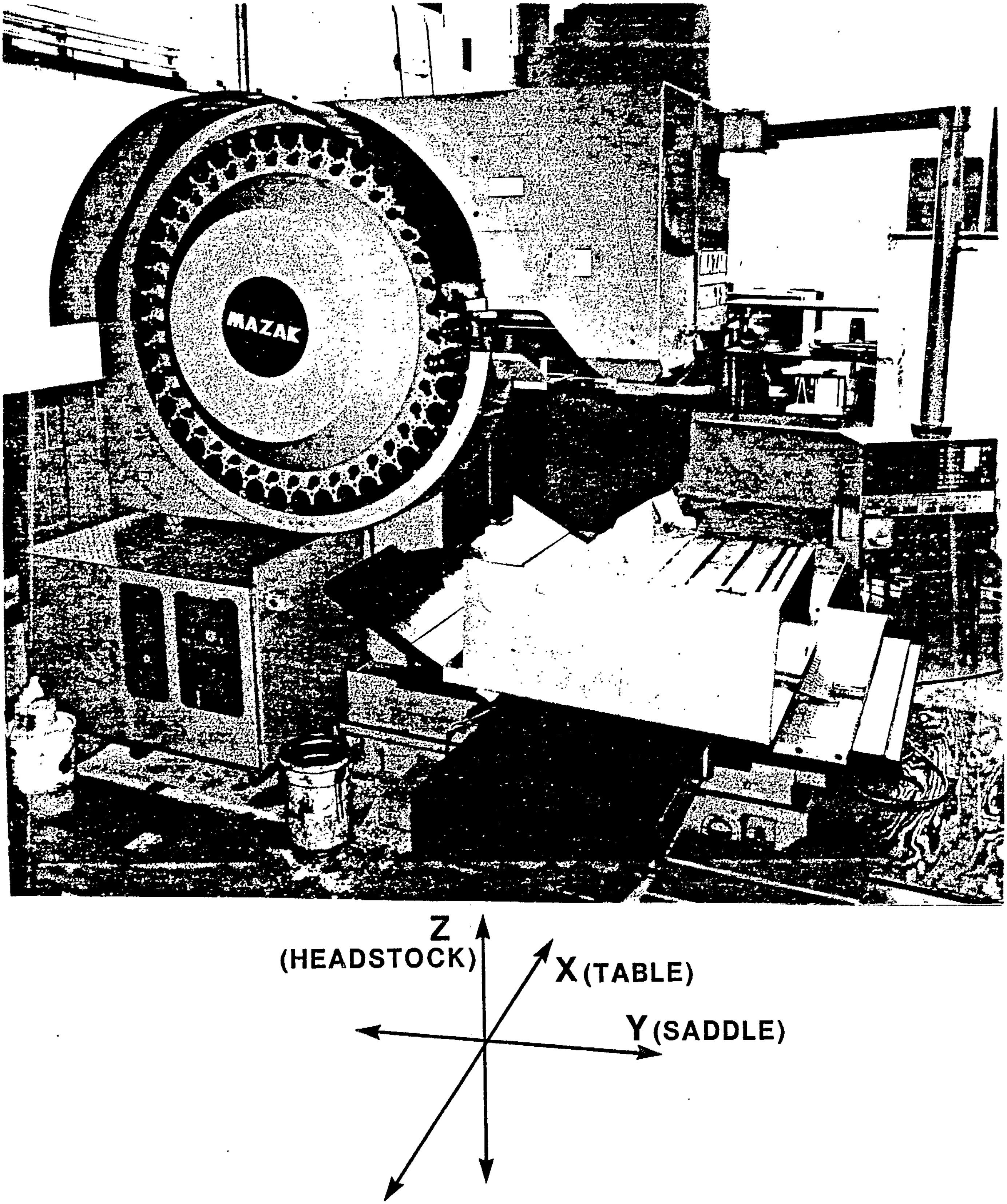


Figure 1.4. 3 Axis Vertical Machining Center (Photograph courtesy of Bristol Aerosapce)

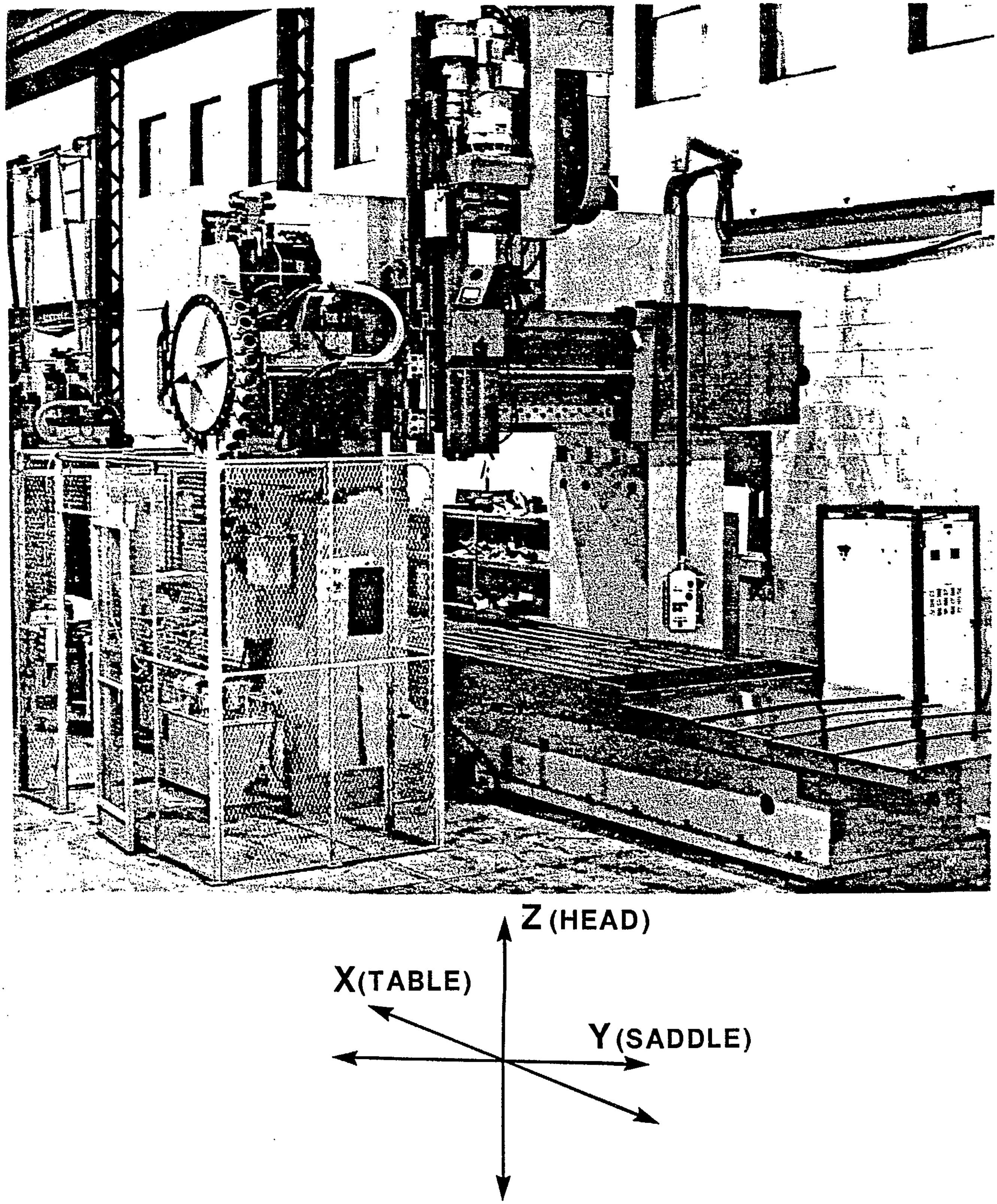


Figure 1.5. 3 Axis N.C. Planomill under construction
(Photograph courtesy of Liné Canada)

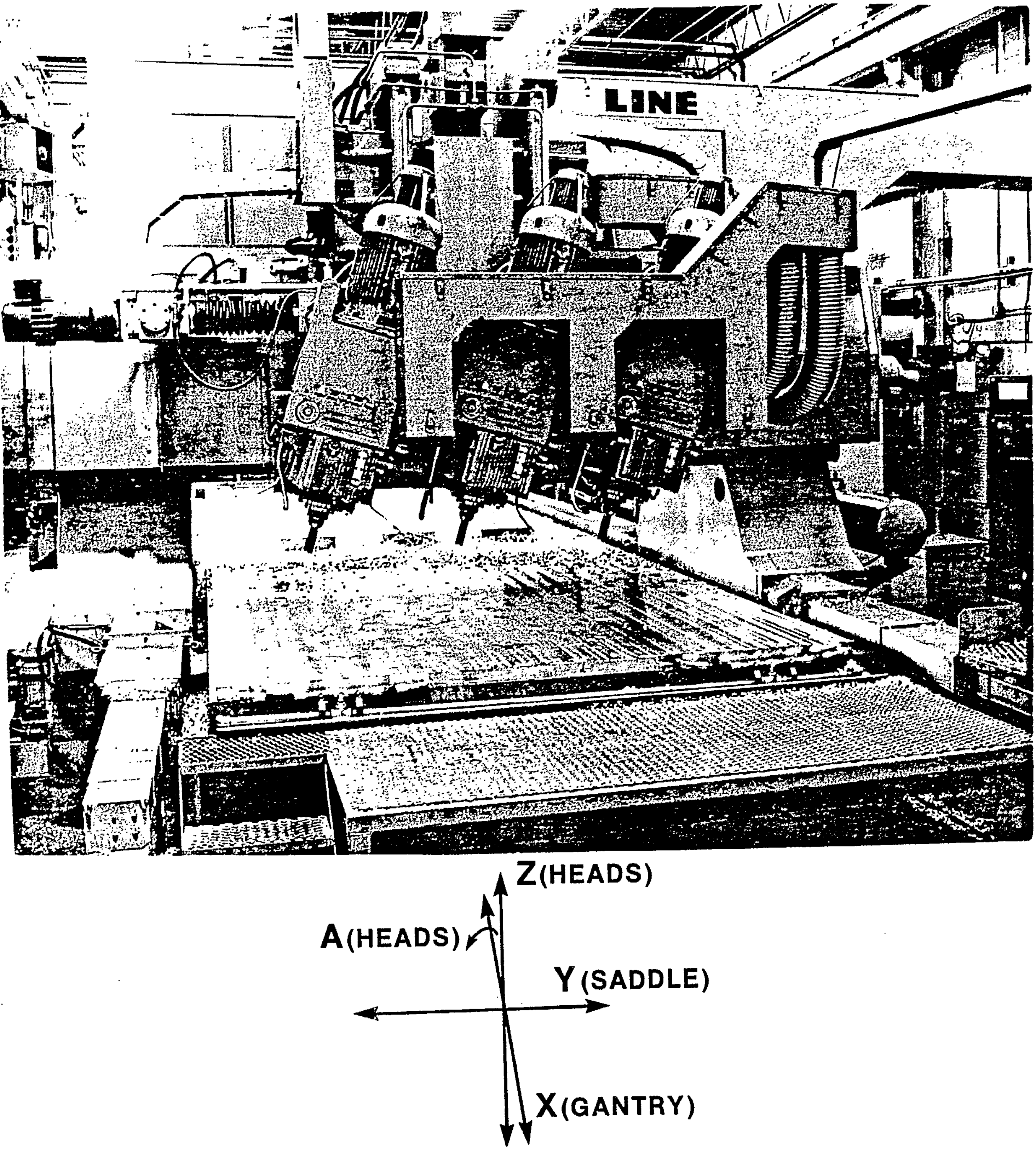


Figure 1.6. 4 Axis N.C. Planomill (Photograph courtesy of Liné Canada)

1.3. THE ECONOMICS OF NUMERICAL CONTROL

1.3.1. The Source of Savings

Numerically controlled machines are, inevitably, more costly than manually operated machines. This arises not only because of the cost of control but also because of the need for improved machine accuracy for the same part tolerance and the more pressing need for improved performance. (These points are covered in more detail later in this chapter). If one must allocate considerably more capital to acquire such machines then it is evident that corresponding gains in productivity must be realizable if one is to pursue the acquisition of NC machines. In the remainder of this section the author will first examine the sources of productivity increase, this will be be followed by an economic analysis of the feasibility of NC under various circumstances.

1.3.2. Increases in Productivity Achievable with NC Machines

The literature abounds with articles which give actual case studies showing productivity ratios between NC and manual operations which make NC appear extremely attractive. In reality of course such ratios are meaningless unless one knows the care given to process planning, tooling and fixturing, maintenance of standards and the production planning function in each case. By virtue of their high capital cost and "visibility", NC machines usually enjoy a higher level of service in all these areas.

Whilst then it is true that ratios of 3 or 4 to 1 in processing time may be achieved on specific parts, the average improvement attainable, given good practice and management of manual machines, will usually be considerably lower. In order to gain an appreciation of the author's reasoning the remainder of this section is devoted to a scientific approach to estimating the expected productivity improvements.

The numerically controlled machine tool reduces process time by reducing operator interaction in the following activities:

a) Setting of spindle speeds and feed rates.

b) Initiating feeds, speeds and other miscellaneous functions e.g. coolant, clamps, etc.

c) Measuring dimensions, trial cuts and moving tool to, or retracting the tool from the cutting stroke.

d) Setting special tools or attachments to provide particular form elements on the workpiece, e.g. rotary tables, compound rest, taper attachment, form tools, etc.

Accordingly, the success of NC machines depends upon the proportion of the operator interaction on a manual machine which may be avoided when NC is used. In general this infers that the higher the complexity of shape and the higher the required accuracy, the more suitable will a component be for the use of NC. In order to gain some appreciation of the potential for productivity gain it is instructive now to examine the machining of a simple shoulder on a shaft. The shoulder is shown in figure 1.7, it is to be machined on a manual lathe of approximately 16 inch swing, (lathe size influences the manipulation times required).

It is assumed that the component is held in a three jaw chuck and that the tolerance on both diameter and length is ± 0.005 inch.

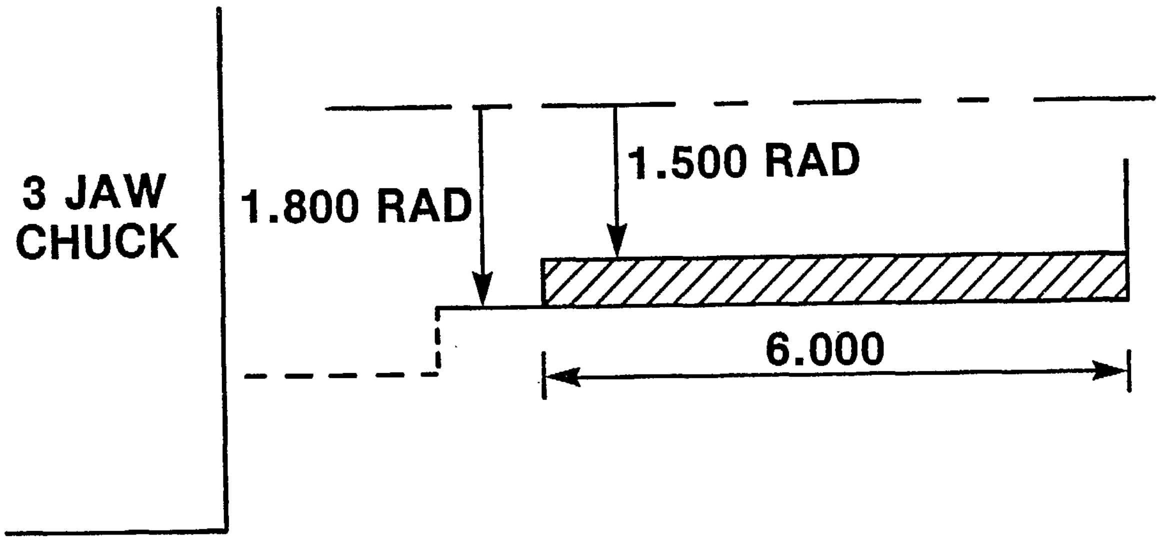


Figure 1.7.

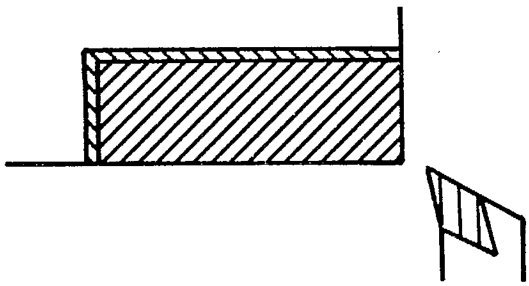
There are, of course, many ways to rough and finish such a simple shoulder depending upon the features of the machine and the required accuracy. In this case the procedure adopted will be as follows:

a) Measure approximate starting diameter.

b) Take two roughing cuts leaving approximately 0.02 inch on both radius and face.

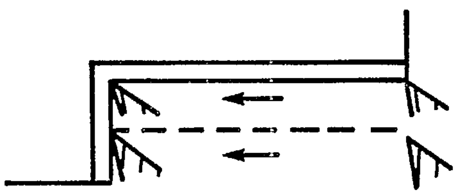
c) Measure resulting diameter and shoulder length.

<u>Operation (10)</u> (Set Ready to cut).



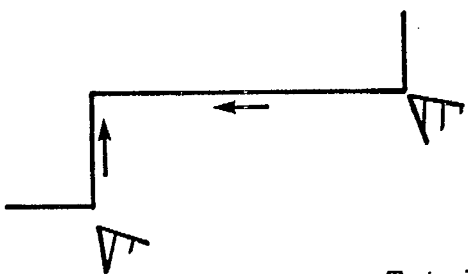
Manual Time TM (Sec)	Cut Time TC (sec)
55	0

<u>Operation (20)</u> (Take Two Rough Passes)



Manual Time TM (Sec)	Cut Time TC (sec)
90	180

<u>Operation (30)</u> (Finish Dia and Face)



Manual Time TM (Sec)	Cut Time TC (sec)
130	140

Total Processing Time TP = 595 sec

Figure 1.8 Roughing and Finishing a Simple Shoulder on a Manual Machine

The detailed operations and approximate time values required are shown in in figure (1.8). It is seen that even though the machine is in the "processing" mode, the actual cutting time is only 61% of the total. In order to arrive at a realistic estimate of the processing time per piece, one must allow for the load unload time per component and the set up time per batch.

Given that the part may be lifted by hand, chucked in a three jaw chuck and the tailstock is not used, then a realistic estimate of load unload time will be given by:

$$TL = 50 \text{ sec.}$$

Thus the floor to floor time per piece

$$TF = TP + TL = TC + TM + TL = 645 \text{ sec.}$$

The set up time required for the batch would probably only allow for the setting of a single tool, setting the compound rest and reading the blueprint. (Assuming the chuck does not need to be changed and measuring tools are available). Under these circumstances a reasonable estimate of set up time per batch would be:

$$TS = 200 \text{ sec.}$$

Thus the total processing time per part assuming five parts to the batch would be as follows:

$$TTOT = TP + TL + \frac{TS}{5} = 685 \text{ (sec)}$$

It is thus seen that even in the simplest of cases the actual cutting time comprises less than half the total processing time.

Having followed the simplistic example presented thus far, the reader will no doubt have realised that the proportion of cutting time on the manual machine is very much dependent on the length of the shoulder. If, for example, one chooses to consider the case of a component with a shoulder length of half that shown, then the cutting time will be halved, (approximately), whilst the manual elements will be essentially unchanged. In the latter case then the cutting time will comprise less than 25% of the total processing time. It is thus evident that, even in a single set up, the proportion of time spent in cutting is related to both the volume of cut and the number of manipulations which must be performed. The three components shown in figure 1.9 demonstrate this point, they all have the same volume of material to be removed, and all elements are simple shoulders. On the other hand, however, the time taken will be significantly different because of the increasing amount of manual intervention required in going from (a) to (d). The same arguments will of course hold true for other types of operations, figures 1.10 and 1.11 show similar situations in milling and drilling respectively.

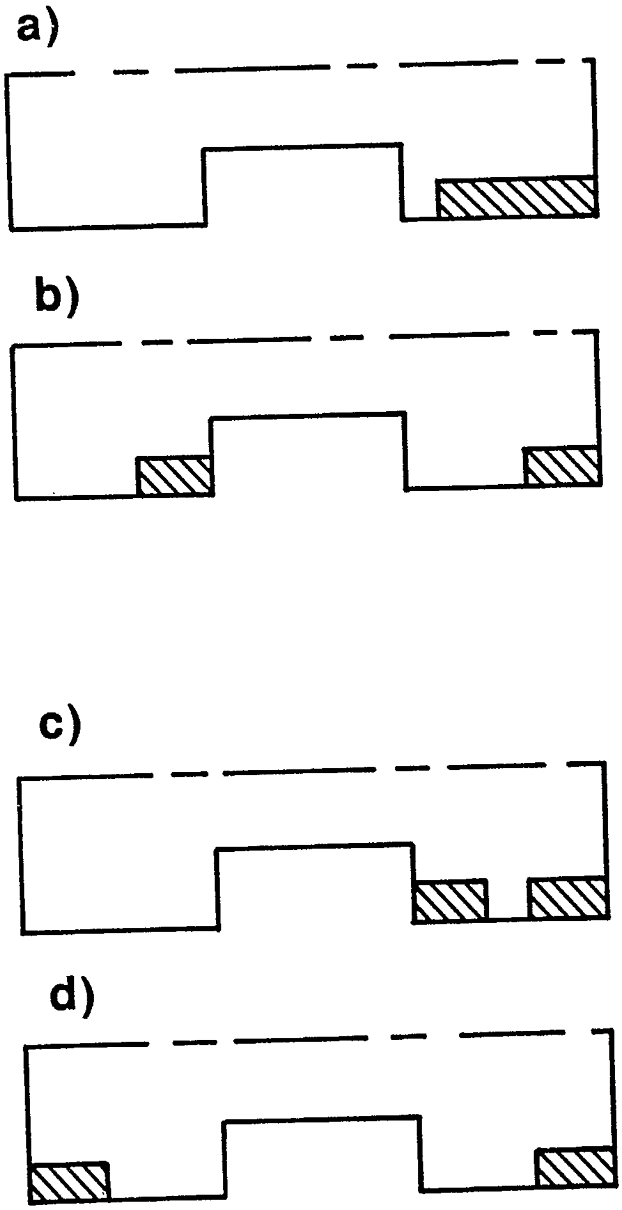


Figure (1.9)

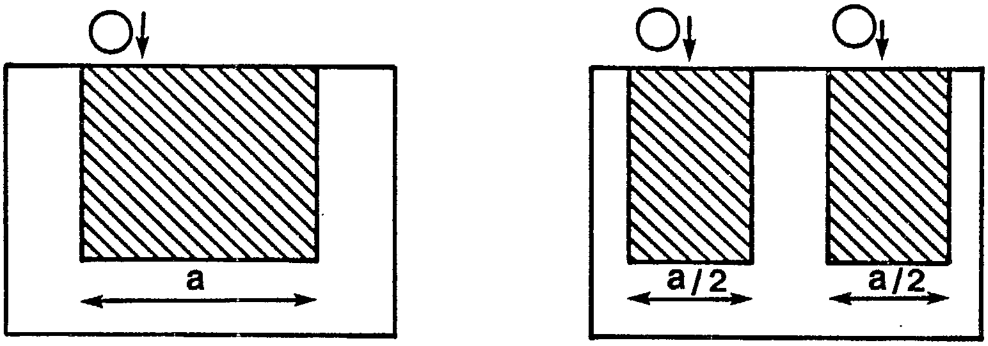


Figure (1.10)

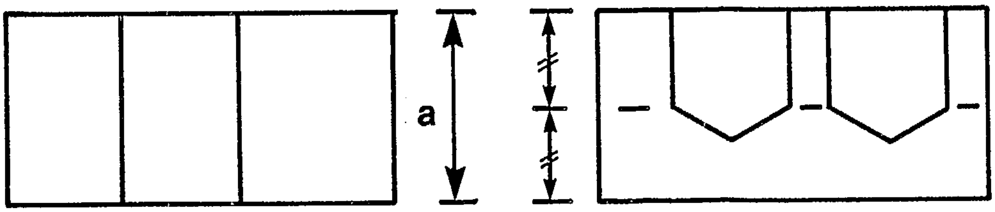
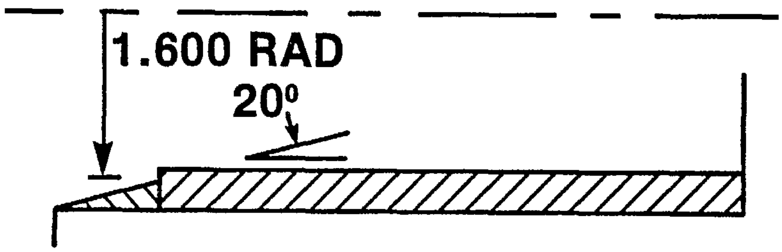


Figure (1.11)

In addition to the amount of material and its disposition, the form and accuracy of the required component exert a considerable influence on the proportion of time spent cutting. In the case of increasing accuracy, additional measurements and trial cuts are necessary. A comparison between the cut time proportions in roughing and finishing the simple shoulder should convince the reader of this fact.

In the case of form elements increased operator interaction is extremely significant. Simple tapers, blending radii and threads are painfully time consuming. In order to demonstrate this point, consider the simplest element, a short taper, which may be produced using the compound rest on a manual machine. It will be assumed that the taper operation is superimposed on the original task of producing the simple shoulder which was the subject of the first investigation. (See figure (1.12)).



Manual Time TM (Sec)	Cut Time TC (sec)
195	25

Figure 1.12.

The taper shown would probably be cut in three passes with hand feed, the cutting time being approximately 70 sec. and the manipulation time being of the same order. Since the use of hand feed lengthens the cut time over that achievable with power feed, then the 70 seconds spent cutting here are construed to mean 25 seconds cutting, (that which would be required if one were able to power feed), plus 45 seconds of manual time. In addition, if the compound is to be used in finishing the face of the component to length, then unlocking, adjustment, locking, unlocking, readjustment and relocking must be made for each part which will consume a total of 80 seconds. The reader will see that in this slightly more complex case the proportion of time spent cutting metal is considerably lower than that in roughing or finishing a simple shoulder. It may be further argued that the setting of a high accuracy in the taper angle would considerably increase the amount of manual interaction, the example presented is by no means a "worst case". By this point in the argument the reader should have no difficulty in believing that providing the following conditions are met:

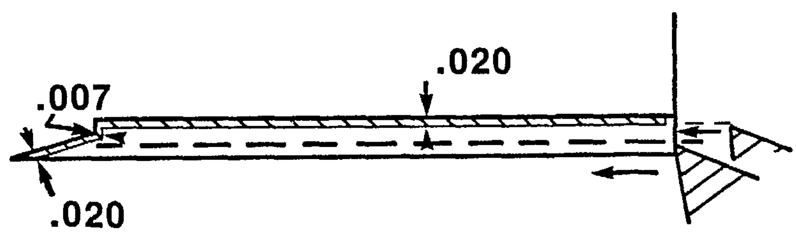
a) Machine is operable and manned.

b) Work and tools are available.

One may, on typical components achieve between 5% and 10% utilization in terms of cutting time. Remembering that most machines are only manned two shifts x 5 days per week and making allowance for shut downs, personal allowances, maintenance and scheduling, then one may be lucky to achieve a metalcutting utilization of 3-4% of the time such machines are installed on the production floor!

The main thrust of the application of numerical control is to reduce the level of manual intervention. In practice many elements still remain and present a challenge for future developments. The nature of the capital investment in such machines has also led to the economic necessity of greater utilization, better maintenance and more accurate scheduling. The net result of these improvements generally means that typical NC machines may give one a metalcutting utilization several (2-4) times that of manually operated machine tools. Before making a detailed comparison of these potential gains it is constructive to examine the machining of the shoulder and short taper on the example part used in the previous example.

The tool motion pattern used in machining the component using NC will be considerably different from that using manual control. The roughing and finishing passes are shown in figure (1.13).



Cut Time TC (Sec)	Rapid Traverse Dwell and Indexing Time (sec)
345	35

Figure (1.13)

The cut time is seen to be a much higher percentage in this case. It may be noted also that it was presumed that a second tool would be used for finishing in an attempt to avoid gauging allowances. Assuming a part load unload time of 50 seconds and a set up time per batch of 300 seconds, (to allow for loading tape and two tools as well as studying blueprint), the total time for a batch of five parts is as shown in table (1) where the comparison with a manual controlled machine gives an idea of the gains which are realisable.

	TC	TM	TL	TS	TTOT	%CUT
NC	345	35	50	300	490	70
Man	345	470	50	200	905	38

TABLE (1)

As will be shown in later sections this comparison is very approximate, also additional elements such as programming and tool setting have been omitted from consideration. The purpose of the comparison however should be seen to be the improvement in possible productive utilization of equipment by the reduction in manual intervention.

Before examining the cost effectiveness of such procedures it is necessary to construct a general economic model and to have a basic understanding of the economics of metal removal processes. These subjects are treated in the remainder of chapter (1) and chapter (2) respectively.

1.4. A Simple Model of the Overall Economics of Numerical Control

In this section the author will derive fundamental relationships comparing the economics of NC machines with manual machines. Whilst the procedure involved to perform this analysis closely resembles that which would be undertaken in a justification study, the author, in this case, is interested in overall economics. In specific cases many additional site specific factors must be accounted for.

The author proposes to examine the purchase of a series of machines to satisfy a known, fixed, product demand. The requirements may be satisfied by acquiring either all NC or all manual machines. Supposing that the demand may be satisfied by N manual machines and the productivity ratio between manual and NC machines is RT, then the number of NC machines is given by N/RT (Assuming the same number of shifts are worked on both machines). (Note, in practice of course both N and N/RT must be integers, this fact will not be unduly stressed here since the author is interested in the general case, then one may assume that both N and (N/RT) are sufficiently large that rounding to integers does not unduly affect the outcome. In many site specific cases, however, this may happen). The major categories of cost involved are the following:

a) Capital cost. (Machine and factory)

b) Direct hourly labour costs.

c) Indirect hourly labour cost. (Setting, maintenance etc.)

d) Supervision costs

e) Professional support costs (planning, tool engineering and programming).

f) Tooling Costs

In order to simplify the analysis, then the following assumptions will be made, (remembering that the two alternatives have equal output capacity).

1. It is assumed that the two types of productive units will require equal floor area, equal supervision and equal tooling costs. (The cost of consumable tooling per given output level is clearly likely to be approximately equal, in many cases it may be found that NC reduces non consumable tooling costs jigs, fixtures etc.)

2. It will be assumed that inspection, material handling and production planning costs are the same. (Again in specific instances NC may reduce all these costs). The analysis will assume that the additional cost elements incurred by NC machines, in particular the programming element may be accounted for by multiplying the labour rate by a factor (1+Y). Thus

$$\text{Total Cost Manual} = N[\text{Capital Cost/Year} + \text{Labour Cost/Year}] + \text{Const}$$

$$\text{Total Cost NC} = \frac{N}{\bar{R}T}[\text{Capital Cost/Year} + (1+y)\text{xLabour cost/Year}] + \text{Const}$$

$$\text{Cost Difference} = N.[CP(MAN)+CL] - \frac{N.}{\bar{R}T}[CP(NC)+(1+y).CL]$$

where CP is yearly capital cost (\$/yr)
and CL is yearly labour cost (\$/yr)

Now introducing some nomenclature to ease the algebra:

a) Assume the ratio of capital costs is given by:

$$K = \frac{CP(NC)}{CP(MAN)}$$

b) Assume that yearly direct labour cost in first year is given by:

$$\text{Labour Cost} = Z.CP(NC)$$

3. Both types of machine have a working life of 10 years and will have zero salvage value at this point. Both machines are depreciated on a straight line basis.

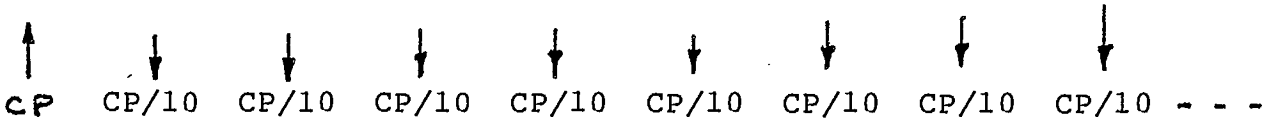
4. The general rate of inflation is ir% and the required rate of return above inflation is ic%. Thus the discounting rate in calculating the net present value is (1+ir)(1+ic)-1. In order to be specific and reasonably realistic, it will be assumed that:

$$ir = 10\%$$
$$ic = 10\%$$
$$ia = 21\%$$

5. The economic analysis is intended to identify the break even condition between the two classes of machine. That is the condition where no difference in net present cost exists with the assumed discounting rate. The influence of taxes is thus not considered explicitly although depreciation is accounted for as a before tax income. Clearly the effective rate of after tax return required at break even will be approximately half ia. (In the absence of specific tax exemptions or inducements).

One may now derive the various components of cost for both options:

a) Capital costs (Pre tax cash flows).



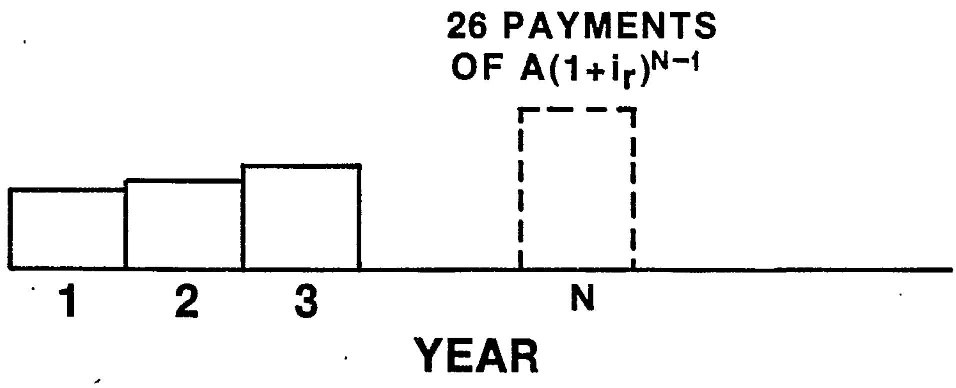
Discounting these cash flows one obtains a net present cost given by the following equation:

$$NPC = CP.[1-\frac{1}{10}\sum_{N=1}^{10}[\frac{1}{((1+ic).(1+ir))^N}]$$

$$= 0.595\ CP$$

b) <u>Labour Costs</u>

Labour costs are assumed to increase at the rate of inflation. Since wages are paid either weekly, biweekly or monthly, then some manipulation is required to find the net present cost. For the purpose of this exercise wages are assumed to be paid every two weeks, thus the schedule of payments is as shown below:



The effective rate of interest for a two week interval which corresponds to an annual rate of 21% is given by:

$$(1+if)^{26} = 1.21$$

$$\text{i.e. } if = 0.736\%$$

The cost of paying any one year's wages in a lump sum at the beginning of each year is thus given by:

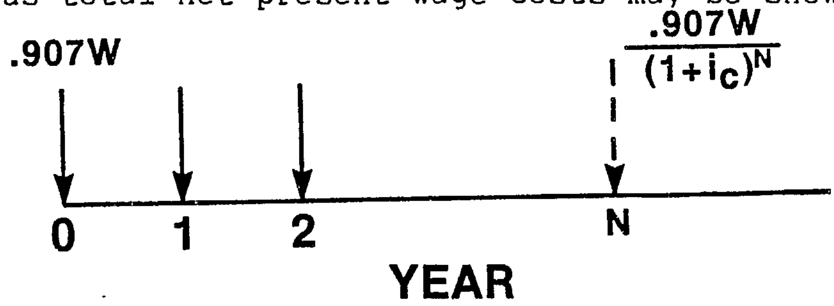
$$C = A\sum_{N=1}^{26}\frac{1}{(1.00736)^N}$$

$$= 23.59\ A$$

$$= 0.907W$$

Since yearly wages correspond to 26A then actual payment required = .907 x yearly wages.

Thus total net present wage costs may be shown as



Thus total net present wage cost

$$= W.(0.907 + \sum_{N=1}^{9} \frac{0.907}{(1+ic)^N})$$

$$= 6.13W$$

$$= 6.13Z.CP(NC)$$

Thus it has been shown that the principal present costs of operating a machine tool for its hypothetical 10 year life are given by:

$$C = 0.595\ CP + 6.13W \doteq 0.6\ CP + 6W$$

One may now compare the manual and NC machines. Assuming for the purpose of convenience that:

$$W = Z.CP(NC) \quad \text{and} \quad K = \frac{CP(NC)}{CP(MAN)}$$

then the cost of operating the manual machines is given by:

$$C = 0.6N.\frac{CP(NC)}{K} + 6N.Z.CP(NC)$$

and the cost of operating the NC machines is given by:

$$C = 0.6\ \frac{N}{RT}.CP(NC) + 6\ \frac{N}{RT}.Z.CP(NC).(1+y)$$

The resulting cost difference (Manual - NC) is then given by:

$$CDIFF = 6N.CP(NC).(0.1(\frac{1}{K} - \frac{1}{RT}) + (Z - \frac{Z}{RT}.(1+y)))$$

$$= 6N.CP(NC).(0.1\ \frac{(RT - K)}{RT.\ K} + Z.(1 - \frac{(1+y)}{RT}))) \ldots (1)$$

It is also possible to obtain a relationship between K and RT for the break even case (CDIFF = 0) as follows

$$0.1\left(\frac{RT}{K}-1\right) = Z.((1+y)-RT)$$

i.e.

$$K = \frac{0.1\ RT}{Z(1+y-RT)+0.1} \qquad \text{.....................(2)}$$

Equation (1) gives one a simple guide as to when to use NC and when not to. It should be noted at this point that the coefficient y must be assessed with some care. Whilst the proportion of time spent by setters, loaders, etc. may be directly determined, that spent by programmers must be factored because of the higher wage rate and the additional overhead required to support those personnel. (Programming costs, equipment space and management).

In typical cases the author would expect that the total cost of employment of a programmer may be approximately double that of a machine operator (bearing in mind that all overheads have been taken from the operator cost). Thus if one programmer supports 4 machines and the machine operator performs all tool setting and loading functions y would be equal to 0.5. On the other hand, care must be taken to ensure that account is only taken of programming effort, over and above planning since it has been assumed that the effort in planning and tooling would be equal.

In examining equation (2), it is obvious that in the case where

$$RT > K$$

and

$$RT > (1+y)$$

then the NC machine will reduce both capital and direct labour. In many cases, however, the NC machine will reduce labour but increase capital costs, in other words

$$K > RT > (1+y)$$

In these cases one must examine the various parameters carefully in terms of equation (1). (Figures 1.14 - 1.16 show typical break even curves for varying Z and Y).

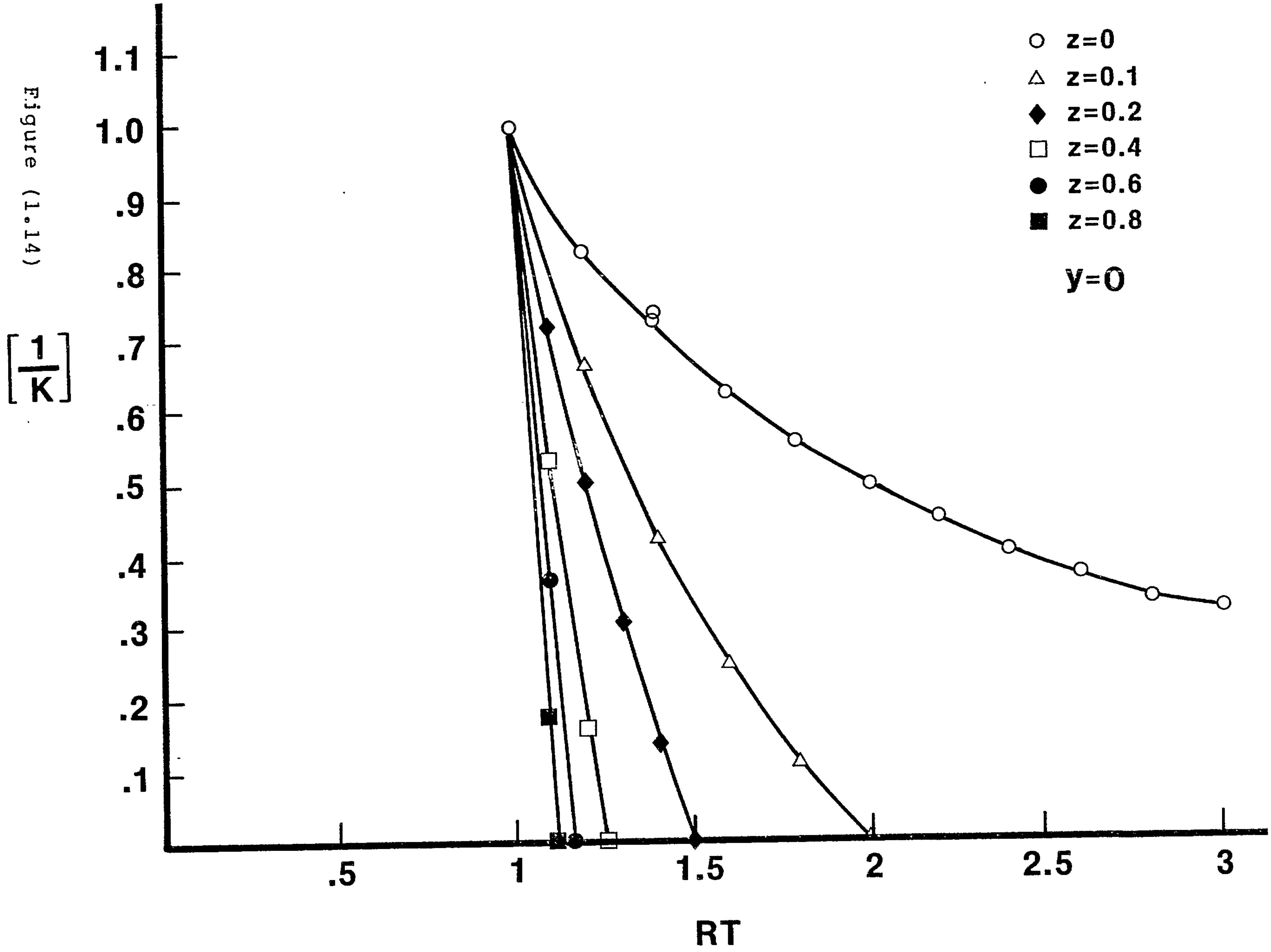
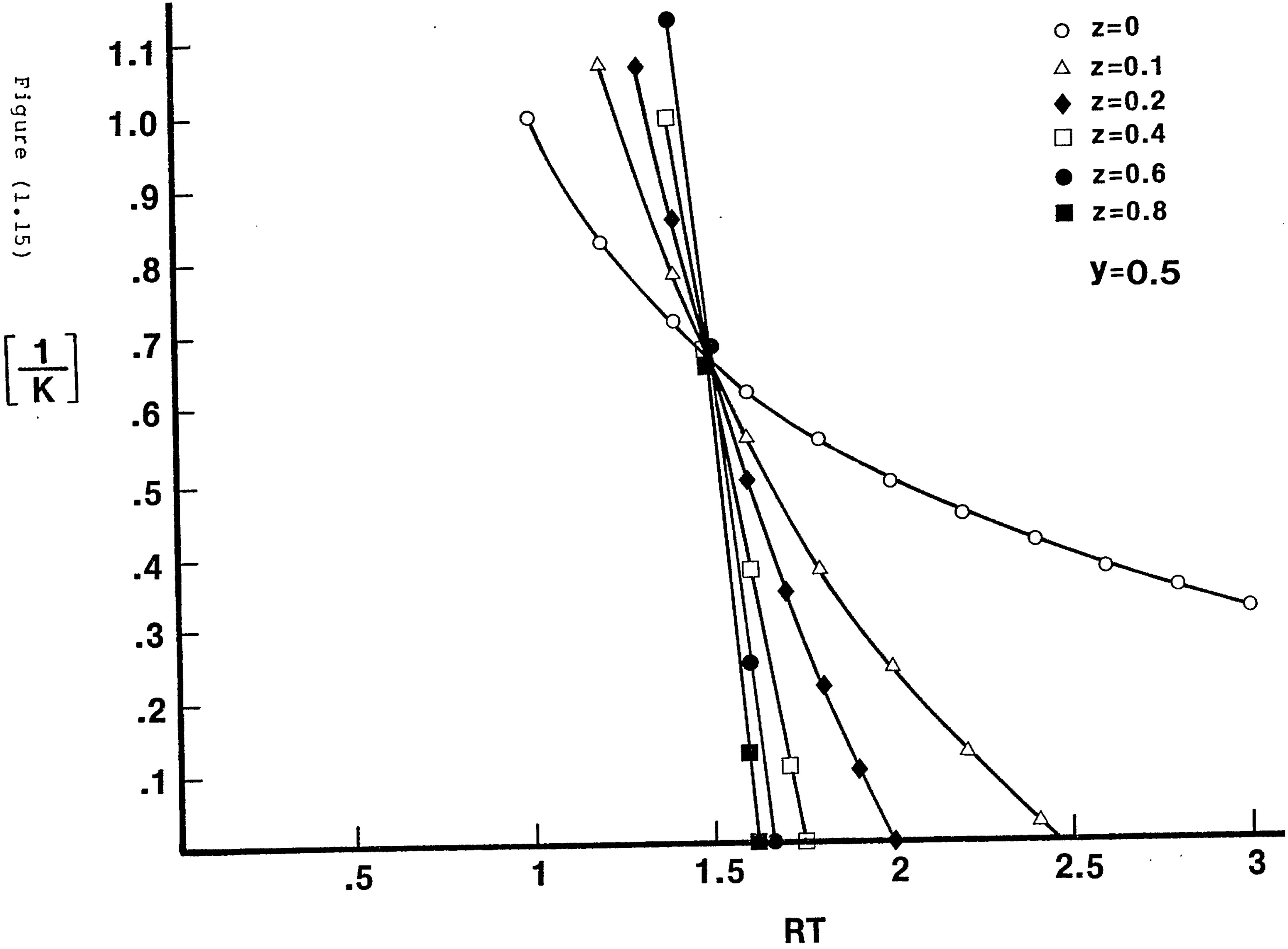


Figure (1.14)

Figure (1.15)



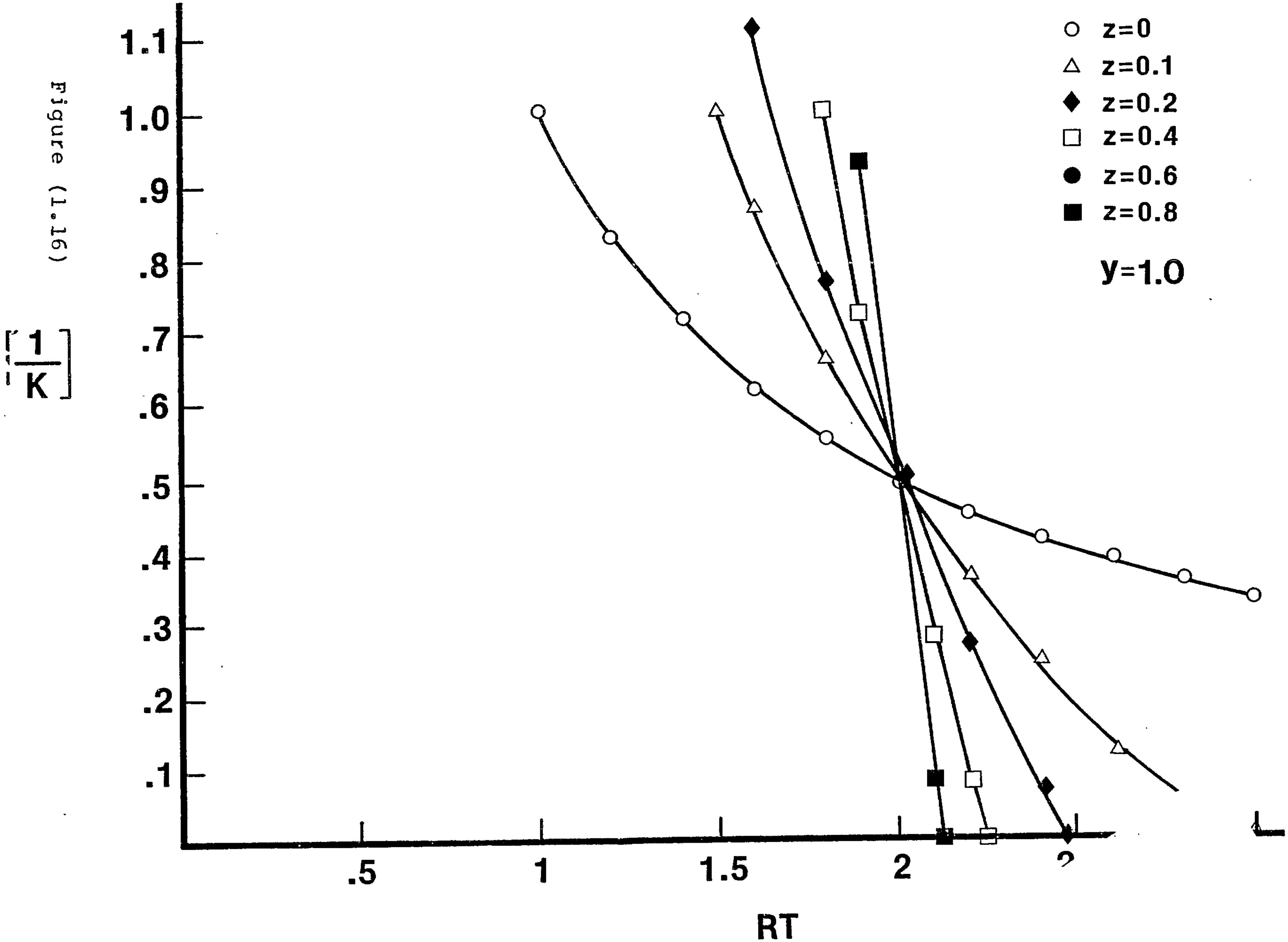


Figure (1.16)

2

1.5. Improvement of Economics of NC

From what has been said to this point it is evident that in order to improve the economics of NC one must seek to increase RT and decrease y. There are many ways of achieving both goals. This section will discuss the more obvious ways to increase the productivity ratio. The reader will also find considerable information pertaining to this subject in Chapter (3).

As may be remembered from section (1.3.2.) the total processing time is given by:

$$TTOT = TC + TM + TL + TS/B$$

The base NC machine had as its aim the reduction in TM. Whilst much of the slack time in this quantity has been reduced, there is still some room to reduce several factors such as the following:

a) Tool change time

b) Measuring time

c) Setting and Resetting auxiliary elements, e.g. tailstock, steadies, rotary tables, angular heads, etc.

All of the above elements can be readily controlled by the addition of increased automation. On the other hand most of the devices will increase the cost of the base machine considerably and hence their application must be pursued carefully in line with equation (1). (A detailed analysis and description of these devices is given in the following chapters).

In many cases the loading time of the component may use an appreciable portion of the cycle, particularly on a machining center or horizontal boring mill, where a casting must be aligned and positioned to L/O lines before machining is commenced. On both manual and NC machines this procedure may be effectively performed at the layout station, usually incurring little additional cost, (the cost of sub plates). Putting operations such as this at arm's length from the productive machine usually reduces part times considerably and has a proportionally greater influence on the NC machine since its processing cycle is already less. The following serves to illustrate the point through a simple example. A medium sized casting is to be machined on a manual machine and on an NC machine, the relevant data is as follows:

2

Number of Parts = 3

	NC Time (min)	Manual
TC	10	10
TM	5	30
TL	10	10
TS/B	20	20
TOTAL	45	70

i.e. $RT = \frac{70}{45} = 1.556$

Consider now the case where the layout operation is also used to pre align the part on a sub base

TC	10	10
TM	5	30
TL	2	2
TS/B	10	10
	27	52

RT = 52/27 = 1.926

Assuming the worst case, i.e. the time saved in the load/unload cycle is simply added to the layout operation, then the labour costs will be unchanged, however, since the machine productivity has improved quite dramatically there will be a considerable drop in associated capital costs. The reader should note too, that as expected in this more efficient operating mode, the NC machine will perform even better relative to the manual machine. This point should be borne in mind, once the initial investment has decreased the cycle time, then equal drops in cycle time achieved by reducing manual elements will increasingly favour the NC machine. If one is spending a constant amount of money, say by adding a tool changer or pallet shuttle, then the effect is magnified since one gets a greater improvement in RT and less penalty in K.

The preceding arguments apply equally well to inprocess measuring, tool changing and the automation of auxiliary elements such as steadies, tailstocks, rotary tables and indexing spindle heads. This should be kept in mind since quite often it may be found, that whilst the adoption of a base level of NC may not be economically attractive, an even higher level of automation may well show significant economic gains.

CHAPTER (2)

METAL CUTTING THEORY

CHAPTER 2

MACHINABILITY, MECHANICS OF METAL CUTTING, TOOL WEAR, ECONOMICS AND PROCESS PLANNING

2.1. INTRODUCTION

A great deal of research effort has been expended in an attempt to understand the process of metal cutting. Understandably, most attention has been focused on the turning operation. In the light of the previous chapter, the reader may well ask why such stress is laid on the machining operations, when actual metal cutting time only comprises 20-25 percent of the total cycle time in well planned cases. In reply the author would make the following observations.

2.1.1. Given the required knowledge to select machining conditions in a scientific manner, the N.C. programmer may reduce costs without adding to the capital burden carried by his company, (i.e. the gains made by adjusting machining conditions are essentially "free").

2.1.2. A knowledge and understanding of alternative methods of producing a given part leads, in many cases, to a significant impact on both the set up and manipulation times, as well as that actively engaged in cutting. For instance, the order of operations and part attitude in a holding device (fixture) can normally be varied; also the pattern of cuts selected for a particular operation will determine positioning time and number of tools to be set and changed in addition to the cutting time.

2.1.3. Whilst the metal cutting time is a relatively small proportion of the total processing time, it is, in reality, the only time in which the part is being actively processed. If the cutting operation is unsuccessful due to chatter, tool breakage, poor surface finish or dimensional inaccuracy, then the whole effort is wasted. On an even more serious note, if a machine is purchased without due regard to speed range, power, force, torque and stiffness requirements then serious losses will occur.

In the author's opinion then this chapter is perhaps the most critical in this monograph and is directed towards programmers, who, on a day to day basis must maintain productivity levels on expensive capital equipment.

2.2. FORCE AND POWER CALCULATION FOR TYPICAL MACHINING OPERATIONS

2.2.1. Introduction

The simplest case of metal cutting occurs when a tool has a straight cutting edge which is perpendicular to the relative work tool velocity and is wider than the workpiece. This process, which is termed orthogonal cutting has dominated research efforts in metal cutting. The process may best be visualized as a shaping or planing operation as shown in figure (2.1).

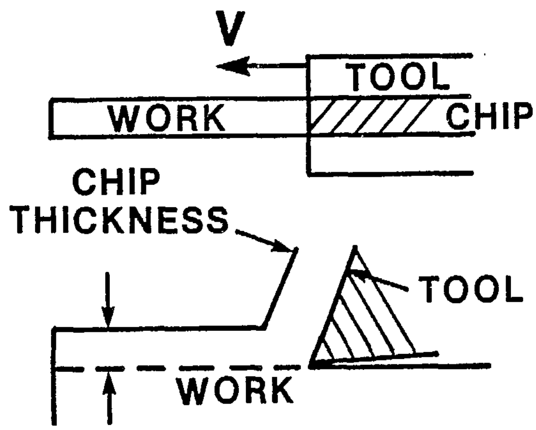


Figure (2.1.)

In actual practice metal cutting tools have none straight cutting edges and some degree of obliquity. Luckily, to the accuracy required, the angle of obliquity may be ignored for most practical tools and applications, with the exception of the calculation of some milling operations. The problem of none straight cutting edges must however, be addressed and care must be taken not to apply the simple equations given here to cases where the angle of obliquity exceeds $\pm 20^{\circ}$ (approximately).

2.2.2. Forces in Orthogonal Cutting and Simplified Turning Operations

In practice the forces which interest the N.C. programmer are those acting in the direction of relative work tool velocity and the thrust force which is perpendicular to this. These forces are shown in figure (2.2) below.

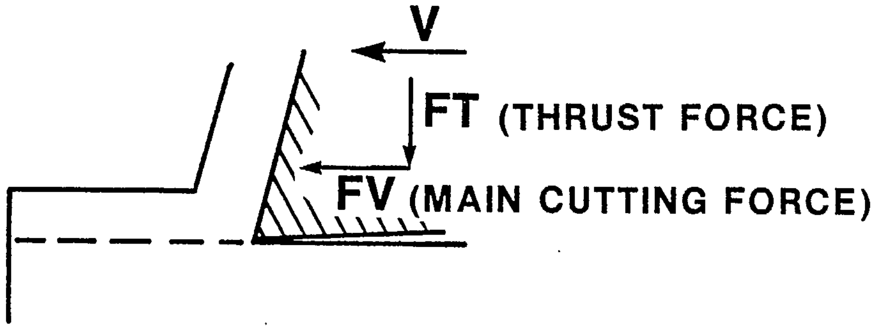


Figure (2.2)

In theoretical work the forces usually considered are those acting along and perpendicular to the tool face and the shear plane respectively (see figure (2.3.)

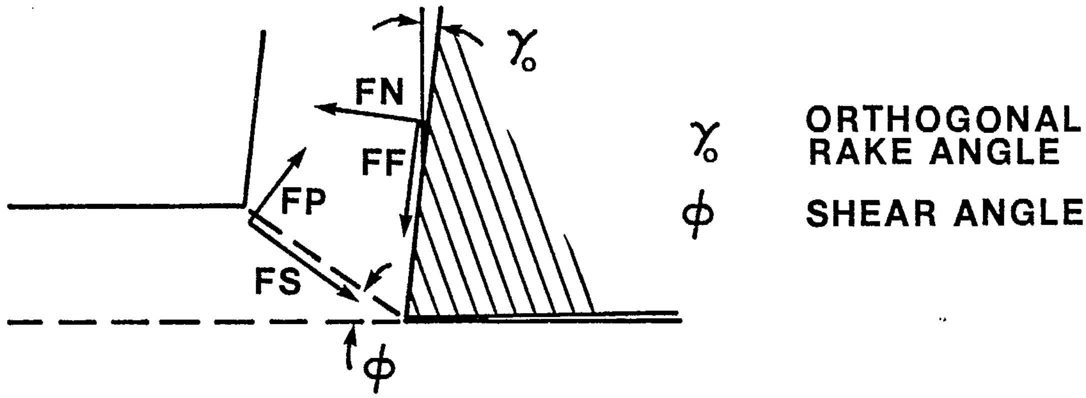


Figure (2.3)

It is usually accepted that the chip is in a state of "quasi static" equilibrium thus the resultant of FP and FS in figure (2.3) is equal in magnitude and opposite in direction to the resultant of FN and FF. Clearly the resultant of FN and FF is also equal to the resultant of the two practically important forces FV and FT in figure (2.2). The force equilibrium concept is due to Merchant whose work may be referenced in the bibliography of this chapter; the corresponding force diagram is shown in (2.4.) from which the following relationships result.

$$\mu = \frac{FF}{FN} = \tan\beta = \frac{FV.\sin\gamma_0 + FT.\cos\gamma_0}{FV.\cos\gamma_0 - FT.\sin\gamma_0} \quad \text{-------} \quad (2.1.)$$

$$r = \frac{FT}{FV} = \frac{\mu - \tan\gamma_0}{1 + \mu\tan\gamma_0} \quad \text{--------------------------} \quad (2.2)$$

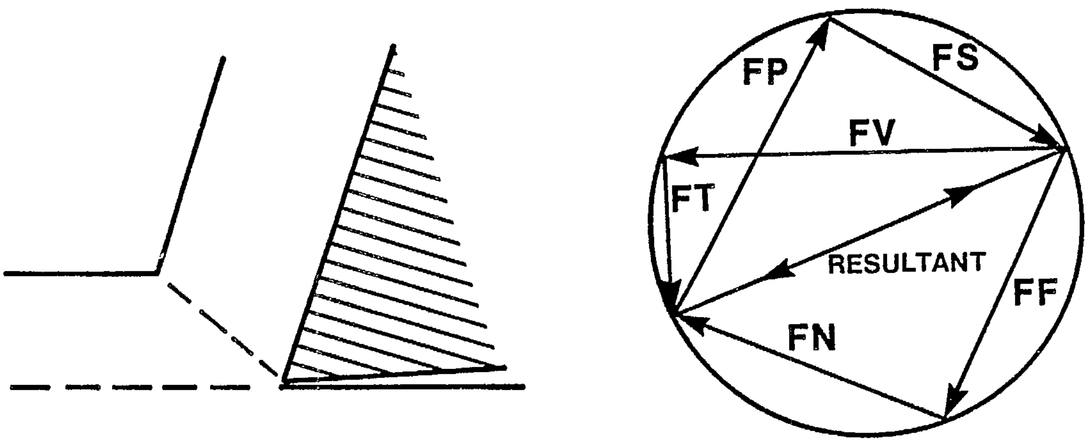


Figure (2.4.)

The main cutting force is the only power consuming force, thus this force multiplied by the velocity yields the instantaneous power requirements. In many cases the main cutting force may be calculated by referring to hand-book values of specific cutting pressure (Ps), this parameter being given by the following expression

$$Ps = \frac{FV}{A} \quad \text{------------------------------------} (2.3)$$

where A is undeformed area of cut.

In practice, because of variations in shear angle, the specific cutting pressure varies with both chip thickness and cutting velocity for a given material. It is however usually acceptable to account only for the change due to chip thickness variations. In general when machining a group of similar materials at cutting speeds which corresponds to realistic tool lives as given below

$$5\text{min} < T > 100 \text{ min} \quad \text{--------------------} (2.4.)$$

then it is possible to express the specific cutting pressure in terms of the Brinell Hardness of the work material. In order to be specific, the author has found the following equation to give realistic values for carbon and low alloy steels, when machined with carbide tools of zero rake angle.

$$Ps = 380,000 \left[\frac{BHN}{300}\right]^{0.5} \cdot \left[\frac{he}{0.010}\right]^{-0.2} \quad lbf/in^2 \qquad \text{---------}(2.5)$$

Where

BHN is work piece Brinell Hardness

and $200 < BHN < 450$

(he) is chip thickness before cutting (inch)

and $.002 < he < .030$

or $$PS = 2600 . \left[\frac{BHN}{300}\right]^{0.5} \cdot \left[\frac{he}{.25}\right]^{-0.2} \quad N/(mm)^2 \qquad \text{---------}(2.6)$$

Where BHN is work piece Brinell Hardness

and $200 < BHN < 450$

and he is chip thickness before cutting (mm)

$.05 < he < 0.75$

Equations (2.5) and (2.6) also give realistic results for high speed steel tools with a rake angle of +15 . The reason for the need for a more positive rake angle on H.S.S. tooling is that the speeds used for the same range of lives are lower and the frictional behaviour on the rake face is not so advantageous as carbide. Thus these two factors which both increase main cutting force must be counter balanced by a higher rake angle, which reduces the strain imparted to the chip and hence reduces the main cutting force. Luckily zero rake for carbide and 15 deg. for H.S.S.also represent fairly well typical practical rake angles.

In the case of both types of tool material a decrease in rake angle will increase the main cutting force, an approximation to this may be had by adding 1% for each degree decrease in rake angle to the value calculated from the equations. Conversely 1% should be subtracted for each degree of increase. The preceding conclusion leads to the following equations for H.S.S. and carbide tools in orthogonal cutting:

a) CARBIDE

$$Ps = 380{,}000.\left(1-\frac{A}{100}\right).\left[\frac{BHN}{300}\right]^{0.5}.\left[\frac{he}{0.010}\right]^{-0.2} \quad lbf/in^2$$

$(-15^\circ < A < 15^\circ)$ A is rake angle ------ (2.7)

b) H.S.S.

$$Ps = 380{,}000.\left(1-\frac{(A-15)}{100}\right).\left[\frac{BHN}{300}\right]^{0.5}.\left[\frac{he}{.010}\right]^{-0.2} \quad lbf/in^2 \quad \text{--(2.8)}$$

$(0^\circ < A < 30^\circ)$

or

a) CARBIDE

$$Ps = 2600.\left(1-\frac{A}{100}\right).\left[\frac{BHN}{300}\right]^{0.5}.\left[\frac{he}{0.25}\right]^{-0.2} \quad N/mm^2 \quad \text{-----(2.9)}$$

$(-15^\circ < A < 15^\circ)$

b) H.S.S.

$$Ps = 2600.\left(1-\frac{(A-15)}{100}\right).\left[\frac{BHN}{300}\right]^{0.5}.\left[\frac{he}{0.25}\right]^{-0.2} \quad N/mm^2 \quad \text{--- (2.10)}$$

$(0^\circ < A < 30^\circ)$

The reader should realize that the equations above have the same restrictions on BHN, (he) and tool life as equations (2.5) and (2.6), if reasonable accurate results are required. Similar equations may be built up by programmers themselves to cope with cast irons, aluminum alloys etc. Interested readers will find references in the bibliography to this chapter which contain sufficient data to allow this. In this light it should perhaps be pointed out that values of specific power or power per unit volume removal rate and specific cutting pressure are linearly related as follows:

$$\text{Power} = FV.V \quad \text{------------------------------------} (2.11)$$

i.e.

$$PR = \frac{Fv.V}{V.A} = Ps \quad \text{-----------------------------------} 2.12)$$

where PR is power/unit volume removal rate

Some care must however be taken in assigning units especially in the imperial system as follows

$$\text{POWER} = \frac{V.FV}{33000} \qquad (H.P)$$

where V is velocity in ft/min.
FV is main cutting force lbf.

$$\text{i.e. } PR = \frac{V.FV}{33000} \cdot \left[\frac{1}{12V.A}\right]$$

where A is the area of cut (in^2).

$$\text{hence } PR = \frac{FV}{A} \cdot \left[\frac{1}{396,000}\right] = \frac{Ps}{396,000} \text{ H.P./cu.inch/min.}$$

thus if a material has a specific cutting pressure of 396,000 lbf/in under particular conditions, then 1HP will be required for every cubic inch/minute removal rate.

Utilizing customary metric usage P=V.FV N.m/min

where V is cutting speed (m/min)

FV is main cutting force (N).

i.e. $P = \frac{V.FV}{60}$ W

thus $PR = \frac{V.FV}{60} \cdot \left[\frac{1}{(V/1000)A}\right] = \frac{Ps}{60,000}$ $W/mm^3/min$

Where A is the area of cut (mm^2)

It is evident, in this case, that the results in metric certainly do not make for as easy memorization as do the imperial, this is due mainly to not adhering to meter and second in the metric derivation. However, the usage above reflects current accepted world wide practice in the specification of units for cutting velocity and chip dimensions.

The important point of the above discussion is that Ps may be derived from a knowledge of PR should data in that form be more readily available or measurable on the shop floor. In passing it should be mentioned that the PR referred to is the power required at the tool. If power values are taken from a power meter on the spindle motor, then the approximate efficiency of the spindle drive must be accounted for and, of course, if PR is calculated from Ps, then in calculating required machine power at the motor one must again allow for inefficiency in the drive.

Having calculated the main cutting force and power requirements for a particular operation the reader may well want to calculate the thrust force (FT). This is best carried out by creating an expression for the ratio of this force to the main cutting force. For almost all materials the apparent coefficient of friction on the tool rake face, ($\mu = \frac{FF}{FN}$), increases in an approximately linear manner with rake angle. For the particular case of carbon and low alloy steels over the range of practical cutting variables specified in the previous equations the following approximate relationships hold true.

a) <u>CARBIDE</u> $(-15^\circ < A > 15^\circ)$

$$\mu = 0.6 + (0.005).A$$

b) H.S.S. $(0^\circ < A < 30^\circ)$

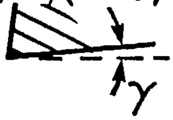
$$\mu = 0.7 + (0.01).A$$

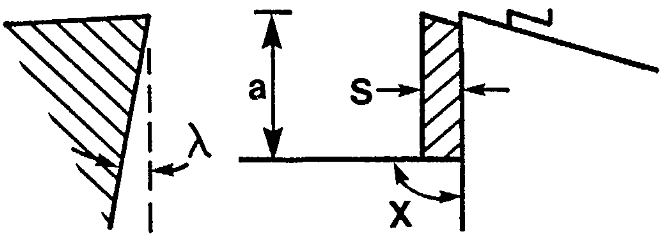
In actual fact the magnitude of μ is also related to the work material/tool material pair, for example harder finer grained materials will tend to decrease μ , as will most coated carbide tools. Again however the relationships should be accurate enough for most practical purposes especially if a conservative approach is taken, in the planning of operations.

It is now possible to examine the force and power requirements of two simple "pseudo orthogonal" turning operations, in both cases it will be permissible to consider the tool as a straight edge with zero obliquity.

Example (1) The bar turning of a carbon steel with a carbide tool with small nose radius and zero approach angle, the details of the operation follow.

V = 400 ft/min
S = 0.020 in/rev
a = 0.125 in
Workpiece Hardness 220BHN
Tool Geometry γ = +5, λ =+5, X = 90 (i.e. approach angle is zero)





In this case the small angle of inclination (obliquity) will be ignored and the rake angle normal to the cutting edge used to calculate the forces. The forces will be calculated in both customary imperial and metric units.

The reader should realize that, because of the constants in the relevant equations the results will not be direct equivalents but will be close enough for all practical purposes.

a) Imperial Units

$$Ps = 380{,}000 . \left[\frac{220}{300}\right]^{0.5} . \left[\frac{.020}{.01}\right]^{-0.2} . \left(1 - \frac{5}{100}\right) \ \text{lbf/in}^2$$

$$= 269{,}000 \ \text{lbf/in}^2$$

$$FV = 269{,}000 .(0.02).(0.125)$$

$$FV = 673 \ \text{lbf}$$

Coefficient of friction on rake face (μ) is given by

$$\mu = 0.6 + .005.5$$

$$= \underline{0.625}$$

Hence ratio of thrust force to main cutting force (r) is given by

$$r = \frac{\mu - \tan\gamma}{1 + \mu\tan\gamma} = \frac{0.625 - .087}{1 + .055} = \frac{FT}{FV}$$

$$r = 0.51$$

and $FT = 343$ lbf

Total power requirement at tool is product of main cutting force and cutting velocity

$$P = FV.V = 673.400 \ \text{ft./lbf/min.}$$

$$P = \frac{673.400}{33{,}000} \ \text{H.P.}$$

$$P = 8.16 \ \text{H.P.}$$

In order to calculate power required at the spindle drive motor assume a typical drive efficiency of 70%.

$$PMOTOR = \frac{P}{0.7} = 11.7 \text{ H.P.}$$

b) <u>Metric Units</u>

$$Ps = 2600.\ (0.95).(0.856).(0.871)\ N/mm^2$$

$$Ps = 1840\ N/mm^2$$

$$Fv = 1840.\ (1.6) = 2940\ N$$

$$r = 0.51$$

hence

$$FT = 1500\ N$$

$$P = 2940.\ \left(\frac{122}{60}\right)\ W$$

$$P = 6\ KW$$

$$PMOTOR = \frac{6}{0.7} = 8.6\ KW$$

Example 2

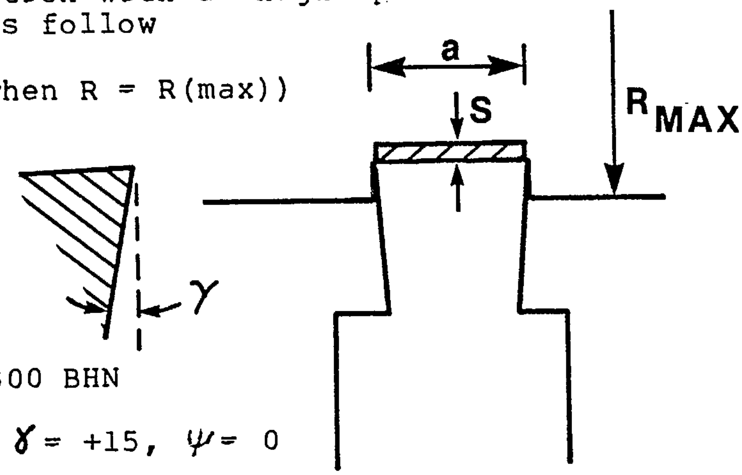
A parting off operation with a high speed steel tool. The operation details follow

$V = 75$ ft/min (when $R = R(max)$)

$S = 0.005$ in.

$a = 0.25$ in

$R_{max} = 1.00$ in



Workpiece Hardness 300 BHN

Tool Geometry $\lambda = 0$, $\gamma = +15$, $\psi = 0$

a) Imperial Units

$$Ps = 380{,}000 \left[\frac{.005}{.01}\right]^{-0.2} \text{ lbf}$$

$$Ks = 437{,}000 \quad \text{lbf/in}^2$$

$$FV = Ps. \quad s. \quad a \quad = 546 \text{ lbf}$$

$$\mu = 0.7 + .15 = 0.85$$

hence $r = \dfrac{0.85 - .27}{1 + .23} = .47$

and FT = 256 lbf

Power required at tool is given by

$$P = \frac{546.75}{33{,}000} = 1.2 \text{ H.P.}$$

Note if the operation is carried out with a constant rotational speed then power requirements will decrease linearly towards the center of the workpiece.

b) Metric Units

$$Ps = 2600 \left[\frac{.125}{.25}\right]^{-0.2} \text{ N/mm}^2$$

$$Ps = 2990 \quad \text{N/mm}^2$$

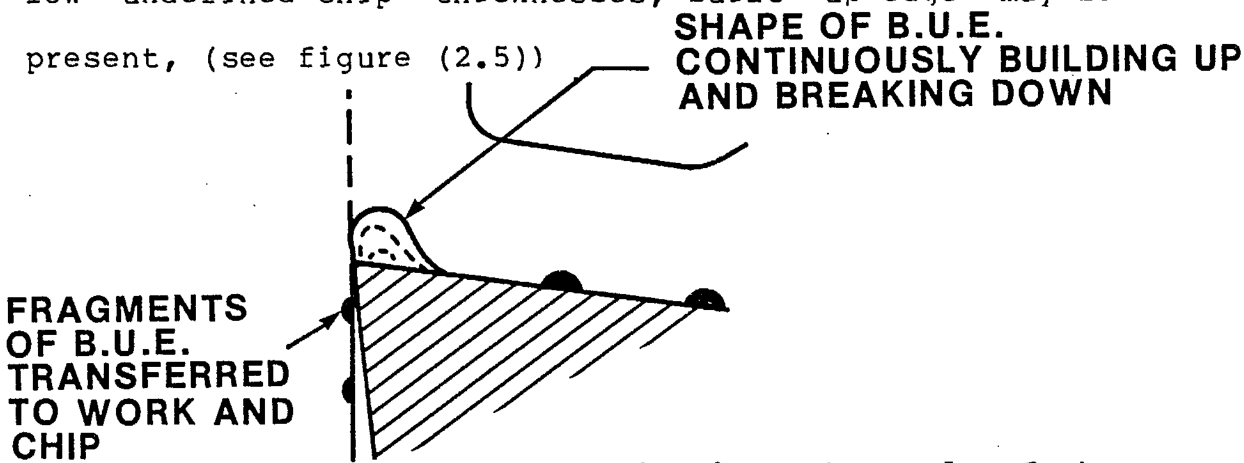
$$FV = 2990.(0.81) = 2420 \text{ N}$$

$r = 0.47$ hence FT = 1138 N

Power required at tool is given by $P = 2420.\left(\dfrac{22.9}{60}\right)$ (W)

P = 0.92 KW

Before proceeding to consider practical cutting tools the author would again stress that the method demonstrated is only intended to allow estimates of cutting force at typical machining conditions which result in practical values of tool life. In particular it should be borne in mind that at low velocities and low undefined chip thicknesses, built up edge may be present, (see figure (2.5))



Built up edge increases the effective rake angle of the tool and lowers forces. Unfortunately built up edge has a catastrophic influence on both tool life and surface finish. The following strategies may be employed to avoid the built up edge

a) Increase undeformed chip thickness.

b) Increase cutting velocity

c) Increase tool rake angle

d) Use a cutting fluid.

In general the relationship between cutting force and velocity is as shown in figure (2.6).

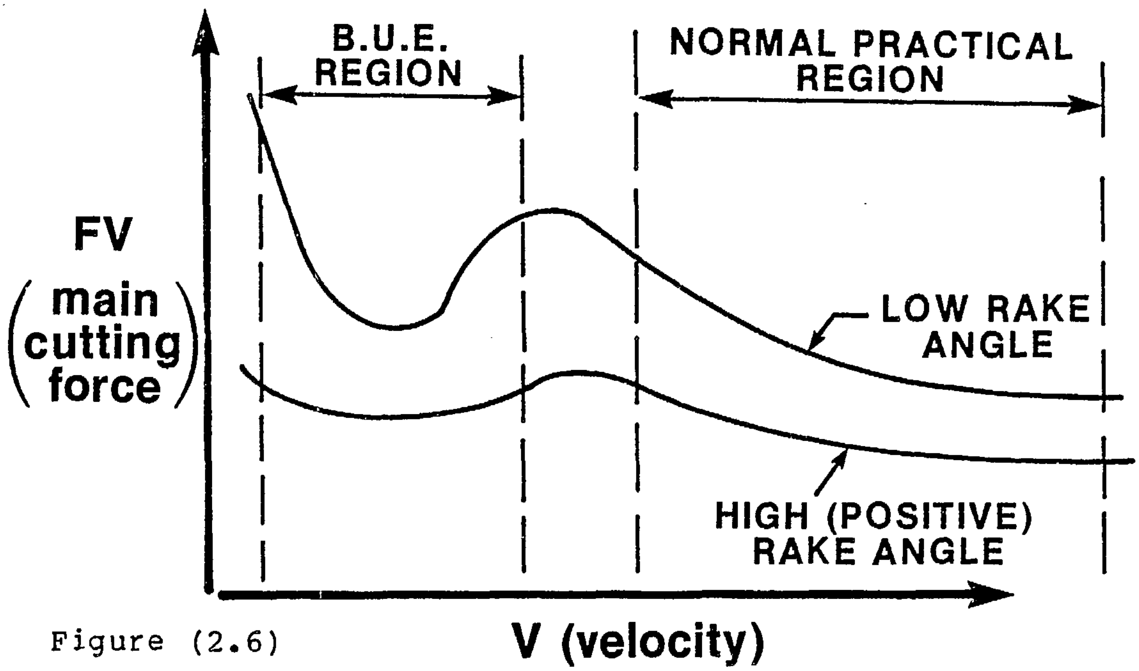


Figure (2.6)

The reader should now be in a position to proceed to the calculation of the three components of force for practical turning tools.

2.2.3. Force and Power Estimation for Practical Turning Tools

Most turning tools have a non straight cutting edge, the calculation of cutting forces in this case is more complicated than is the case in the previous section. The main practical influences of a nose radius are chip "thinning", deflection of chip flow direction and variation in the direction of the resultant force. In order to demonstrate this effect one may first examine the analogous case of a varying approach angle on a tool of zero nose radius, (see fig (2.7)).

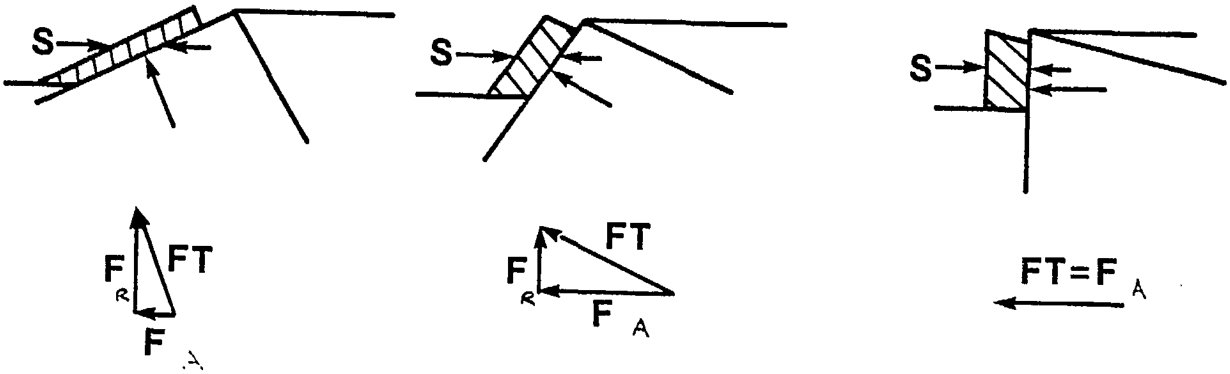


Figure (2.7)

In examining the affect of increasing approach angle, the following points should be evident to the reader

a) The area of cut A in figure 2.7 is independent of approach angle and given by

$$A \doteq s.a$$

where s is the feed/rev

a is the depth of cut

A direct comparison with orthogonal cutting leads to the following comparisons.

a) Width of cut $w = \dfrac{a}{\cos\psi}$

b) Undeformed chip thickness $he = s \cos\psi$

These conclusions are depicted more clearly in figure 2.8

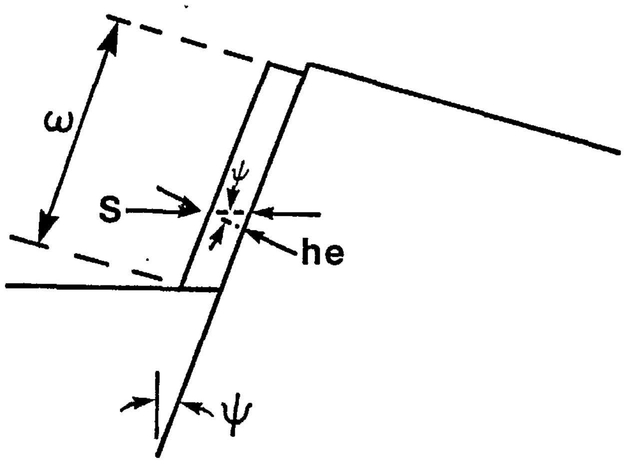


Figure (2.8)

In turning one is normally concerned with three components of force. The thrust force being divided into its components in the radial and axial directions. The primary influence of an increased approach angle in straight diameter cutting is to increase the radial component. The two components of force are given by the following expressions.

$$FA = FT.\cos(\psi) \quad \text{------------------} \quad (2.13)$$
$$FR = FT.\sin(\psi) \quad \text{------------------} \quad (2.14)$$

In this case the axial force will remain essentially constant since the decrease due to the cosine term is balanced to some extent by the influence of chip thinning on the specific cutting pressure. The latter phenomenon will of course result in an increase in main cutting force.

With increasing approach angle the direction of chip flow moves away from the finished workpiece surface. In practice this is advantageous since it reduces the chance of damaging the machined surface.

The influence of a nose radius may be thought of as resulting from an ever increasing approach angle, as shown in figure (2.9) below.

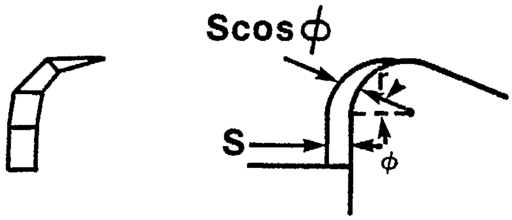


Figure (2.9)

Since the chip thickness, in the case of a nose radius varies continuously then a situation exists where adjacent portions of the chip will constrain each other. Whilst the behaviour is exceedingly complex it is found that good results may be obtained based upon the mean value of chip thickness in the cutting process. The mean chip thickness is usually termed the equivalent chip thickness (he) and is a powerful concept in tool life considerations, as well as in the calculation of forces. The equivalent chip thickness is given by the following expression

$$he = \frac{A}{la} \qquad \text{-------------} \quad (2)$$

where A is (undeformed) area of cut

la is length of active cutting edge involved in the operation.

If now one considers again the case of cutting with a zero nose radius but varying approach angle, the expression above gives values which are essentially equivalent to those which were derived previously, (see figure (2.10)).

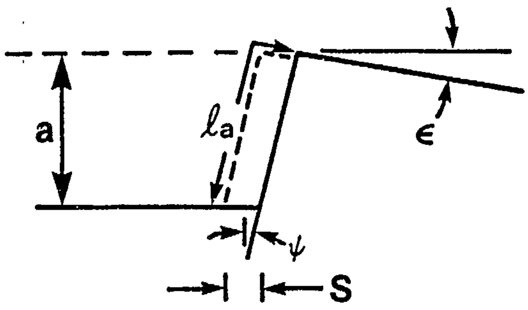


Figure (2.10)

From a consideration of Figure (2.10),

$$A = s.a.$$

$$la = \frac{a}{\cos\psi} + (s/\cos\epsilon) \text{ ------------------ } (2.16)$$

or providing a >> s

then

$$la \doteqdot \frac{a}{\cos\psi} \text{ ------------------------------ } (2.17)$$

and $he = \frac{s.a.\cos\psi}{a} = s.\cos\psi$

It should be noted that equation (2.17) is obtained by neglecting the contribution of the secondary cutting edge. In many practical cases it is permissible to either neglect or approximate the contribution of this edge. In particular for tools which have a nose radius it is usually assumed that the length of the secondary cutting edge is equal to half the feed. In the case of a tool where the whole active cutting edge is on the radius then the following applies

Figure (2.11)

From figure (2.11) is is evident that

$$la \doteq r.\theta_s + s/2$$

where $\theta_s = \cos^{-1} \left(\frac{r-a}{r}\right)$ rad

thus $$he \doteq \frac{s.a}{(r.\cos^{-1}(1-a/r)+s/2)} \quad \text{-----------(2.18)}$$

In the most usual practical case the active cutting edge length is comprised of both straight and curved portions (see figure (2.12))

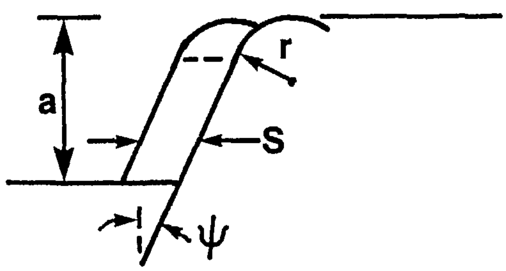


Figure (2.12)

In this case the length of active cutting edge is given by

$$la \doteq \left(\frac{a-r.(1-\sin\psi)}{\cos\psi}\right) + \frac{(90-\psi).r.\pi}{180} + \frac{S}{2}$$

thus

$$he \doteq \frac{s.a}{\frac{(a-r.(1-\sin\psi))}{\cos} + \frac{(90-\psi).r.\pi}{180} + s/2} \quad \text{------- (2.19)}$$

It has been shown, by Yellowley and Barrow, that for approach angles of 45 deg. and less this expression may be simplified as follows:

$$\frac{1}{he} = \frac{1}{s.\cos\psi} + \frac{1}{2a} + \frac{0.57.(r.\cos\psi)}{s.a} \qquad \text{-------} \quad (2.20)$$

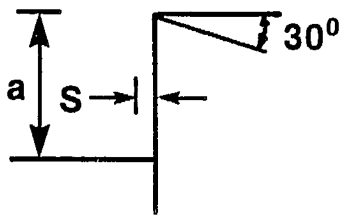
Armed with a knowledge of the equivalent chip thickness the reader should now be able to calculate forces in practical cutting operations. Because in reality the preceding calculations were simplified the author will begin by recalculating the forces in the simple bar turning operation considered earlier.

<u>Operation Details</u>

V = 400 ft/min

S = 0.020 in

a = .125 in



Workpiece Hardness 220 BHN

Tool Geometry $\gamma = +5$, $\lambda = +5$, $\psi = 0$

$$he = \frac{0.020.(0.125)}{.125 + .023} = .0169 \text{ in.}$$

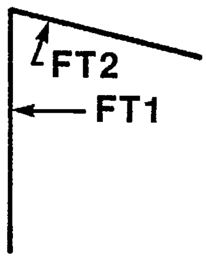
$$\text{thus} \quad Ps = 380{,}000.(0.95).\left[\frac{220}{300}\right]^{0.5} . \left[\frac{.0169}{.010}\right]^{-0.2}$$

$$Ps = 278{,}340 \text{ lbf/in}^2$$

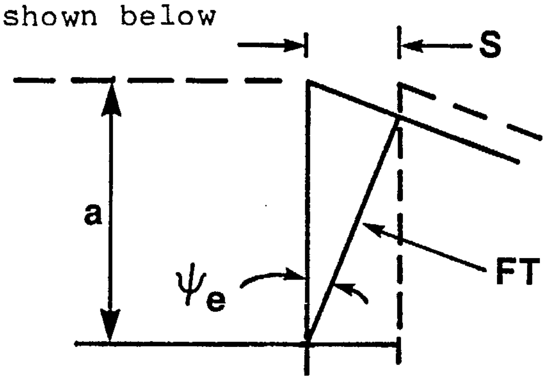
Thus main cutting force

FV = 696 lbf & P = 8.4 H.P.

Now calculation of the two other orthogonal force components is complicated by the secondary cutting edge. If the two edges cut separately the forces would be as shown below



In order to allow simple calculations the author will postulate that the resultant thrust force direction will be equivalent to that on a tool which has a single straight edge as shown below



The approach used was initially suggested by Colwell*, other approaches are available, the interested reader should consult the bibliography. In this case

$$\tan\psi_e = \frac{s}{a-(s.\tan\epsilon)} = .176; \quad \psi_e = 10 \text{ deg.}$$

* Colwell, L.V., Trans A.S.M.E., Vol.76, (1954), P199

Now one must calculate FT and resolve to find FA and FR. A particular problem arises in this case and particularly later in terms of which rake angle to use. Since one is only interested in approximate values and a detailed discussion of oblique cutting is beyond the scope of this chapter, the author would suggest the use of the rake angle in a plane normal to the main cutting edge and parallel to the velocity vector. (The reader will notice that an angle of +5 was already used for calculation of the main cutting force). It should also be pointed out, in passing, that this angle, for small obliquity, is very close to that which would be obtained in a plane perpendicular to the cutting edge and the rake face.

Now μ = 0.625 and r = 0.51

Hence FT = 355 lbf

Resolving this force into the axial and radial directions

i.e. FA = <u>350 lbf</u>

and FR = <u>62 lbf</u>

It is seen then that the only major difference between this series of calculations and those performed previously is the ability to predict the radial component of force.

A second example will now be given to demonstrate the approach when a tool has a finite nose radius.

Operation Details

$V = 400$ ft/min.

$s = 0.02$ in/rev

$a = 0.200$ inch

$r = 0.050$

$\psi = 30^\circ$, $\gamma = +5$, $\lambda = +5$

Workpiece low alloy steel 300 BHN

$1/he = 57.7 + 2.5 + 6.2$

$he = .015$ in

$Ps = 380,000.(.95).(1.5)^{-0.2} = 333,000 \text{ lbf/in}^2$

$\mu = 0.625 \quad r = 0.51$

$FV = 1330$ lbf & $FT = 679$ lbf

In order to calculate FR and FA one now needs to calculate effective approach angle, (see fig. (2.13)).

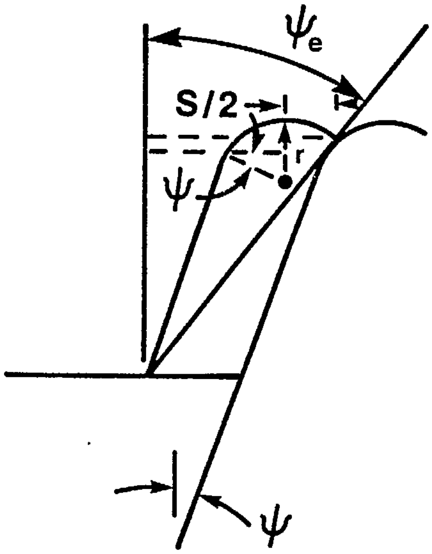


Figure (2.13)

From figure (2.13)

$$\tan\psi_e \simeq \frac{(a-r.(1-\sin\psi)).\tan\psi+r.\cos\psi+s/2}{a}$$

$$\text{i.e.} \tan\psi_e \simeq \frac{.154}{.2}$$

$$\text{i.e.} \quad \psi_e \simeq 37.6^{\circ}$$

Thus FA = 538 lbf and FR = 414 lbf

2.2.4. Force and Power Estimation in Milling

The milling process is much more complex than turning, never the less it is of major importance to be able to calculate forces, torques and power in such operations. In this section the author will describe methods to find the feeding and normal thrust forces in peripheral milling (end milling) and square shoulder face milling. The methods of analysis may be extended by the reader to other milling processes. It should be pointed out that, in the case of helical milling cutters an axial component of force is produced which in the normal case of R.H. cutting R.H. helix has the tendency to pull the tool out of the chuck, or chuck out of spindle should the retention bolt fail. This axial force is extremely difficult to calculate with any accuracy, hence is neglected in this section. However the reader is reminded of the traditional method of coping with this force in slab milling operations, which is to use two cutters of opposite helix angle. It is also evident that in the case of end milling or face milling the axial force may be made to be less objectionable by applying a chamfer or nose radius to the end of the tool.

Figure (2.14)

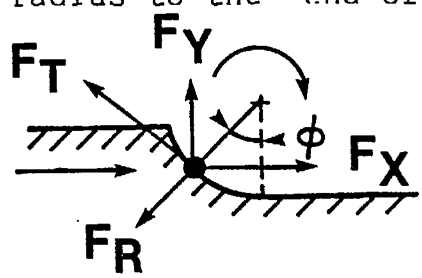
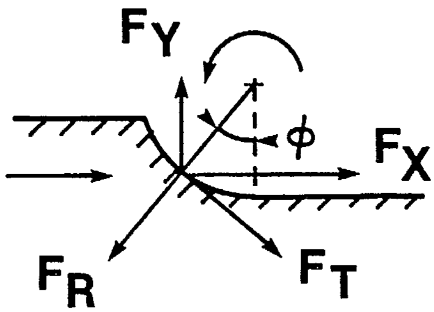


Figure (2.15)



The forces acting on a single tooth of a milling cutter are shown for conventional and climb milling in figures (2.14) and (2.15). The forces shown must be resolved a follows.

a) <u>Conventional Milling</u>

$$FX = FT.\cos\phi + FR.\sin\phi = FT.(\cos\phi + r.\sin\phi)$$

where $r = FR/FT$

$$FY = FR.\cos\phi - FT.\sin\phi = FT.(r.\cos\phi - \sin\phi)$$

and

b) <u>Climb Milling</u>

$$Fx = FR.\sin\phi - FT.\cos\phi = FT.(r.\sin\phi - \cos\phi)$$

$$FY = FR.\cos\phi + FT.\sin\phi = FT.(r.\cos\phi + \sin\phi)$$

It is evident that, as the cutter rotates, not only does the chip thickness vary but also the direction of the forces vary. If, in addition to these variables, one realizes that the number of teeth in contact will generally be greater than one and in the case of H.S.S. cutters a helix angle will be used then the reader will not be surprised to learn that numerical analysis, using the computer, is about the only way to estimate accurately the varying forces in milling. (The interested reader should consult the bibliography for further information.) In those cases where the axial depth and radial width of cut are large then the pulsating component of the cutting force is relatively small in comparison to its mean value. Under these conditions, (which are of course extremes, hence are most useful to be able to calculate), approximate average values of the forces FX and FY may be evaluated by considering the tool to have an infinite number of teeth of infinitesimal spacing, (this device allows integration and an analytical solution, again the reader should consult the bibliography).

The resulting equations are as follows:

a) Conventional Milling

$$FX = \frac{P_s \cdot a \cdot R}{4} \cdot \left(\frac{v}{V}\right) \cdot ((1-\cos(2\phi s)+r(2(\phi s)-\sin(2\phi s)) \quad (lbf)$$

$$FY = \frac{P_s . a . R}{4} \cdot \left(\frac{v}{V}\right) \cdot (r(1-\cos(2\phi s))-((2\phi s)-\sin(2\phi s))) \quad (lbf)$$

and

b) Climb Milling

$$FX = \frac{P_s . a . R}{4} \cdot \left(\frac{v}{V}\right) \cdot (r.((2\phi s)-\sin(2\phi s))-(1-\cos(2\phi s))) \quad (lbf)$$

and

$$FY = \frac{P_s . a . R.}{4} \left(\frac{v}{V}\right) \cdot (r.(1-\cos(2\phi s))+((2\phi s)-\sin(2\phi s))) \quad (lbf)$$

where k is the specific cutting pressure (lbf/in^2)

v is feeding speed of cutter (ft/min)

V is cutting velocity (ft/min.)

R is cutter radius (inch)

a is axial depth of cut (inch).

s is swept angle of cut (radians).

Similarly it may be shown that the approximate torque acting on the milling cutter is given by

$$T = P_s . a . R . \left(\frac{v}{V}\right) . d \quad (in\ lbf)$$

where d is the radial width of cut (inch)

It should be noted that particular care should be taken in the calculation of Ps. It is recommended that the following equation be used when using either standard H.S.S. end mills or carbide end mills with an approximate normal rake angle of zero.

$$Ps = 380{,}000.\left[\frac{BHN}{300}\right]^{0.5} \cdot \left[\frac{he(mean)}{.010}\right]^{-0.2} \text{ lbf/in}^{2} \quad \ldots\ldots \quad (2.21)$$

$$\text{or } Ps = 2{,}600.\left[\frac{BHN}{300}\right]^{0.5} \cdot \left[\frac{he(mean)}{.25}\right]^{-0.2} \text{ N/mm} \quad \ldots\ldots\ldots\ldots \quad (2.22)$$

where (he) mean is the average value of equivalent chip thickness in cut, (in either mm or inch depending upon which equation is used). In order to calculate (he) mean, one first calculates the equivalent average feed which corresponds to the sinusoidally varying feed in milling thus

$$seq = \frac{1}{\phi_s}\int_0^{\phi s} st.\sin\phi \; d\phi$$

$$\text{or} \quad seq = \frac{st}{\phi s}(1-\cos\phi s)$$

$$\text{but } \phi s = \cos^{-1}(1-d/R)$$

$$\text{thus } seq = \frac{st}{\phi s}.\frac{d}{R}$$

$$\text{or } \frac{seq}{st} = \frac{d}{R.\,\phi s}$$

Note: ϕs in radians

st is feed per tooth

The mean value of (he) is then calculated as for turning with seq being the equivalent feed, for standard end mills of course he (mean) and seq may be regarded as being equal in most practical cases. (No nose radius and zero approach angle).

The following is an example calculation of an operation which may be thought of as extreme on a small capacity machining center (10.H.P. spindle drive continuous rating).

Operation specification (see figure (2.16)).

Cutter 4" dia shell end mill. (12 teeth)

Width of cut 2"

Depth of cut 0.5"

Rotational speed 100 RPM

Feed per tooth 0.007 ipt

Work material Carbon Steel 200 BHN

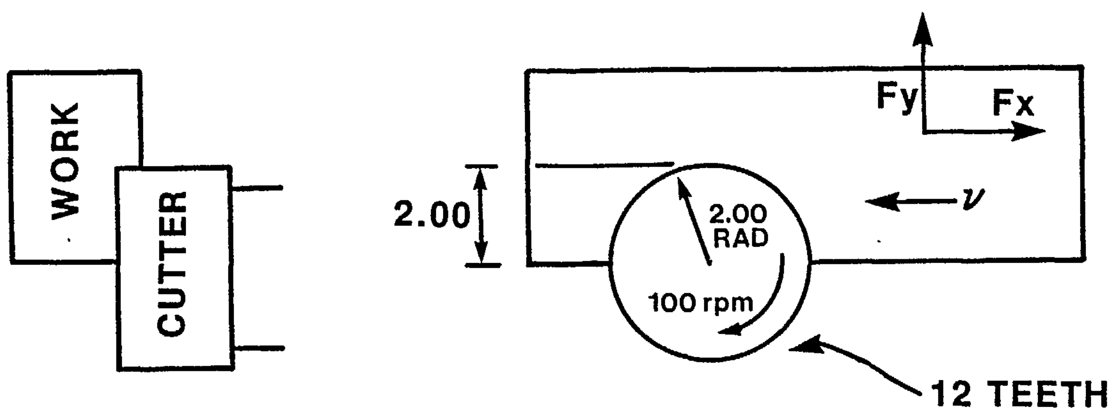


Figure (2.16)

$\phi s = \underline{\pi/2}$ Radian

$$seq = he\ (mean) = \frac{.007\ .(2)}{2.\ \pi/2} = \underline{.0045\ inch}$$

$$P_s = 380{,}000.\left[\frac{200}{300}\right]^{0.5} . \left[\frac{.0045}{.010}\right]^{-0.2} = 364{,}000\ lbf/in^2$$

$$\mu = 0.7 + (.01).(15) = 0.85$$

$$r = \frac{0.85 - 0.268}{1 + 0.228} = \underline{0.474}$$

$$FX = \frac{364{,}000\ .(0.5).(2)}{4} . \frac{0.7}{104.7}((1+1)+0.474.(\pi - 0))$$

$$FX = 608\ (3.489) = \underline{2121\ lbf}$$

$$\&\quad FY = 608\ ((0.948.(2)) - \pi\ ) = -\underline{1334\ lbf}$$

$$T = 364{,}000\ .(0.5).(2).\frac{(0.7)}{(104.7)}.(2)\ \text{in lbf}$$

$$= 4867\ \text{in lbf}$$

$$T = \underline{406}\ \text{ft lbf}$$

$$P = \frac{406.\ (100).\ (2).\pi}{33{,}000}\ \text{H.P.}$$

$$P = \underline{7.73}\ \text{H.P.}$$

The specific power is very close to the normally assumed value of 1 HP/ cu in./min. for such materials, the latter fact being useful to cross check calculations. It is seen that, from a power standpoint the machine would have little difficulty in performing the operation. The following points however would now be checked.

a) Thrust capacity on feeding axes (X or Y)

b) Torque capability at 100 RPM.

c) Torque holding capability of rotary table, (should the part be held on a rotary table).

The last check is particularly important should a full contouring table be used on the machine. In some cases the momement capacity of the table may be compromised. However this is more usually a problem in drilling.

2.2.5. The Estimation of Thrust and Torque in Drilling Operations

Drills, whilst being among the most commonly applied tools have an exceedingly complex geometry, (see figure (2.17)). In particular the normal rake angle varies widely from the point to the peripheri. In addition of course the cutting velocity varies from zero at the point, where material is displaced rather than cut, to some nominal value at the peripheri.

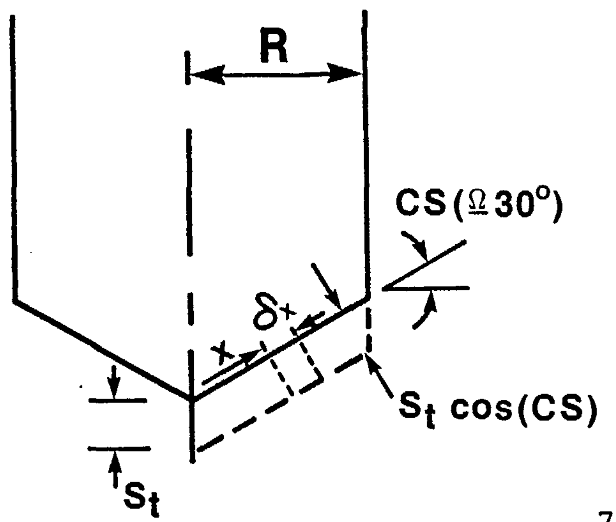


Figure (2.17)

Again the reader who is interested in examining the process in greater depth is referred to the bibliograph. Luckily it transpires that reasonable estimates of torque and thrust may be made for "standard" H.S.S. drills by making use of the previous work in turning as follows:

The approach taken is to examine the forces required to remove the elemental area shown in figure (2.17) and to integrate these forces across the drill to find the total force.

$$d(FV) = Ps . St. \cos (cs) dx$$

$$FV = Ps.St.\cos(cs) \int_{x=0}^{x=R/\cos(cs)} dx$$

$$= Ps.St.R \quad \text{(for a single edge)}$$

Similarly the torque is given as follows

$$d(T) = Ps.St.\cos (cs).dx.x.\cos (cs)$$

$$T = Ps.St \int_{x=0}^{x=R} x \ dx$$

$$T = \frac{Ps.St .R^2}{2} \qquad \text{(for a single tooth)}$$

or the total drill torque is given by

$$T = \frac{Ps. S . R^2}{2} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2.23)$$

(where S is the feed per revolution)

If one now assumes that the elemental thrust force is given by

$$FT = r \cdot FV$$

then the normal thrust force is given by

$$FA = r.Ps.St.\cos^2(Cs) \int_{x=0}^{x=R/\cos(Cs)} dx$$

$$FA = r.R.Ps.St.\cos(Cs) \quad \text{(for one edge)}$$

or total thrust required on drill

$$FA = r.R.Ps.S.\cos(Cs) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.24)$$

(Where S is the feed per revolution)

Despite the gross approximations made in the analysis, the resulting expressions give a reasonable portrayal of the relationship between the thrust, torque and practical variables.

In order to demonstrate the use of the equations two simple examples will be presented. (Note it will be assumed in all cases for H.S.S. drills that r=0.8 and the effective rake angle is zero)

Example 1

1/2" diameter drill (118 deg. point angle).

Feed .010 inch/rev.

Rotational speed 500 RPM

Carbon Steel workpiece (200 BHN)

$$Ps = 1.15(380,000).\left[\frac{200}{300}\right]^{.5}.\left[\frac{.005 \cos 31}{.010}\right]^{-0.2}$$

$$= \underline{423,000} \text{ lbf/in}^2$$

$$T = 132 \text{ in.lbf}$$

i.e. $\underline{T = 11.0 \text{ ft.lbf}}$

$$FA = 0.8.(423,000).(0.25).(0.010).(0.857) \text{ lbf}$$

$$\underline{FA = 725 \text{ lbf}}$$

Example 2

50 mm diameter drill (118 deg. point angle)

Feed 0.5 mm/rev.

Rotational speed 100 RPM

Work Material Low Alloy Steel (300 BHN)

$$Ps = 1.15.(2600).\left[\frac{0.25 \cos(31)}{0.25}\right]^{-0.2}$$

i.e. $Ps = 3083 \text{ N/mm}^2$

$$T = \frac{3083 (0.5)(25)^2}{2} \text{ N.mm}$$

or $\underline{T = 482 \text{ N.m}}$

$$FA = 0.8(3083).(25).(0.5).(0.857) \text{ N}$$

$$\underline{FA = 26,421 \text{ N}}$$

It should be noted in passing that, for small diameter drills, the thrust force is dependent, to a large degree on the type of point and the extent of wear.

Conventional chisel points on small diameters of drill, with an average degree of wear may give thrust forces which are 20 - 30% higher than indicated by these simple calculations.

In assessing the suitability of a given machine tool or fixturing arrangement for a particular drilling operation it is necessary to examine carefully, not only the axis thrust and torque requirements, but the moments and torques which result. This is particularly the case on large machines, e.g. horizontal boring mills where most reputable manufacturers will specify limit thrusts in extreme working conditions to prevent damage to drives, ball screws and tables. In the case of fixtures of course, it is up to the end user to design these with the forces in mind, (unless a turnkey arrangement has been made with a machine tool builder supplying the complete package). In any case the end user should not accept a simple statement of maximum drill size as necessarily meaning that such holes may be drilled from solid in all practical working positions.

2.3. TOOL WEAR AND MACHINING ECONOMICS

2.3.1. Introduction to Tool Wear

The subject of tool wear is exceedingly complex. A basic understanding of the physical processes occurring between chip and tool is unfortunately beyond the scope of this work. Interested readers should, again consult the bibliography for further information. This section discusses briefly the manifestations of the wear process and attempts to give general guidelines to the selection of economic machining conditions.

2.3.2. Failure Criterion for Metal Cutting Tools

In the general case a cutting tool may reach the end of its useful life through wear on either or both of the flank or rake face areas. The useful life being defined by accuracy, surface finish or simply the ability to continue cutting. The criteria of useful life is then difficult to specify precisely since it will vary with tool material, work material and the specific characteristics of the operation being performed. In the author's experience with correct grade and geometry application, the tool life is generally determined by flank wear; the remainder of this subsection will concentrate on flank wear characteristics.

A typical flank wear scar is shown in figure (2.18) below

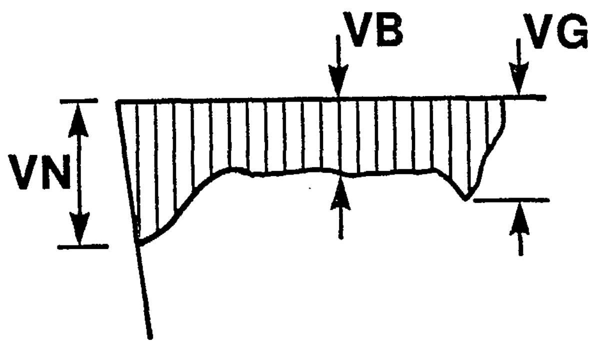


Figure (2.18)

In the general case the flank wear scar may show regions of concentrated wear, particularly at the interfaces between chip and air where oxidation plays a primary role. The concentrated nose wear is generally only a problem in high speed finishing operations whilst the depth notching is particularly prevalent when machining heavily work hardening materials or components with a hard or abrasive "skin". In any case limits for all of these features must be established. In general for finishing operations typical limits are:

VB = 0.01 inch (0.25mm)

VN = VG = 0.02 inch (0.5 mm)

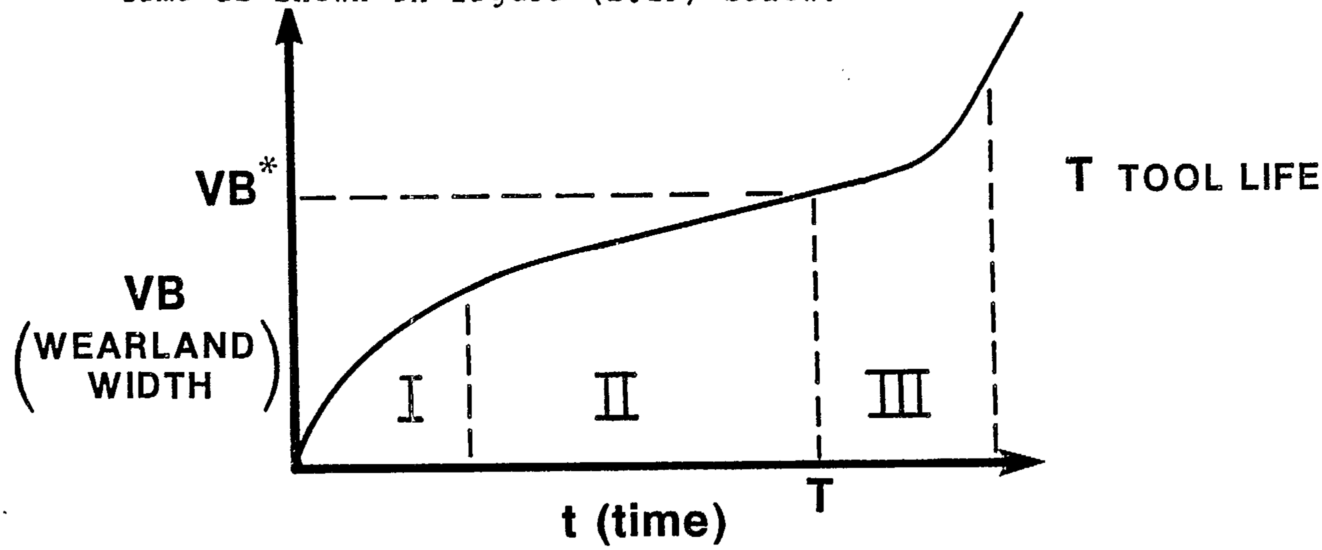
and for extreme roughing operations

VB = 0.02 inch (0.5 mm)

& VN = VG = 0.03 inch (0.75 mm)

Typically reasonable wear limits will lie between those given although in the cases of extreme precision requirements and in the absence of tool wear monitoring or workpiece gauging, smaller limits may be required to ensure dimensional accuracy.

The wear on the clearance face (flank) progresses with time as shown in figure (2.19) below:



It should be noted that the failure criterion VB* must be chosen to avoid the catastrophic wear region (tertiary) if tool breakage is to be obviated. Again in specific circumstances, particularly the machining of high strength steels this means using a lower value of VB as a failure criterion. It should also be kept in mind that, in general the value of wear land at which the tertiary region starts is generally related to the actual tool life i.e. tools which are used at higher production rates will generally require a more conservative flank wear land criterion than those which are utilized at lower production rates and higher tool lives.

An interest in tool life is not motivated simply by a desire to know when to change tools but by an ambition to use the available tools in the most economical manner. In order to achieve this end it is necessary to examine the relationship between tool life and the practical variables.

2.6.3. Tool Life and Process Economics for the Turning Operation

The primary variable influencing the life of a given tool cutting a given work material is the cutting speed. Given the assumption of a fixed value of wearband as signifying the end of a tool's useful life the relationship between velocity and tool life over the normal practical range can usually be expressed in the following form:

$$V.T^{\alpha} = \text{Const} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.25)$$

Equation (2.25) is usually referred to as the Taylor equation, after F.W. Taylor who first proposed such a relationship in 1907. It should however be realized that this equation is an approximation which is only valid in the normal practical region of cutting lives. It does not apply for instance under circumstances where built up edge is present and even where lives have a spread of more than say twenty to one, the relationship between log T and log V is usually distinctly non linear and concave to the origin as shown below in figure (2.20)

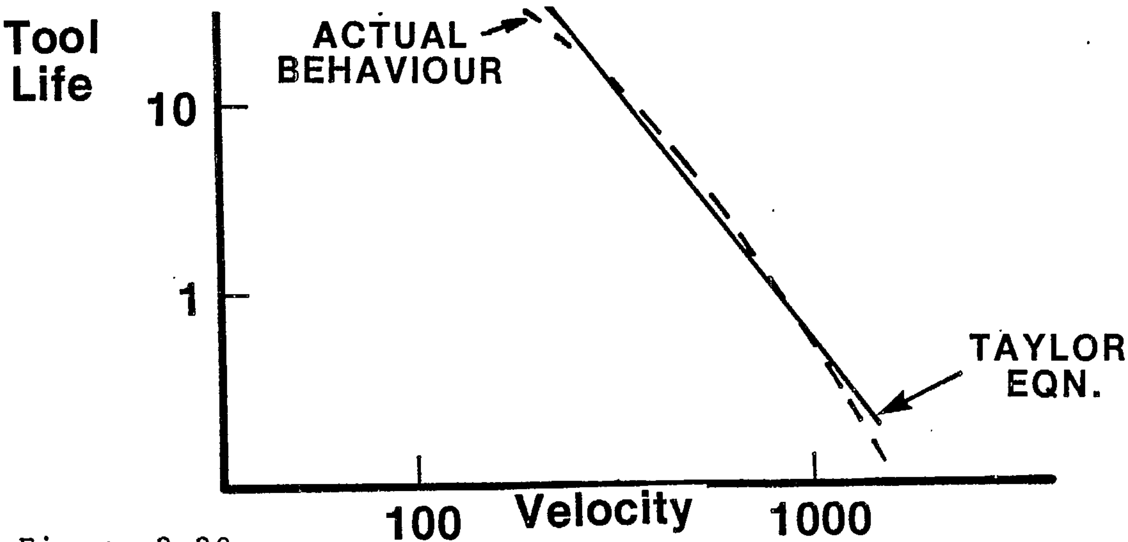


Figure 2.20

More complex relationships have been proposed in practice, however, provided that the tool life is kept within practical limits i.e.

90 min. > T > 5 min.

then the simple Taylor relationship is usually sufficiently accurate.

In general the value of α in the Taylor equation is considerably less than unity and H.S.S. tools give considerably lower values than carbide (i.e. such tools have a wider variation in tool life for a given range of velocity or have a much lower band of practical cutting speeds).

Typically

$0.5 > \alpha > 0.1$

The major variables to be considered following the cutting speed are the feed(s) and depth of cut (a). These variables are usually incorporated into the so called extended Taylor relationship as follows:

$$V.T^{\alpha}.S^{\beta}.a^{\gamma} = \text{Const} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.26)$$

Typically

$1 > \beta > \gamma$

i.e. the velocity has a greater influence on tool life than feed which again has a greater influence than depth of cut. (It may be noted that for work materials which exhibit relatively small changes in shear angle with cutting conditions then β does approach unity, (Titanium alloys and very high strength steels are typical examples). The extended Taylor relationship again is only an approximation and may only be used over the practical range of tool lives; moreover a small change in the tool geometry say tool nose radius will lead to a change in both β and γ. For the latter reason it is now, in scientific research, at any rate more common to formulate tool life equations in the following form:

$$V.T^{\alpha}.he^{\delta} = Const \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.27)$$

(where (he) is the equivalent chip thickness introduced in an earlier section) Equation (2.27) has two main advantages over the extended Taylor relationship i.e.

a) It has one less experimental constant

b) It allows the prediction of the influence of changing nose radius and approach angle on tool life, (providing the effective rake angle does not vary appreciably.

The reader will no doubt appreciate that equation (2.27) infers that in machining with a given tool geometry the ratio (β/γ) in the extended Taylor relationship is approximately constant irregardless of work material. In developing the economics of the metalcutting process the author will first use the traditional approach and employ the extended Taylor relationships, the more fundamental approach using the concept of equivalent chip thickness will be employed to explain the selection of conditions in multi pass rough machining operations.

In examining the economics of any process one normally has one of three objectives in mind i.e.

a) Minimization of process time.
b) Minimization of process cost.
c) Maximization of profit.

Depending upon specific circumstances any one of these criteria may be important, moreover each one will typically lead to the selection of different conditions. In the section which follows the author will examine how both time and cost may be minimized.

The minimization of profit has been treated in the literature but is somewhat difficult to pursue without the assumption of many site specific factors.

Let us first then consider the simplest case of minimizing the time required to conduct a single pass turning operation.

The times involved in such an operation, (see figures (2.21)), are the following:

a) A constant amount of time to manipulate tool, set speeds, feeds, etc. (This may also include setting of first tool, machine set up and workpiece load and unload).

b) The machining time for the given length of cut.

c) The time required to change tools which have reached the end of their useful life.

Since one is interested in minimizing the production time through a judicious selection of both speed and feed then the constant time consumed in manipulation is of no interest in this case, one is only concerned with the variable time elements.

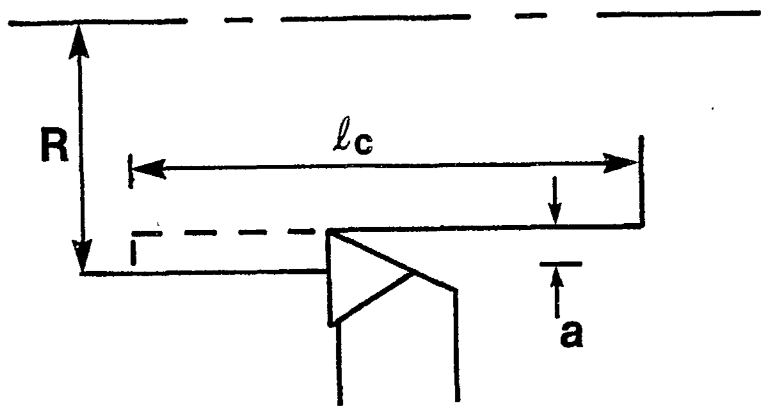


Figure (2.21)

In this case then the total variable time is given by the expression

$$t_v = \frac{lc}{RPM.s} + \frac{lc}{RPM.s} \cdot \frac{ts}{T} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2.28)$$

where RPM is the workpiece rotational speed

s is the feed per rev

ts is the time required to replace a worn tool

T is the tool life.

Since both the RPM and tool life may be expressed in terms of velocity i.e.

$$RPM = \frac{V}{2\pi R} \quad \text{and} \quad T = \left[\frac{Const}{V.S^{\beta}}\right]^{1/\alpha}$$

2

then the expression for total variable time may be rewritten

$$t_V = \frac{lc.2.\pi.R}{V.S} + \frac{lc.2.\pi.R}{V.S} . \frac{ts.V^{1/\alpha} . S^{\beta/\alpha}}{(Const)^{1/\alpha}}$$

$$= \frac{lc.2.\ .R}{V.S} . \left[1 + \left[\frac{ts.V.^{1/\alpha}\ S^{\beta/\alpha}}{(Const)^{1/\alpha}}\right]\right]$$

Now if one assumes for the moment that the feed is limited to some value, (S1), then

$$t_V = \frac{lc.2.\pi.R.}{V.S1}\left[1 + \left[\frac{ts.V^{1/\alpha} . S1^{\beta/\alpha}}{(const)^{1/\alpha}}\right]\right]$$

where S1 is the selected value of S.

and $$\frac{dt_V}{dV} = lc.2\pi.R.\left[-\frac{1}{(V.S1)^2} + \left[\frac{(1/\alpha - 1).S1.^{(\beta/\alpha - 1)} V^{(1/\alpha - 2)} . ts}{(Const)^{1/\alpha}}\right]\right]$$

at a stationary point

$$\frac{dtv}{dV} = 0$$

i.e. $$\frac{1}{(V.S1)^2} = \frac{(1/\alpha - 1).S1^{(\beta/\alpha - 1)} . V^{(1/\alpha - 2)} .ts}{(Const)^{1/\alpha}}$$

or $$1 = \frac{(1/\alpha - 1).S1^{\beta/\alpha} . V^{(1/\alpha)}\ ts}{(Const)^{1/\alpha}}$$

since $$1/T = \frac{V^{1/\alpha} .S1^{\beta/\alpha}}{(Const)^{1/\alpha}}$$

then

$$T = (1/\alpha - 1).ts \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.29)$$

Thus the optimal value of velocity is that which corresponds to a tool life which is given by eqn. (2.29). This tool life moreover is independent of feedrate, how then should feedrate be selected? A first approach may be to conduct the same exercise again holding V constant and examining $\frac{dtv}{ds}$, the reader who performs this exercise will discover that the optimal tool life is now given by:

$$T = (\beta/\alpha - 1).\ ts \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.30)$$

Since, in general, $\beta < 1$ then it is necessary to examine both variables simultaneously in finding a true optimum. Whilst the problem thus phrased may be considered as a simple geometric programming problem, the answer in fact is intuitively obvious and may be inferred by inspection of the initial relationship for variable time.

In equation (2.28) there are two terms, the first of which is inversely proportional to metal removal rate.

If one now fixes the product (VS) ie metal removal rate to any arbitrary value, then the first term is a constant. Consider now the process of varying V and S in such a way that the product is still constant. Fairly obviously since one knows that the extended Taylor relationship applies i.e.

$$VT^{\alpha}.S^{\beta}.a^{\gamma} = \text{Const}$$

then since $\beta<1$, the higher the feed selected when V.s is a constant then the higher will be tool life, the variable cutting time will thus decrease as the feedrate is increased. The answer then is fairly clear, one should select as high a feed as possible then select the velocity to give a tool life which corresponds to eqn. (2.29). In actuality should one have chosen to analyze a multipass roughing operation and had allowed the depth of cut to be varied to then the following conclusions would have been evident.

a) choose maximum depth of cut

b) choose maximum feed

c) Optimize velocity so that the tool life would, again correspond to that demanded by equation (2.29)

Before considering the nature of the constraints, the author will pass on to the consideration of minimum machining cost where similar trends are to be found.

The total variable cost of performing a single pass operation at constant depth of cut is given by:

$$CV = \frac{lc}{RPM.s} \cdot x + \frac{lc}{RPM.s} \cdot \frac{1}{T} .(x.ts+Ct) \quad ....(2.31)$$

where x is machine overhead rate

Ct is tool cost

the remaining variables are as in equation (2.28).

Again substituting for RPM and for tool life from the extended Taylor relationship,

$$CV = \frac{lc.2.\pi.R}{V.s} . x + \frac{lc.2.\pi.R}{Vs} . \frac{V^{1/\alpha} . S^{\beta/\alpha}}{(Const)^{1/\alpha}} . (x.ts+Ct)$$

on $$CV = \frac{lc.2.\pi.R}{V.s} . \left(x + \frac{V^{1/\alpha} . S^{\beta/\alpha}}{(Const)^{1/\alpha}} . (x.ts + Ct)\right) \quad ...(2.32)$$

Using the same logic as before it would seem likely that the feed (s) should be chosen as large as possible and the optimal value of velocity found by differentiating CV with respect to (V) and equating to zero, thus,

$$\frac{dCv}{dV} = lc.2.\pi.R \left(-\frac{x}{V^2.S} + \frac{(1/\alpha-1)V^{(1/\alpha-2)} . s^{(\beta/\alpha-1)} . (x.ts+Ct)}{(Const)^{1/\alpha}}\right)$$

equating to zero,

$$x = \frac{(1/\alpha-1).V^{1/\alpha}.s^{\beta/\alpha}.(x.ts+Ct)}{(Const)^{1/\alpha}}$$

substituting for tool life

$$T_{(min\ cost)} = \frac{(1/\alpha-1).(x.ts+Ct)}{x} \quad ....(2.33)$$

A comparison between equations (2.29) and (2.33) will convince the reader that the tool life for minimum cost is always higher than that for maximum production rate, (provided the tool cost is non zero).

A simple example will serve to illustrate the calculation of tool life values.

Assuming the following:

a) Tool edge cost - \$3.00 (Ct).

b) Tool change time - 1.5 min (ts).

c) Machine overhead rate - \$0.50/min (x)

d) Exponent of tool life in extended Taylor relationship 0.3 (α)

$$T_{max\ prod} = (1/\alpha - 1).ts$$

$$= \underline{3.5\ min}$$

$$T_{min\ cost} = \frac{(1/\alpha - 1).(x.ts + Ct)}{x}$$

$$= \underline{17.5\ min}$$

The reader should note that, not surprisingly, minimum cost is the usual criterion and that the minimum cost tool life is primarily dependent on the ratio of tool cost to machine cost, thus those tools which are either expensive or have long setting times will have high optimal tool lives, whilst expensive machine tools, particularly N.C. machines will dictate low tool lives. The latter point is worth noting since it implies that N.C. machines will normally be run at higher cutting velocities than equivalent manual machines.

Now one must in, most cases, perform the following sequence of operations to ensure efficient machining conditions.

a) Maximize depth of cut.

b) Maximize feed rate

c) Calculate approximate economic tool life.

d) Estimate required velocity.

e) Adjust velocity on the shop floor to achieve required tool life.

It is necessary now to examine the constraints to such an approach. This will be done in the same order as above.

a) The depth of cut, as a single variable is limited only by the chatter threshhold and by the capability of the tool (length of cutting edge and chip breaking capability). It should be noted that the depth of cut limitation imposed by chatter is strongly influenced by tool geometry, particularly approach angle and nose radius. On a typical lathe for instance a 45 deg. approach angle will lead to approximately half the limit depth of cut of a zero approach angle, when cutting a plain diameter. (This is due to the orientation of the forces, since both for conventional lathes and typical workpieces the stiffness parallel to the axis of rotation far exceeds that in directions perpendicular to that axis).

b) The feedrate is primarily limited by tool breakage in roughing operations. (Care should also be taken to ensure that the combination of feed and depth allow chipbreaking). A reasonable approximation to the strengthening and chip thinning actions of approach angle and nose radius may be had by assuming that edge breakage will occur at a constant value of equivalent chip thickness (he). Thus a 45 deg. approach angle tool may be fed approximately 40% faster than a zero approach angle tool and is useful if a relatively small depth is to be removed from a diameter. Note too that the combination of feed and depth of cut determines total force or torque which again will constitute a limit constraint for feed (not depth of cut). In the case of a finish pass, the feed will normally be limited by required surface finish.

c) In practice the velocity will usually be limited by power and must be reduced in accordance if this occurs. In some circumstances, machine tools or holding devices, (chucks in particular), may constrain velocity below its optimal value. The reader should also realize that in many cases the stiffness or holding capability of the fixture or chuck will limit the applied forces. Since this is difficult to treat, in a general manner, such considerations are neglected in the analysis given in this chapter.

The sequence of constraints described above is more meaningful than it first appears. Since one wishes to maximize first depth of cut then feedrate, it follows that when purchasing machine tools one must be concerned with the machine related parameters which will allow these two variables to be maximized. Also the machine tool must of course be capable of providing the economic cutting speeds. This point is particularly important on N.C. machines where the in cut time is a relatively high proportion of the total time. The buyer of machine tools then must have some familiarity with machine tool performance testing and should give due consideration to the usually unspecified parameters of dynamic stiffness and damping. (Usually this must be done by performing cutting tests although great strides have been made in indirect tests and analytic models). The importance of this statement may be realized by simply considering that the metal cutting time may be almost halved if the limit depth of cut is doubled, further gains may be had by improving torque and power capability (coupled with improvements in cutting tool technology).

2.3.4. Economics of Multi Pass Turning Operations

The subject of optimizing the cost of multi pass operations has particular significance to N.C. machining. In particular the development of strategies for depth partition are important since, whilst feed and speed may be overridden on the machine, changes in the depths of cut require editing of the program, a process one would rather avoid if possible. The subject will be introduced by examining the case of the two pass operation with no surface finish or power constraint evident. The basic process is depicted in figure (2.22).

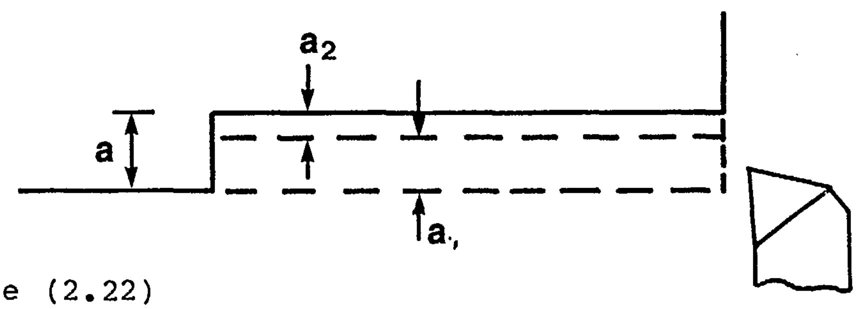


Figure (2.22)

$$a = a1 + a2 \;>\; a\ lim.$$

where a is total depth of cut

a1 and a2 are depths of cut in first and second passes respectively.

a lim is chatter limit depth.

In the problem as described, one is faced with having to conform to only tool breakage and chatter constraints. The tool breakage constraint may be handled by assuming that for each pass the feedrate is increased until a maximum constant value of equivalent chip thickness is reached.

Since the equivalent chip thickness is then a constant in each pass then in order to minimize the cost of each pass, tool life will be set to a constant optimal value, hence from equation (2.27), the velocity of cut will be constant in each of the passes. Under these circumstances the total cost of the operation is proportional to the total cutting time for the two passes i.e.

$$t_{(1+2)} = lc.\left(\frac{1}{RPM(1).s(1)} + \frac{1}{RPM(2).S(2)}\right) \quad \ldots (2.34)$$

$$\text{or } t_{(1+2)} = \frac{2.\pi.lc}{V}\left(\frac{R(1)}{S(1)} + \frac{(R(1)-a(1))}{S(2)}\right) \ldots\ldots\ldots\ldots (2.35)$$

where R(1) is initial component radius.

Now assuming first that the initial component radius is large compared to the limit depth of cut, then

$$R(1) \simeq R(1) - a(1)$$

and the problem reduces then to minimizing the sum of the reciprocals of the feedrates in the two passes.

$$t_{(1+2)} = \text{Const}\left(\frac{1}{S(1)} + \frac{1}{S(2)}\right)$$

In order to assess the best way of achieving this goal consider figure (2.23) which shows the relationship between the depth of cut and the reciprocal of feedrate for a constant value of equivalent chip thickness

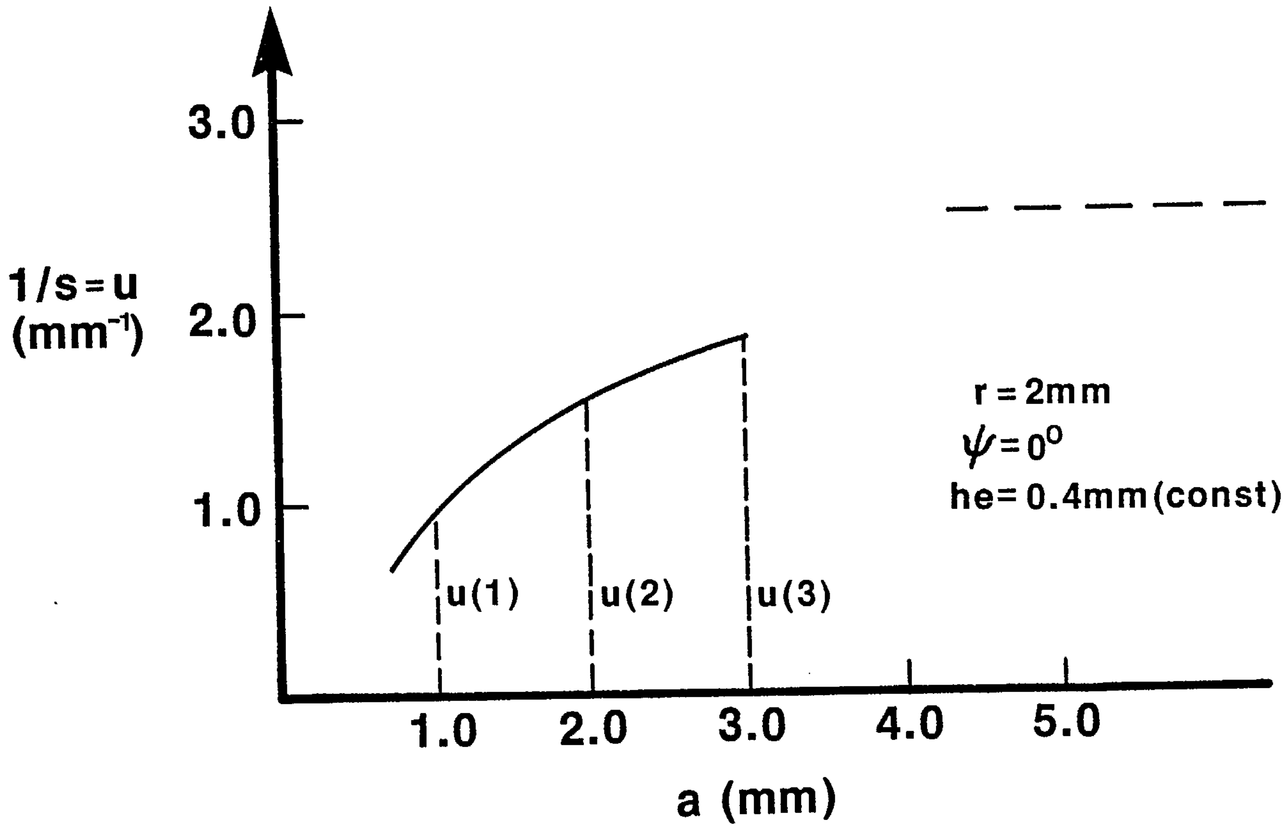


Figure (2.23)

In all cases the relationship between u, (1/s) and (a) is such that $\frac{du}{da}$ decreases with increasing (a). Consider now a two pass operation with a total depth of 4mm and a chatter limit of 3mm. Most usually a programmer would choose to cut this element in two even passes. However it will be seen from a consideration of figure (2.23) and equation (2.35) that since $\left(\frac{du}{ds}\right)$ decreases with increasing (a) then

$$u(1) + u(3) < 2\, u(3), \text{ always}$$

hence in actuality the practice of removing two even passes will always lead to the maximum cost. Good practice dictates the use of one pass at maximum depth of cut and one pass to take the remainder.

In these cases where the depth of cut is an appreciable portion of the initial component radius then consideration of equation (2.35) leads to the conclusion that for external turning the large pass should be taken first. For internal turning, the reverse applies, however, if the final pass is a finish pass rather than a semi finish pass, (i.e. one tool is being used to rough and finish), then in most cases practicality will dictate taking the large pass first even in internal turning (boring) operations.

The logic described above has been extended to examine the case where a power constraint is binding at two even cuts and where the surface finish constrains the feedrate in the second pass. In the rather unlikely case that power constraints are predominant, then it is difficult to give a general rule for the selection of depths of cut. However in all other cases the following procedure should be adopted to yield good solutions to the problem in external turning,

a) The initial depth of cut should be chosen to be as high as possible.

b) In the absence of a surface finish constraint on the second pass, both passes should be run with feedrates which yield the same maximum value of equivalent chip thickness. (In the presence of a surface finish constraint, the feedrate in the second pass should be reduced in accordance.)

The same logic may be applied to operations which require more than two passes. For instance, if one is faced with a total depth of cut in a roughing operation of 10 mm and a limit depth of 4 mm, then one would take two passes of 4 mm followed by a final pass of 2 mm depth. Whilst the foregoing would not seem at first to be particularly important, it may be carried out with no knowledge of a material's machinability and will normally yield a saving of 10% - 20% over the conventional strategy of taking even cuts, (excepting in those cases where a power constraint binds well before the chatter and tool edge breakage constraints, a likelihood which is easily predicted using the material presented earlier in the chapter). Readers who are interested in the more detailed analysis of this problem will find relevant references in the bibliography.

2. .5. Tool Life and Process Economics in Peripheral and Square Shoulder Face Milling

Milling cutters are in general used much more conservatively and with much less understanding of their characteristics than turning tools. This arises because of the greater complexity of the process and a very significant lack of research effort. The basic peripheral milling process, (commonly termed end milling), is shown in figure (2.24), the basic practical variables are the following:

a) Cutting velocity (V)
b) Width of cut (d)
c) Axial depth of cut (a)
d) Feed per tooth (st)
e) Cutter radius (R)

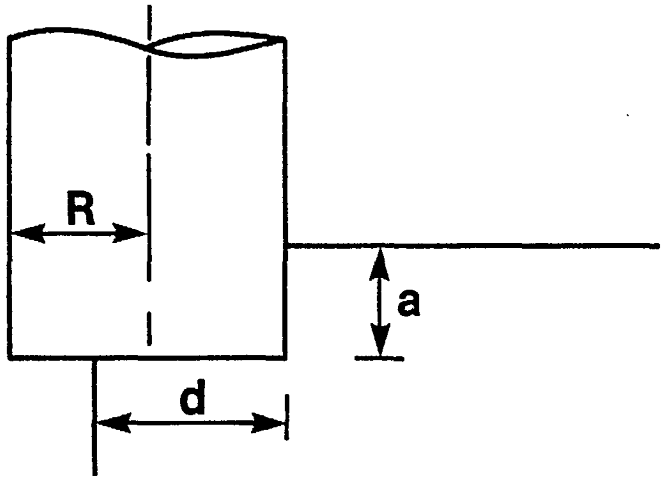


Figure (2.24)

As it happens the relationship between velocity and tool life all other variables being constant may be expressed in the familiar form of the Taylor Equation:

$$V.T^{\alpha} = \text{Const.}$$

Hence, once again equations (2.29) and (2.33) may be used to predict the tool lives which result in minimum cutting time or cost respectively. Unfortunately this latter problem is a relatively small part of the total problem. One must first decide on the values to be chosen for the other variables in a reasonably efficient manner. It is normally found that the axial depth of cut has a relatively weak influence on tool life and may be included in an extended Taylor type relationship as follows:

$$V.T^{\alpha}.a^{\gamma} = \text{Const} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.36)$$

where $\gamma << 1$

The remaining variables are more complex and in fact interrelated. A brief discussion follows; however, interested readers should consult the bibliography if they require significant detail. It should also perhaps be stated that the view portrayed is a very personal one, there are, in reality many differences of opinion still to be resolved regarding the selection of conditions in milling.

In order to gain an appreciation of the influence of width of cut and feedrate the author will first consider the case of cutting with a constant radius of cutter. Figure (2.25) depicts this situation, from figure (2.25) the following equations result

$$\phi s = \cos^{-1}\left(1 - \frac{d}{R}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.37)$$

where ϕs is the swept angle of cut and $S_{max} \simeq st.\sin\phi s$; $(\phi_s \leq \pi/2)$

where S max is the maximum "feed" seen by a point on the cutting edge during a single revolution. (It may be noted that, by virtue of the helix angle, the mean chip thickness along a cutting edge varies in cut and is a maximum during one revolution for the trailing edge of the helix. This leads to a variation in wear along the helix, a point which will not be further pursued in this description).

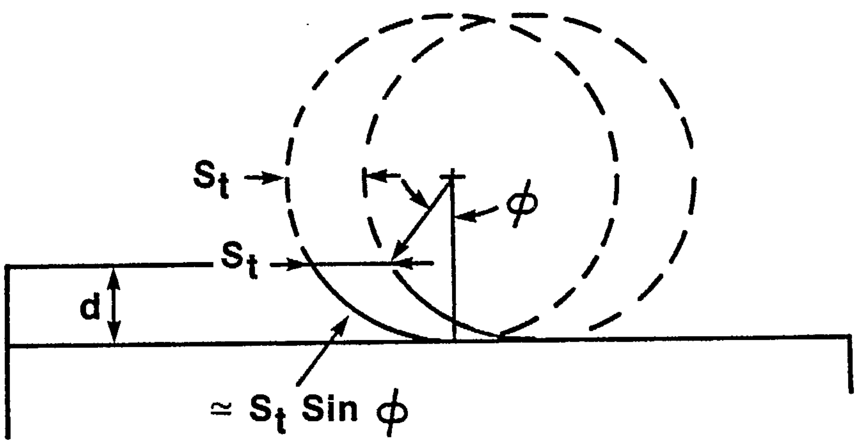


Figure (2.25)

It will be realized that the influence of width of cut is twofold; i.e.

a) It influences the proportion of the time the cutter is actually cutting as opposed to rotating in air.

b) For widths of cut less than the cutter radius, reducing the radial width reduces both the maximum and average values of feed which the milling cutter tooth encounters.

Whilst both the above observations are true and tool life will increase as the width of cut decreases from a value equal to the radius, there are unfortunately additional parameters to consider.

The problems are best summarized as follows:

a) It is known that for one width, depth, velocity and work-tool pair, that tool life may be expressed as follows:

$$sT^{B} = Const \qquad (2.38)$$

b) Following from eqn.(2.38) one may now integrate the actual wear rate resulting from a sinusoidal variation in feedrate. In the particular case of B=1, then the following results:

$$seq = \frac{st}{\phi s}\int_{0}^{\phi s} \sin\phi \, d\phi = \frac{st}{\phi s}(1-\cos\phi s)$$

$$\text{or } seq = st \frac{.\ d}{R\phi s} \qquad (2.39)$$

where $\phi s = \cos^{-1}(1-d/R)$ and is the swept cycle of cut.

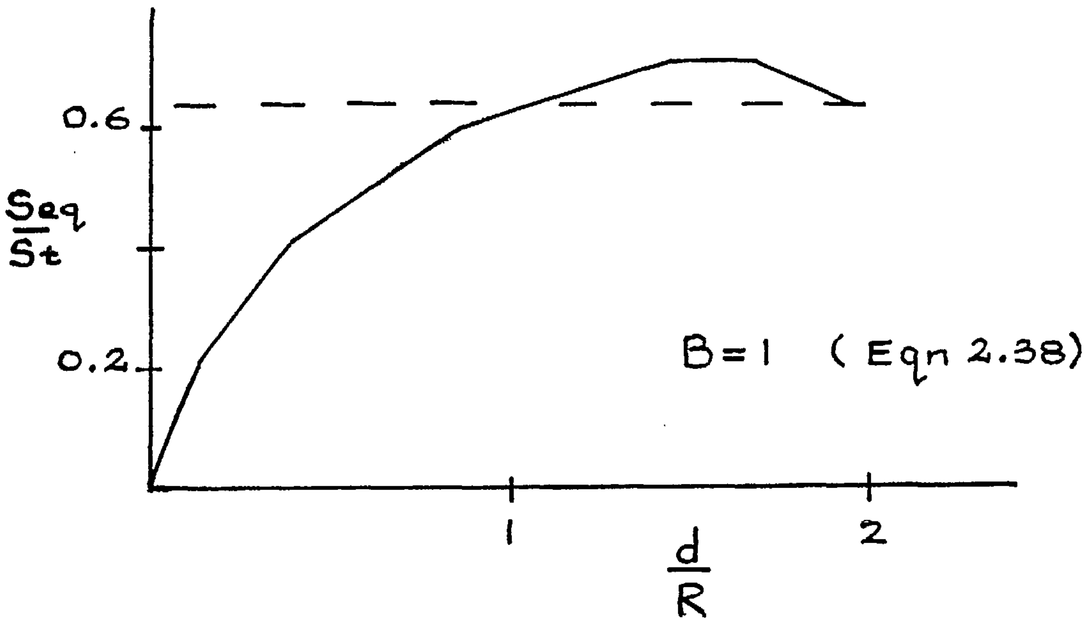


Figure (2.26) Variation in ratio of equivalent feed to feed per tooth as a function of width of cut.
(Note: ratio is the same for slotting and half immersion).

The reader should notice that seq is the mean value of feedrate in this case and is defined as the constant value of feed which will result in the same wear rate as the varying feed in milling. Figure (2.26) shows the typical variation in seq with width of cut when St is held constant. It should be noticed that the values for a width equal to the radius or the diameter then the same equivalent feed results. Based on the reasoning used earlier and this finding, one may thus expect that the actual cutting time to failure for slotting (d = 2R) and half immersion (d=R) will be the same i.e. the slotting cut will have half the tool life. This is not the case, even in cases where both up and downcut milling have approximately the same lives, one finds that the tool life in slotting is the same or greater than either of the two half immersion cuts, (i.e. the cutter survives for twice the length of time actually incut!). This surprising finding has lead to the development of new tool life equations and their use to evolve good economic models of the cutting process. The interested reader should examine the bibliography, all that will said here is that given reasonably economic cutting conditions for a particular width of cut, the required feedrates for other widths in the absence of power, shank breakage, chatter and torque constraints may be estimated in typical cases from figure (2.27). Also, as in turning for any given axial depth of cut, the width will be maximized followed by the feedrate followed by an optimization of velocity. It is also evident that in multi-pass milling as many passes as possible should be taken, with maximum width, the last pass taking the remainder. Again the author would emphasis the use of the Bibliography and data from cutting tool suppliers for those readers who are interested in this complex problem. The author's intention in this section is merely to point out the problems. A detailed discussion of the economics of milling is outside the scope of the monograph.

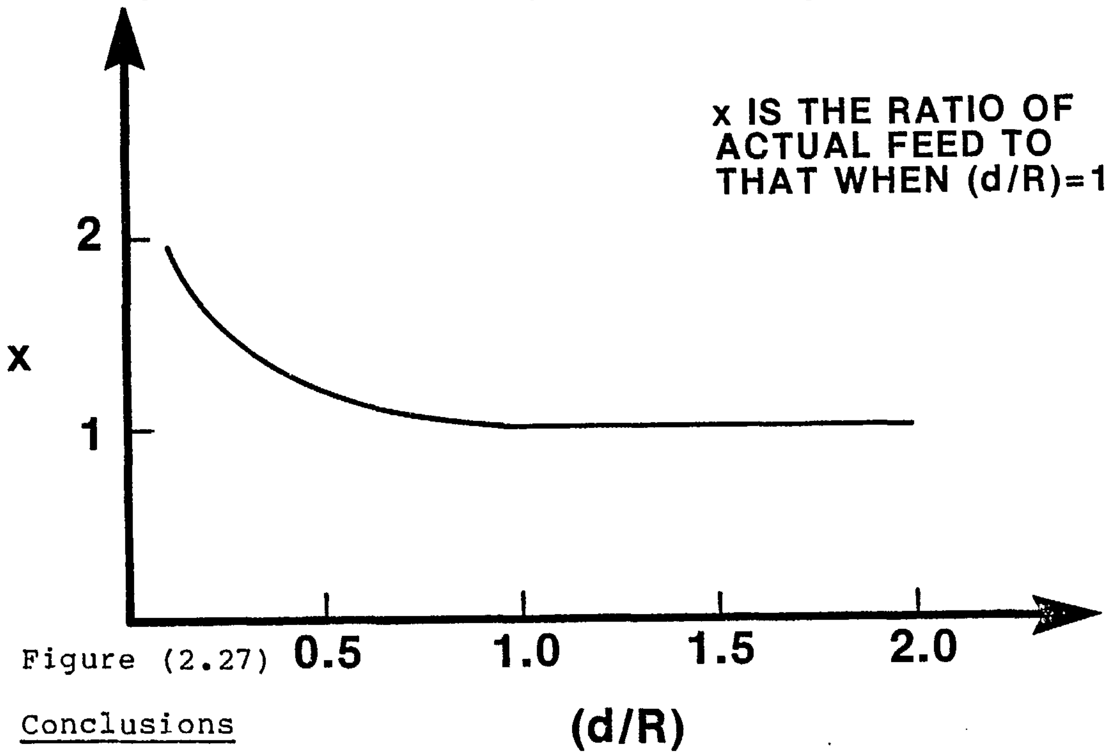


Figure (2.27)

2.4. Conclusions

Whilst the author has devoted more of this monograph to metalcutting than he would really like, it would seem that programmers will have to devote a considerable amount of effort to searching the literature and making use of information provided by tool suppliers and machine tool companies. Hopefully, at the very least the author has indicated the current state of knowledge and given a starting point for further study. In reality of course, the practical planning operation is much more complex and wide ranging. The N.C. programmer must decide not only an machining parameters but also make decisions regarding type of operations, their sequence, holding attitudes and machines. This more practical problem together with a discussion of machine parameters and workshop organization is the subject of the final chapter.

2

CHAPTER (3)

PROCESS PLANNING, MACHINE TOOL SELECTION AND GROUP TECHNOLOGY

3.1. INTRODUCTION

In the past the activities of process planning and machine tool selection have been regarded as mystical arts, the only apparent method of assimilating the skills being by the osmotic relationship of master and apprentice. In reality of course a knowledge of past history or hindsight is a great teacher, it is not however, always the best guide to the specification of machines, tooling and systems, in an age when the development of all these is progressing at a hitherto unknown rate. In this chapter the author will attempt to treat these topics within the framework of Numerically Controlled Metalcutting machines, in a relatively scientific manner. The reader should be aware however, that there are no simple general solutions. The author can, at best, relay the areas of concern, point to possible directions of investigation and supply general tools for the analysis of the very specific problems which occur in various individual industrial settings.

In general an overall view of the productivity of N.C. machines within an industrial enterprise must examine the following:

a) In cycle machine productivity.

b) The reasons for machine time spent out of cycle, (set ups, measurement, maintenance, lack of work etc.

c) The efficiency of use of staff resources, (programmers, tool and manufacturing engineers, supervision etc), all of whom influence the overhead cost of the metal cutting machines.

d) The flexibility of the production units. This is a complex question since one is interested, not only in whether it is possible to accommodate new designs or products but primarily one is concerned with the variation in costs with product mix, total volume and individual batch size. Having the theoretical capacity for change, is of no benefit if the costs incurred following change are not competitive. (Moreover since one inevitably pays a price for flexibility in either machine purchase price or in less efficiency for each specific group of parts, then it is obviously of great importance to assess this factor carefully).

A realistic evaluation of the factors described above cannot be had without input from a wide ranging cross section of interests within a particular company. Typically the following would be involved,

a) Design engineering

b) Production, inventory control

c) Production engineering, (machine tool purchase, process planning, tool design).

d) Computer systems, (programming and systems CAD/CAM).

e) Shop supervision

f) Marketing

g) Quality control

In addition if large projects are considered then it is obviously necessary to involve the financial planners. Not surprisingly then, since in reality the production floor represents the major contribution to the wealth of most companies, any fundamental changes there must be supported by and communicated to almost every sector of the company, if it is to be successful. The manufacturing engineer or facilities planner who does not both actively seek this input and communicate required changes to the various other departments will likely regret his lack of action. New equipment, methods or tooling are not personal "toys" but hard earned assets which must be appreciated by all areas of the company if they are to be exploited for total economic benefit.

In order to undertake an integrated study of a production system one must set up guidelines in order to examine the potential gains to be extracted from all areas within the company. At the risk, of overstressing the point, the author will again stress the importance of not working in a vacuum and assuming that the only influence of increased automation is the decrease in direct labour cost associated with an increase in machine capability and cost. An "optimum" selected on this basis with no regard for the influences on other factors will, inevitably, be useless information.

One of the most useful tools in structuring an integrated approach to the problem in a typical low batch size environment is Group Technology. Since most of Canadian industry suffers from a lack of competetiveness due to a lack of scale then the author will describe this concept in some detail before continuing to examine its applicability to the specific task in hand.

3.2. GROUP TECHNOLOGY

The formal concept of group technology is commonly attributed to Soviet workers.

In the Western World and particularly within machine oriented activities much credit must also be given to Opitz and his fellow workers at Aachen, (see Bibliography) who pioneered the development of coding systems. There are many advocates however who point to implementations which considerably predate any formal research in this area and this is natural since the basic concepts underlying group technology are fairly simple. Unfortunately the term Group Technology has many connotations and because of the wide ranging list of publications much of the simplistic elegance of the concept has been lost. In the simplest terms Group Technology attempts to gain the advantages of mass production in a small batch environment, by either the grouping of parts into families of similar components, or the design of production systems which are more tolerant and flexible with regard to differences in product geometry. In essence when faced with a problem such as high set up times one may either take a mechanistic view and optimize the resulting costs or one may be creative and examine ways to avoid such costs and the complexity of attempting to schedule economic batch quantities. Extensions of the approach to the formation of working groups and the developments in coding systems to aid in both design and production bring other advantages. However, the author will first describe the primary goal.

3.2.1. Decreased set up and Increased Automation

In dealing with mechanical automation, it is found, in general that increased automation of a single machine leads to the following

a) Reduced piece run times

b) Increased setting times between batches of dissimilar parts

c) Increased capital costs

Ignoring for the moment the fact that automation will increase machine cost (and indeed that it will usually have a detrimental influence on up-time), then the choice of level of automation may be made by simply examining the relationship between time/component and batch size, (the reader will, no doubt, realize that what one is really doing here is finding RT and assuming that K = 1 and Y = 0 (See Chapter (1)).

In the typical case on will arrive at curves which resemble those in figure (3.1), for three levels of automation

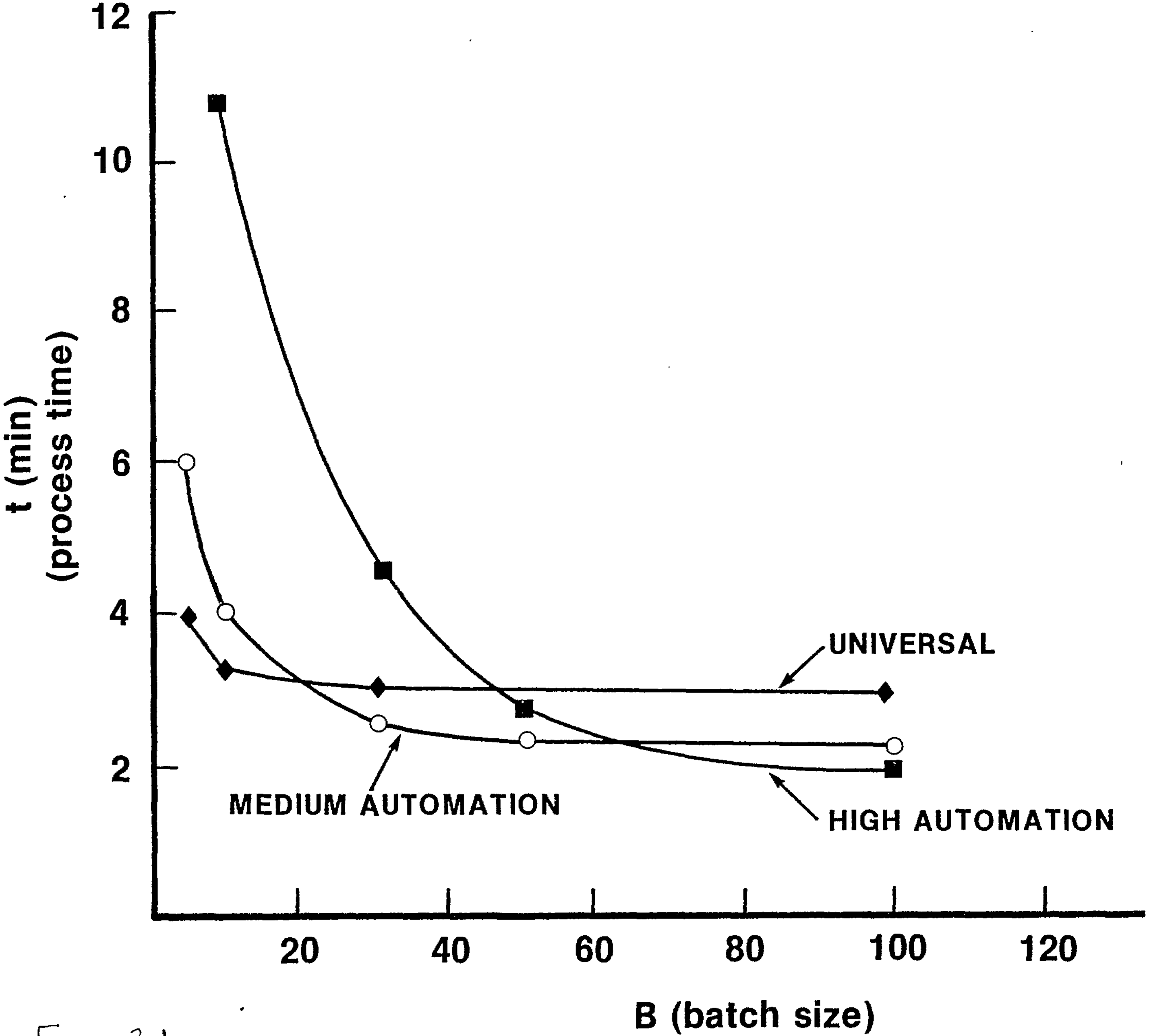

t (min)
(process time)
12
10
8
6
4
2
20
40
60
80
100
120
B (batch size)
UNIVERSAL
MEDIUM AUTOMATION
HIGH AUTOMATION

Fig. 3.1

114-A

The curves shown in figure (3.1), illustrate the problem which is twofold.

a) An increasing batch size leads to decreased costs on each machine.

b) A company with low batch sizes is at an even larger disadvantage since, even if these may be increased by various inventory strategies, they will still not likely be able to justify the more highly automated equipment and hence be at a considerable disadvantage.

Consider now the case where a small scale manufacturer adopts the technique of grouping similar parts and succeeds in reducing his set up time by 60%, (a not uncommon occurrence). If that manufacturer now performs the same analysis again the scenario depicted in figure (3.2) results.

Considering now two specific cases:

a) Low volume manufacturer has average batch size of 10.

His initial cost using a universal machine is $3.50.

His cost after part grouping is $2.80 using the mid level of automation.

Competitive companies not using G.T. need an average batch quantity of 25 to be comparable.

i.e. he is able to compete with other suppliers where volume is up to 2 1/2 times his own.

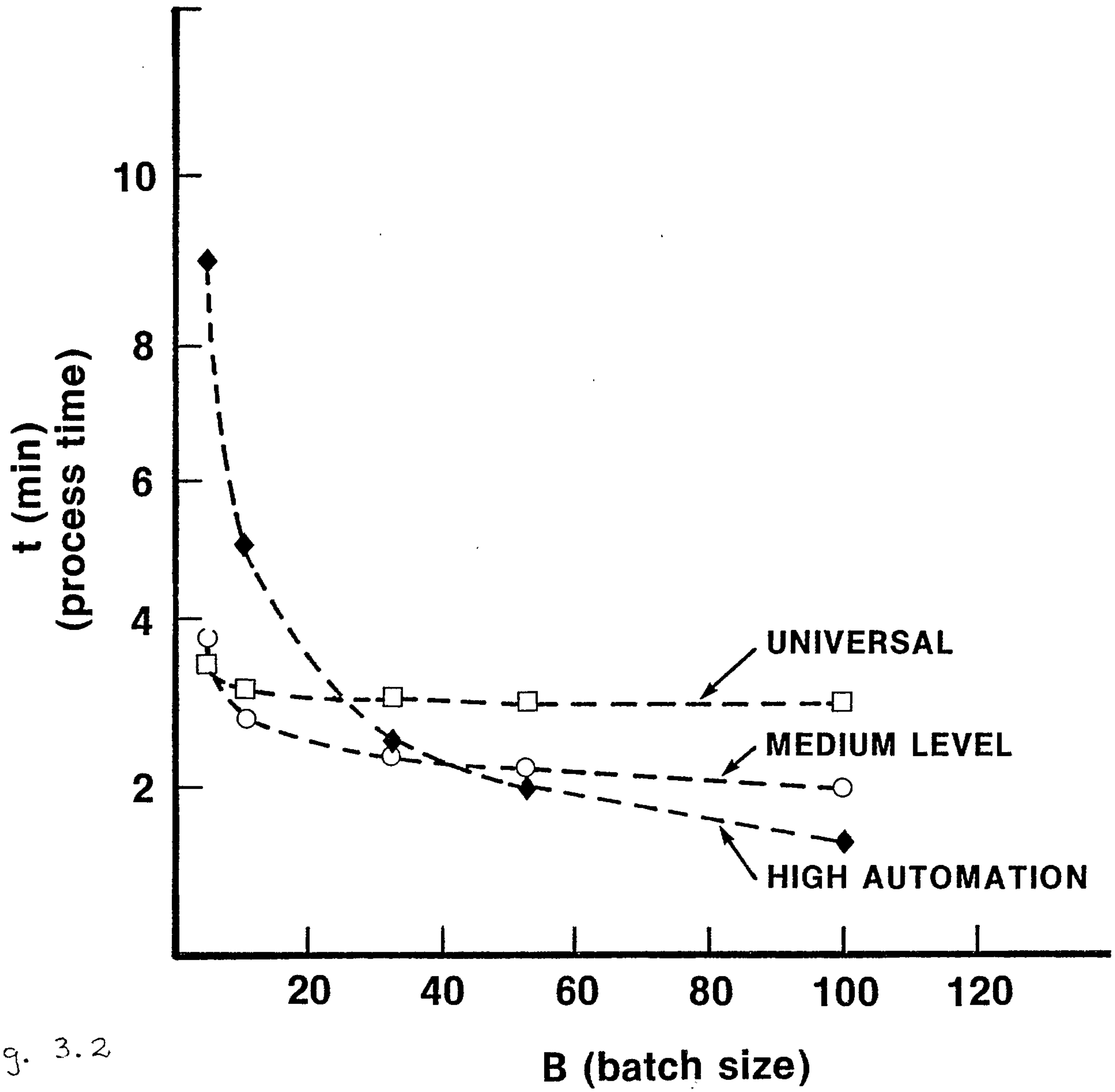

t (min)
(process time)
10
8
6
4
2
UNIVERSAL
MEDIUM LEVEL
HIGH AUTOMATION
20
40
60
80
100
120
B (batch size)

Fig. 3.2

115-A

b) Low volume manufacturer has an average batch size of 50. His initial cost using a machine of medium automation is $2.40. His final cost is $2.00.

This cost is comparable with another manufacturer with double the volume.

The reader will realize that the arguments presented thus far are simplistic. The arguments presume that parts may be grouped in such a way that innovative tooling and fixturing may be developed to handle a range or family of parts, the adjustments which need to be carried out between batches have been either eliminated or facilitated. Such approaches have been repeatedly reported in the literature. In considering the specific case of N.C. machines however one must take into account that such machines already mitigate, to some extent, the set up elements involved with mechanical automation.

N.C. machines, given a part correctly located and held, a proven part program and the necessary tooling obviate the necessity of making adjustments to the machine to suit the particular part being machined. The procedures to achieve this are now coded on the control tape. The requirements then to assemble a part family are considerably different and certainly less related to overall part geometry. On the other hand the part programming process cost is related to the similarity between the various parts particularly if "macros" are to be heavily used. A detailed discussion of these factors is included in a following section, the author will continue to address some of the other known advantages which may arise as the result of applying group technology.

3.2.2. Machine Tool Groupings

In addition to forming families of parts, it is usual in the application of Group Technology, to group the productive equipment into "cells", each cell having the capability to completely process a given part family. Indeed it has been suggested that in many cases a more convenient manner of approaching Group Technology is the identification of machine cells first, from routing sheets, then the formation of families from those parts which are accommodated on the machines. There is certainly much to recommend this procedure, particularly if the process planning has been done well in the first place. Interested readers may consult the bibliography for further reading on this technique (production flow analysis) and other approaches to Group Technology.

The advantages of grouping machines are many, the main advantages are listed below:

a) The machines may, in essence be operated as a mixed model flow line, ie batch splitting between machines is allowable, resulting in a large decrease in work in process inventory.

b) The problems of machine loading and scheduling are much reduced when considering a number of autonomous cells as opposed to a large plant. The practical result is more timely information and much shorter planning periods

c) The relative uniformity of methods which result should allow greater labour flexibility and utilization.

d) There is a definite responsibility for quality, timeliness and cost.

e) There are also obviously many sociological consequences which result from the group working environment which are outside the scope of this section.

f) Each machine, because of the need for less flexibility may usually be made more productive for the particular family of parts under consideration.

3.2.3. Relevance of Group Technology Practices to Numerically Controlled Machine Tools

Group technology had as its primary aims the reduction in set up times and work in process inventory, through the grouping of parts and machines respectively. Such a technique had particular importance when metal cutting machines had a relatively limited range of application in terms of the processes and physical component shapes they could accommodate. As mentioned earlier, an N.C. machine does to a large extent remove the importance of shape as a production characteristic. Physical size, weight and disposition of material are however, still important. Moreover the development of both N.C. machines and tooling has lead to the point where a single machining center may perform the complete variety of tasks that a group of milling machines, drilling machines, vertical turning lathes and grinding machines would have been required for two decades ago. To some extent then one may regard the single N.C. machine as a group technology cell, in many cases a single part being completely processed in a single set up, certainly the number of set ups may be drastically reduced. The numerically controlled machine then brings the opportunity of gaining many of the advantages of Group Technology. In order to capture these benefits the user must adopt more flexible attitudes to process planning, tooling and fixture design. In many cases sacrifices must be made in the productivity of individual operations in order to allow the processing of several features in a single set up.

Despite the comments made to this point Group Technology still has a role to play in the utilization of N.C. machines. In the following sections the role of Group Technology in the following areas will be highlighted.

a) Process Planning and tool design.

b) N.C. Programming

c) Machine tool specification and purchase.

3.3. PROCESS PLANNING, FIXTURING AND TOOLING

3.3.1. Introduction

The process planning function, in simplest terms, consists of the specification of the processes required and their order from a consideration of the drawing information, (or CAD database). Fairly obviously the process is hierarchical in nature, table (3.1), below shows the various principal levels which must be covered in most cases.

LEVEL	PROCESS PLANNING FUNCTIONS
HIGH	Selection of Basic Processes and sequence
	Selection of specific machines and order
	Design of holding devices, approximate ordering of main operations at each machine
	Subdivision of operations, detailed operation order selection of tool types
LOW	Optimization of cutting conditions and tools
N.C. PROGRAMMING	Detailed evaluation of tool paths Cost estimating

Table 3.1.

The hierarchical nature of the planning problem creates significant problems. Fairly obviously, if one is planning, without prior experience of similar parts, then decisions at the higher levels which must be made first are made in ignorance of detailed problems which will occur later. For instance it may be found impossible to accommodate adequate fixturing to perform the operations envisioned, there may be unforeseen tooling problems or, the required tooling may be inordinately expensive or, the mode of process planning may be lead to a significant overload on a particular machine tool. Such problems inevitably result in having to proceed back to a higher level in the decision process and start again. After some experience with each type of part and the machinery available, the process planner will tend to avoid such problems at the higher levels and fewer parts will require replanning.

The considerations covered to this point indicate that there are two basic approaches to the process planning problem, these are as follows:

a) <u>Generative</u>

In this scheme the planner attempts to use logic at each level to produce a good feasible plan at the lower level.

b) <u>Variant</u>

In this case the planner will essentially follow a fixed set of rules which have been developed by experience on parts which are similar from a manufacturing point of view ie they are members of a production part family.

Both approaches have advantages, however, the following points should be borne in mind.

1) The variant technique, whilst useful at the higher levels of planning, has little benefit in the detailed operation planning phases where normally one is interested in generating an optimal solution for each specific part.

2) There is the possibility of preventing evolution let alone a revolution in manufacturing methods if the variant system is adopted. On the other hand should one continue to examine part family production plans for further improvement, then following the identification of significant gains, these may be applied to all components in the particular part family.

3) The use of purely generative techniques unless limited by practical constraints will lead to the adoption of differing methods for relatively small gains on similar parts. It should be

remembered that tooling, fixture and set up costs comprise a large portion of the total, hence a uniformity of approach may reduce these costs over the whole spectrum of parts whereas on a part by part basis a generative approach will not recognize this.

Over the past decade attempts have been made to integrate the CAD/CAM process, the subject of process planning is evidently the key to any such integration. For this reason considerable efforts have been applied to the development of Computer Aided Process Planning (CAPP) systems. Such systems understandably tend to utilize both the variant and generative techniques, the main difference between the various systems being the level of application of the generative approach. In the author's opinion, there is still considerable scope for an extension of the range of applicability of the generative approach. Bearing in mind however the points made earlier it will be unwise to pursue such an approach at the very highest levels. The author will now continue to examine the generation of process plans. In order to be reasonably specific, this approach will be demonstrated with respect to machining center work.

3.3.2. The Generation of Good Low Level Process Plans

The lowest level, which occurs usually within the N.C. programmers area of responsibility, is that of cutting a specific volumetric element of given width, depth and length. This problem is essentially the machining economics problem which was treated in the previous chapter.

It is to be expected that programmers will have at their disposal feed and speed information to produce realistic tool life values for the work tool combinations in question. In this case then the approximate costs of performing the operation are also available at this stage, (provided one knows, the tool cost and machine overhead rate). In order to be specific tables (3.2) and (3.3) show approximate machining conditions and costs respectively for rough milling a simple shoulder or face. The reader should note that in this case the recommended cutter diameter for each combination of width and depth has been specified. In many cases of course several different cutters may be used for each shoulder should that be economically viable.

It may also be noted that, if these tables are to be useful then a considerable amount of analysis will be required to ensure their accuracy. Again readers, with this in mind should consult the bibliography.

The next level of the problem concerns the subdivision of the total volume to be cut into individual volumes. To be specific consider the simple workpiece shown in figure (3.3), below:

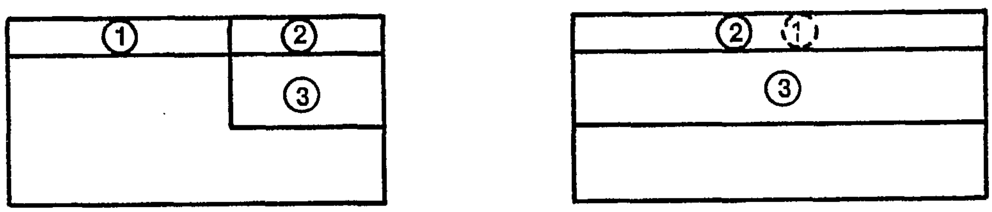


Figure 3.3

As may be seen the part requires two operations, face milling and shoulder milling. However, of course the cost of performing either one of these operations is dependent on the order of machining since each one will reduce the volume taken by the second operation. In fact from an analysis point of view it is preferable to view the problem as that of removing three elemental volumes. The problem thus phrased may be thought of as shown below in table (3.2)

<u>Elemental Volumes</u>

Combined Volumes	V_1	V_2	V_3	COST
S_1	x			
S_2		x		
S_3			x	
S_4	x	x		
S_5		x	x	

Table 3.2

2

Radial Width (Inch)	0.125	0.25	0.5	1.00	1.50	2.00	0.500
Axial Depth (Inch)							0.5" dia, 4 teeth, 1100 RPM Slotting
0.125	.22	18	18	15	10	10	18
	(0.5" Dia, 4 Teeth) (1100 RPM)						
0.25	20	17	14	14	10	10	12
			(1.00" Dia, 6 Teeth) (500 RPM)		(2.00" Dia, 8 teeth) (220 RPM)		
0.50	16	14	12	12	9	9	7

TABLE (3.2) Approximate Feedrates (IPM)
M2 HSS Endmills Cutting Steel (250 BHN)
Rigid Workpiece and Machine

Radial Width (Inch)	0.125	0.25	0.5	1.00	1.50	2.00	0.5
Axial Depth (Inch) 0.125	CL=0.0455 CV=2.91 [0.50"Dia]	CL=0.0556 CV=1.778	CL=0.0556 Cv=0.889	CL=0.0667 CV=0.533	CL=0.100 CV=0.533	CL=0.100 CV=0.400	.05"dia, slotting CL=0.0556 CV=0.533
0.25	CL=0.050 CV=1.60	CL=0.0588 CV=0.941	CL=0.0714 CV=0.571	CL=0.0714 CV=0.286 [1.00" Dia]	CL=0.100 CV=0.267	CL=0.100 CV=0.200 [2.00" Dia]	CL=0.0833 CV=0.667
0.50	CL=0.063 CV=1.00	CL=0.0714 CV=0.571	CL=0.0833 CV=0.333	CL=0.0833 CV=0.167	CL=0.111 CV=0.148	CL=0.111 CV=0.111	CL=0.143 CV=0.571

Approximate Values

$$\text{Cost/Unit Length} = \frac{CL \cdot (x)}{(1-\alpha)} \ \$/\text{inch}$$

$$\text{Cost/Unit Volume} = \frac{CV \cdot (x)}{(1-\alpha)} \ \$/\text{inch}^3$$

x - machine overhead rate \$/min.

α - exponent in Taylor equ.

$\alpha \doteq 0.5$

TABLE (3.3)
Cost indices corresponding to machining information in Table (3.2), (M2 end mills/250 BHN Steel)

NB The results obtained will be approximate, the approach assumes that the total cost of machining is in direct ratio to the machining time. This is only true if the cutting conditions are close to optimal and no power constraints are evident. Such assumptions do, however, lead to a considerable decrease in data requirements. Interested readers are directed to ref:(1.4.8) in the bibliography for more details

A solution to the problem shown above is a set of combined volumes (s(i)) such that each elemental volume is cut once and only once. Fairly obviously the strategy will be to determine which choice of the combined volumes constitutes the lowest cost solution.

Now in practice the problem may be reduced in complexity when one realizes that one must consider the possibility of taking several cuts to remove any one particular volume. Considering figure (3.3) again it is seen that the individual volume element V2 does not have as boundaries any finished machined face.

As a result V2 does not have to be considered as a separate volume element, it will always be combined with either V1 or V3. If then the method of subdividing either one of the compound volumes (V1+V2), (V2+V3) leads to V2 being cut as a separate element, then V2 will be cut as a separate volume, if not it doesn't matter. The problem then may be reduced in size, this reduction in many cases may be significant, in the case considered earlier the result is as shown below:

Elemental Volumes

Combined Volumes		V_1	V_2	V_3	COST
	S_1	x			
	S_2			x	
	S_3	x	x		
	S_4		x	x	

In this case it is easy to see that there are only two feasible solutions, which correspond in fact to the two operations mentioned earlier i.e.

a) S1 + S4

b) S2 + S3

In the general case many combinations of volumes will exist and a method of determining a good feasible solution must be specified. In practice this procedure may be performed using the heuristic solution method described below. (The reader should realize that in most cases the process planner will ignore some of the combinations, knowing that in fact they will not be selected, this is demonstrated in the example following the description of the solution method).

<u>General Solution Method</u>

a) Arrange the unit volumes and combinations as shown in Table (3.4).

b) Select the combined volume with the lowest relative cost per volume (Cv) and assign.

c) Delete from further consideration all combined volumes which contain any individual volume elements already assigned.

d) Repeat b) and c) until all volume elements are assigned.

e) Select the order of volume removal so that tool change and idle positioning time is minimized.

The solution obtained will always be feasible and will represent a good solution although it is not guaranteed to be optimal. The algorithm works well because, in fact, the value of Cv decreases with increasing volume. The initial elements selected then are not only the lowest cost elements but are also the major elements of our total cost.

The procedure will be demonstrated with a simple example. The component is shown below figure (3.4), and the resulting volume elements are shown in figure (3.5).

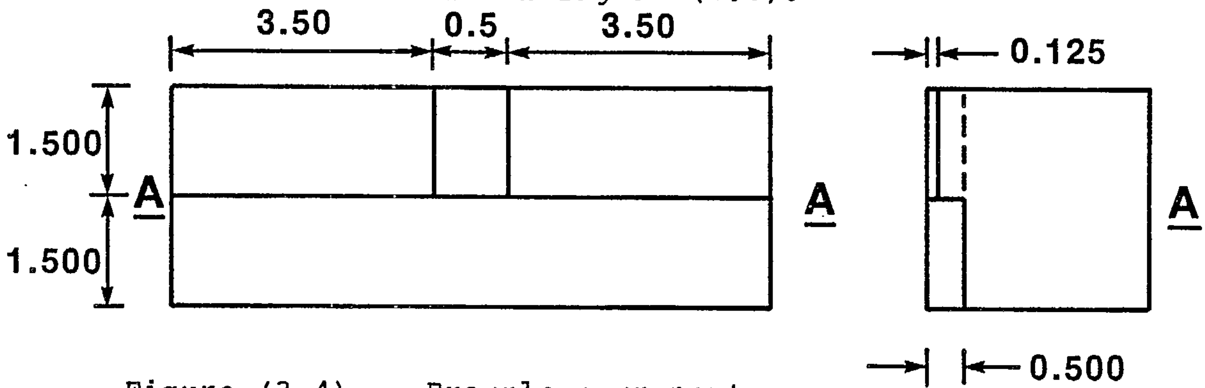


Figure (3.4) Example component

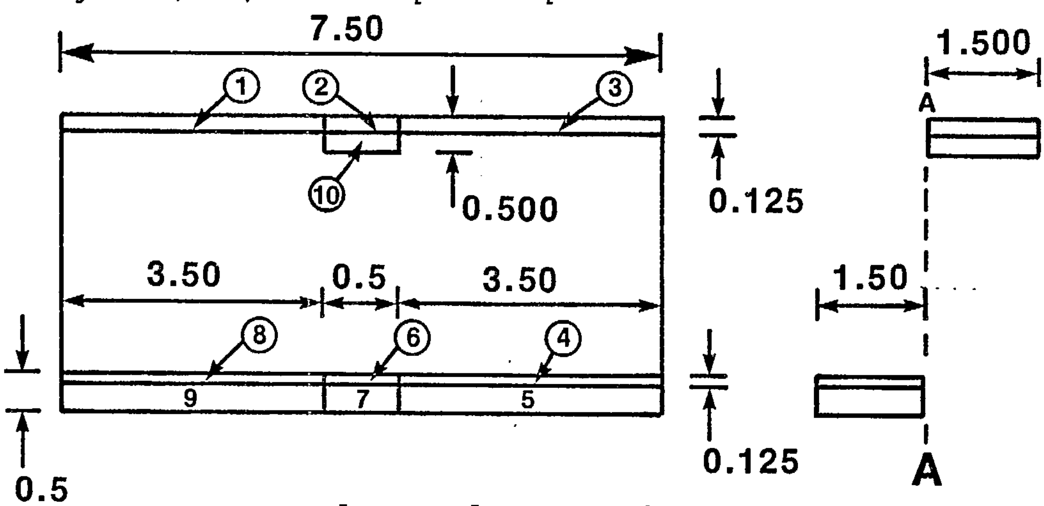


Figure 3.5. Volume elements with component split along Line A-A for Clarity

Likely candidates for combined volumes are shown in table (3.5) below together with selected tools and costs

Volume/Tool	a	d	L_{EFF}	CL	REL COST	REL COST/ VOL
1÷2÷3-4-6÷8/4" Carbide Face Mill	0.125	3	12	0.15	1.8	0.6
9÷7÷5/2" End Mill	0.375	1.5	10	0.105	1.05	0.233
10 /1" End Mill	0.375	1	2.5	0.077	0.193	0.343
4÷5÷6÷7÷8÷9/2" End Mill	0.5	1.5	10	0.11	1.11	0.185
1÷2÷3/2" End Mill	0.125	1.5	10	0.1	1.00	0.667

Table (3.5) Combined volumes and costs

Several points should be noticed from table (3.5). The problem has in fact been must simplified by discarding several feasible combined volumes which are obviously disadvantages. For example one might have considered the combined volume

$$Vx = V2 + V10$$

The cost of cutting Vx is higher than cutting V10 alone hence if it is to be considered then the additional cost concurred by cutting V2 must be compensated when V1 + V3 is cut instead of V1+V2+V3, evidently with the diameter of cutter used one may not achieve an advantage by doing this. The same logic applies when it was decided to ignore the following volumes:

$$Vy = V10+V7$$

$$Vz = V10+V7+V2+V6$$

By utilizing this simple approach the total problem is much reduced and of course no opportunities for cost reduction are lost in the process. The final problem is now represented by the matrix in table (3.6).

Combined Unit	1	2	3	4	5
1	x				x
2	x				x
3	x				x
4	x			x	
5		x		x	
6	x			x	
7		x		x	
8	x			x	
9		x		x	
10			x		
CV	0.6	0.233	0.343	0.185	0.667

Table (3.6) Resulting Problem

The solution now proceeds as laid out earlier:

1. V4 is selected
2. V2 and V1 are discarded
3. V3 is selected
4. V5 is selected.

From table (3.6) one sees that the total relative cost of the cutting portion of the operation is as follows:

C1 = cost(V4) + cost (V3) + cost V5

= 1.11 + 0.193 + 1.00 = 2.303

One may compare this, for the sake of completeness with the remaining feasible solution

C2 = cost (V1) + Cost (V2) + cost V3

= 1.8 + 1.05 + 0.193 = 3.043

The difference in cutting costs (tool and time) is considerable, again it should be realized that many worse solutions have been obviated by not including the corresponding combined volumes in the problem formulation. What is more, of course, good machining conditions and choice of cutter are available for all alternatives. Hence in practice the difference between the good solution obtained and other solutions may be much more marked.

The actual total costs corresponding to the two solutions may be estimated as shown below assuming a machine overhead rate of $0.5/min. It should also be noted that for the better solution the slot is machined last hence only two tool changes are used.

a) Better Solution ($\alpha \simeq 0.5$)

$$C = \frac{(2.303).(0.5)}{(0.5)} + (1.5).(0.5)+(0.5).(.5)+(3).(.5)$$

cutting time + idle motions + tool change+load/unload

i.e. C = $4.803

Assuming tool change = .25 min cut to cut

Load unload time = 3 min.

Other solution, (with same assumptions),

$$C = \frac{(3.043).(0.5)}{(0.5)} + (1.75).(0.5) + (0.75).(0.5) + (3).(.5)$$

C = $5.793

Thus the cost increase in going from the better solution to the next best is 20.6% a difference which can hardly be regarded as insignificant.

2

3.3.3. <u>The selection of Process and Machine sequence</u>

The methods described in the previous section, can in fact be extended to handle the next higher level of process planning. Unfortunately, however, as may be expected, the problem rapidly expands in size when it is realized that each specific volume may be accessed from several different directions on several different machine tools. Moreover the penalty cost associated with using additional set ups to accommodate more efficient processes are usually high enough to preclude such analyses. In this case then, despite the fact that the author is currently examining this problem and significant gains are to be expected in extending a generative approach to process planning to higher levels, the author will in this section merely indicate conventional wisdom rather than trying to explain more complex techniques which are still to be proven in a practical environment. The following would constitute a reasonable approach to such a problem.

a) Identify the individual process that must be performed and the minimum number of machine tools that may be used to perform the operations.

b) Deduce the sequencing of operations which will be required to meet functional specifications of tolerance and surface finish. Many of these requirements e.g. roughing all the major elements before any finishing is done or interposing stress relieving operations will normally have been identified previously on similar components and process specifications may well be available in house.

c) Arrange the groups of operations in sequence into set ups on individual machines. It must be endeavoured to achieve the maximum benefit from each set up. In order to do this at this stage, innovations in tooling and fixturing must be examined. Also the capabilities of each machine-tool must be carefully examined. One does not, for instance, wish to duplicate set ups on two similar machines because one has a particular feature which is desirable, one wishes to maximize the ratio of run time to set up time. This procedure may also be extended to examine new methods of producing specific elements e.g. the use of face mills with wiper inserts to replace grinding operations, the use of automatic back spot facers, roller burnishing tools, circular interpolation of bores on machining centres to avoid vertical turning lathe work and so on and so on. Whilst the process planner may regard such investigations as extreme, there is no doubt that experience gained with such considerations will yield gains on other new components as they come along.

d) Once part attitudes have been selected, the detailed fixture design must be completed. In many cases should the planner have attempted to be innovative to this point, the final fixture design process may be more prolonged, due to the fact that a detailed study of the forces and their direction may be required. This point becomes more and more important as the more innovative one becomes, the less conservative one is able to be in fixture design, hence the more calculations will be necessary.

e) The final phase corresponds to the problem described in the previous section.

The procedure just described is amenable to and normally simplified by the application of group technology. As was mentioned earlier however, one is not so concerned with detailed geometrical similarity but rather with grouping together parts which are similar in physical size and processing requirements. Once a grouping has been established, tooling and fixturing may be selected, hopefully, on a modular basis to accommodate the various configurations. In many cases outline part family work plans will also be developed, however, usually these will contain a fair amount of detail hence several plans may be required to accurately outline the required process. All will however, use similar techniques, fixtures and tooling. Such an approach will considerably reduce the cost of producing the individual components as well as reducing the lead time for programming and planning new components. Such an approach also enables new developments and innovative ideas to be applied simultaneously to the whole range of components if managed properly. The idea of standardization must not be to stifle evolution but rather to ease its introduction.

3.4. SELECTION OF MACHINE TOOLS

3.4.1. Introduction

In this section the author will attempt to describe in some detail the manner in which N.C. machines may be selected. The majority of the section will be devoted to machining centers both because of their increased complexity and the fact that they embody more potential for gain than lathes if utilized correctly. (It might also be borne in mind that, in the author's opinion the future will bring increased popularity to machining centers with significant turning capability)

In reality however, there are many similarities in the process undergone in machine selection, irregardless of the type of machine. These points will be covered before any specific machines are discussed.

The first point to be borne in mind is that one does not in general have a firm idea of either the type of machine or the required level of automation until a considerable amount of work has been carried out. This first phase of planning is the most important and time consuming and may be thought of as comprising the following steps.

a) The candidate parts, or a representative grouping are assembled.

b) The parts are subdivided into natural families.

c) For each family examine in detail the possible methods of production, rough sketch the required fixtures and list the tooling. Even at this stage attempts should be made to ensure wherever possible that standard items are used.

d) For each possible method on each group of parts estimate the run and set up times associated with a "base level" N.C. machine and attempt to quantify the savings which would result from higher levels of automation.

e) Catalogue carefully the required machine specification for each group. Such a specification should, for the base level machine, specify the following as a minimum:

1. Machine type and capacity, (traverse lengths, maximum part and fixture size and weight).

2. Spindle power, torque and speed range.

3. An approximate statement of machine accuracy.

   This should comprise as a minimum the following data:

   I Unidirectional Positioning Accuracy.

   II Lost Motion

   III An indication of alignment requirements particularly axis straightness and squareness at common working positions. Spindle runouts, both at the spindle flange and some distance away.

Specific machines will usually dictate which alignments are critical.

4. The planner should also request information on further levels of automation, e.g. tool changers, pallet shuttles or robotic loading, probing cycles, DNC links, rotary tables, head changers, etc. so that at the next stage a reasonable economic solution may be chosen.

f) Following receipt of the required information on capabilities and cost of the various alternatives, the planner must now examine the best machine or machines to carry out the task in hand. In most practical cases in Canadian industry,the volume of each group will not be sufficient to warrant dedicated machinery hence the planner, armed with more detailed information, must now merge his groups and modify methods with the minimum sacrifice in economics, till the machines selected are fully loaded. Again as much commonality in methods, tooling and fixturing must be aimed for. During this process which is both messy and iterative with constant communication back and forth with machine tool companies, the planner must assess carefully the preferred level of automation. This latter topic is of such importance that the author will devote the following section to its discussion. However, at the point at which the planner reaches this stage he will in all likelihood have narrowed his choice to a relatively low number of alternatives. The author would suggest this to be the ideal time to not only pay a preliminary visit to likely machine tool builders, but also a good time to visit as many possible similar installations to see in practice the problems which may arise.

g) The final stage in the process does of course involve the preparation of a purchase order specification. This task should be carried out very carefully. In essence, the buyer is writing a cheque. He will get only what is agreed to in the purchase order. At this stage also the planner must decide upon acceptance procedures. Different companies have different opinions on the manner of acceptance. The author strongly suggests that the following options are considered:

a) Witnessing of positioning and alignment testing at machine tool builder's plant.

b) Specification of a long term reliability test where all functions of the machine are actioned over a specific period of time. Any major failure being cause for the test to be restarted.

c) The cutting of specific parts in the builder's plant with required accuracies and run times. This latter procedure can become difficult since it will usually require use of the customer's parts, fixturing and tooling; if this is the case then the responsibility for failure to comply with specifications is sometimes difficult to assess.

d) In the case of problems with (c) above the planner may consider the witnessing of full power and torque tests together with finishing tests on prearranged test specimens available from the builder.

e) The repetition of all tests following installation in the customer's plant.

f) The training of operators, programmers and maintenance personnel prior to machine acceptance.

The procedure described is general and personnel involved in the selection process need the necessary skills to enable sound investment decisions to be made. The author strongly believes that most companies do not spend sufficient time weighing the real alternatives but instead concentrate their efforts on comparing the detailed differences between machine specifications from several builders, having made the initial decision as to type of machine by what may only be construed as a process of hopeful inspiration.

2

3.4.2. Required Level of Automation

Before progressing to examine strategies to increase the productive capacity of N.C. machines it is worthwhile to consider the approximate level of utilization of N.C. machines. Many surveys have been conducted of N.C. machine utilization and various figures are available in the literature. In the author's opinion the following table reflects the best average utilization that may be achieved on base level N.C. machines. It should be noted that the level of utilization will vary considerably, depending upon the specific environment.

IN Cut	CYCLE Positioning Tool Change	SET UP/ LOADING GAUGING	MAINTENANCE	NO WORK OR TOOLS OR PROGRAM	TECHNICAL PROBLEMS TAPE PROVE
18	25	22	15	10	10
(a)		(b)	(c)	(d)	(e)

Table (3.4) Typical Percentages of Time Utilization during Active Shifts, (Base Level N.C. Machines). Good Maintenance, scheduling and Production Practice.

Given that the table above represents good practice, then it seems that one must put up with the losses in productivity resulting from (c), (d) and (e) although as the reader will see later in this section, they may be impacted to some small extent. Evidently however, one should concentrate, in the first instance, on the in cycle losses and those due to set up, load and unload. These elements will now be examined in some detail.

a) <u>In Cycle losses</u>

The losses here are ascribable to three main elements listed in descending order of importance, (for typical parts machined on N.C. machines).

I Gauging
II Tool Change
III Idle Motions

The first area of gauging is probably one of most promising areas of improvement at the present time. The use of so called touch probes, developed at first for coordinate measuring machines but now used routinely on both lathes and machining centers means that many difficult time consuming measurement and calculation tasks may now be performed routinely. Such developments not only allow gauging of finished part dimensions, other uses which are being developed allow the assessment of stock removal and inclusion or exclusion of additional roughing passes, hence reducing the idle movements. Other applications involve the location of features such as cored holes and offsetting of program information to allow for the shifting of such features. Evidently then much progress has been made in this area, the use of such devices bring us one step closer to unmanned machining. At the same time one must be careful to have the facility to datum such devices or use other methods to ensure that machine tool inaccuracies are accounted for. Care must also be taken to ensure that surfaces are clear of chips. It should also be noted that some of the major elements of time consumption on N.C. machining centres such as resetting and retrieval of adjustable boring bars still remain as major manual elements. In light however, of the large gains available from probing systems prospective purchasers should pursue the adoption of such devices and ensure that the capability of controlling probe cycles is accommodated by the N.C. controller. Other N.C. users may well wish to assess the possibility of retrofitting such devices. In the final analysis of course, only an economic analysis will tell whether the increased programming effort and capital cost is justified. This is, however, one of the most promising areas of increased automation.

The subject of automatic tool changing is more complex than it would seem at first sight. Most machining center manufacturers include a tool changer as a standard item, whilst most lathe manufacturers tend to remain with turret type machines. It may be noted that there are exceptions, notably larger turret lathes where tooling is naturally heavy, have utilized tool changers for a considerable time and some manufacturers of lathes are offering unit tool change systems. In many cases, also machining centers which utilize a very large number of tools on each job and typically have small batch sizes, are often offered without the tool changer. (Horizontal boring mills being typical examples).

In practice the economic viability of a tool changer is determined by the number of times a specific tool is automatically changed into the spindle. Clearly there is little point in loading a tool changer if each tool is only loaded once into the spindle. One may as well load the individual tools directly into the spindle. Clearly also, the success of the tool changer is related not only to the batch size which determines the number of times an individual tool is used, but also to the accessibility and ease of loading both the spindle and the tool changer. Weight and size constraints imposed by the toolchanger are also critical in this regard. The reader should realize however, that economic gains are realizable in many instances as a result of standardization of methods. For instance a user with small batch sizes who has standardized his choice of milling cutters may leave the whole range of milling cutters set in the changer. For each individual part then only part specific tools such as tap drills and tapping heads, reamers, etc. would be loaded. It may also be viable to leave rough boring bars and common drill sizes in the changer. Such possibilities require a careful analysis of the frequency of usage of tools and a detailed investigation of tool changer size. It should also be remembered that should a company intend to pursue further automation, e.g. sparse manning or unmanned manufacturing then the use of tool changers, (either conventional or robotic) must usually be pursued.

Finally the reader should realize that in recent times many companies have developed tool changing devices which allow the changing of special tools such as cluster drilling heads, right angle and universal holders and probes, hence contributing greatly to machine flexibility and productivity without incurring significantly increased set up times.

Idle motions unfortunately comprise a reasonable proportion of the time irregardless of the parts machined. There are, however, many strategies available to reduce such idle times. These may be summarized as follows:

(I) Careful sequencing of operations and programming will lead to significant reductions.

(II) The use of rotary tables or multiple parts to allow as much use of a specific tool at one time is usually worth considering.

(III) The consideration of machines with higher rapid traverse systems. This latter alternative must be approached with care since the drive system and ways will always represent a compromise between stiffness, accuracy, damping, life, speed and cost. The machine tool user then must weigh all these factors in making his choice.

b) <u>Set up and Loading</u>

The remaining major factor to be considered is that of set up and part load/unload. The proportion of time involved in these activities will likely be the major non productive elements in most plants. The set up time comprises many different element, on a typical N.C. machine. The following elements may be considered.

I) Loading of tape and reading of information and drawings.

II) Presetting of tools and loading the tool changer if one is available.

III) Set up of fixturing and alignment with respect to machine tool.

Depending upon the system involved the load unload time may comprise many elements. At the lowest level it will involve positioning of the part in the fixture and clamping followed by release, removal of the part and clearing off of the fixture ready to accommodate the next part.

In general of course it is preferable to perform the majority of the set up external to the machine where overhead rates are lower and in most cases, due to the method of design of such facilities, the time required is generally less than that required on the productive machine. The real question is what level of automation should be applied to reducing such activities. Before this may be answered one must also consider that one may reduce the times involved in these activities by two means i.e.

1) The actual time involved in set up and loading may be decreased by automation.

2) The proportion of the time spent in such activities decreases as machine flexibility increases and less set ups are required.

It will be seen then that an increased flexibility in the machine tool will lead to a poorer economic case for increased automation. Typical methods of increasing flexibility involve the following:

a) The use of rotary tables.

b) The use of head changers or pivoting spindles to allow access to five faces of a workpiece.

c) The automation of auxiliary devices such as steady rests, tailstocks, etc.

d) The application of turning tables on machining centers or live spindles on lathes and vertical turning lathes.

As time progresses it may well become difficult to describe such multipurpose machines. The benefits which they bring are certainly significant in reducing idle time. Even in cases where machines are relatively flexible and the work is well planned, there will be advantages to automating the set up to some extent. The typical order of elements to be considered may be as follows:

a) Presetting of tools

b) Prefixturing of parts on pallets

c) Automatic pallet alignment on the machine.

d) Automatic pallet loading either through shuttles or robotic devices.

e) Buffer storage carrousels for parts and linking of machines.

The stages in hardware automation will normally be matched by software automation so that at the highest level the numerical control machine tape is distributed via DNC links and real time scheduling of the parts within the machine system is enacted. In the author's opinion, there are relatively few companies who will find the highest level of automation to be the most economical attractive, nevertheless it behoves the engineer to carefully examine each possible level of automation and the various economic factors influenced. It may be noted at the higher levels of automation significant savings in work in process inventory may be had by batch splitting between machines as indicated previously in this chapter.

3.5. CONCLUSIONS

In this chapter the author has outlined the major areas of concern in the selection and utilization of Numerically Controlled metal cutting machine tools. It is hoped that the reader is more fully aware of the possibilities available and better prepared to make realistic economic decisions. The author, purposely chose not to discuss some of the concepts which have high visibility at the current time. This applies particularly to Flexible Manufacturing Systems (FMS). Interested readers may consult the bibliography for further information. The author would, however, caution the reader not to fall into the trap of believing that such developments are universally useful. As pointed out by the author, the manufacturing engineer must examine all aspects of his system before any decisions may be made regarding either type of machines, machine flexibility or machine automation. The final economic analysis is the decision process, not current fashion. The engineer may use simplified analyses such as presented in chapter (1) to guide his progression, the final alternatives being compared according to individual company policy. The following appendix provides some examples of typical N.C. machines and their application as well as examples of new tooling developments.

2

APPENDIX (A)

EXAMPLES OF N.C. MACHINE UTILIZATION

A.1. INTRODUCTION

The intention of this Appendix is to give examples of some of the points covered in the body of the monograph. The author is deeply indebted to the companies credited for each figure. The comments relating to each figure are however, the author's own interpretation and responsibility.

A.2. TOOL PRESETTING AND WORKPIECE PALLETIZATION

Figure A.1. shows a typical optical tool presetter with digital readout of position on two axes. The presetter may be used with suitable attachments to set tools for most types of N.C. machine.

Figure A.2. shows a manually operated layout machine which may be used either to speed the layout process or for the accurate setting of parts on pallets prior to machining. As the reader will appreciate, this machine will significantly decrease the set up time at the machine tool provided a method of aligning the pallet on the machine table is available.

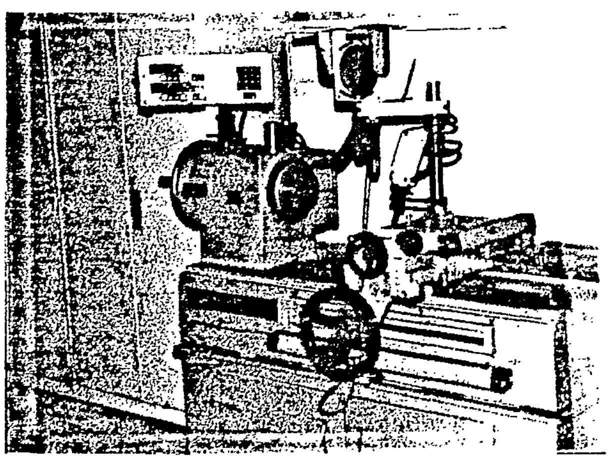
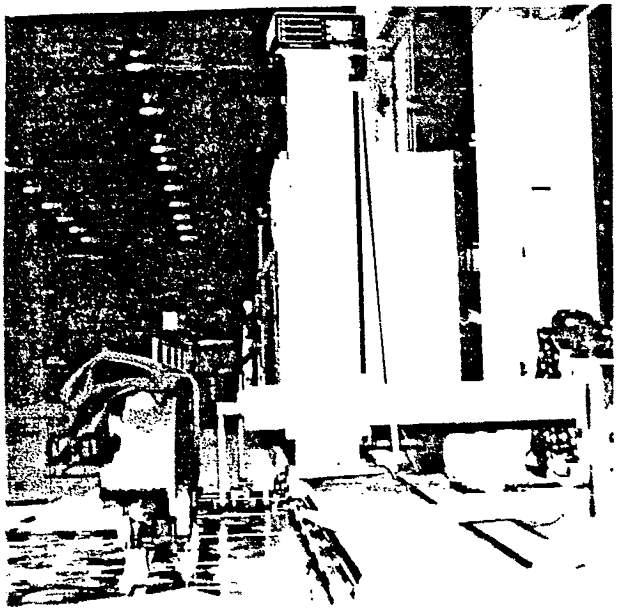


Figure A.1.

Tool Presetter

Figure A.2.

Component Layout Machine



Figures A.1. and A.2. courtesy of Westinghouse Canada

A.3. INCREASED FLEXIBILITY THROUGH THE USE OF ROTARY TABLES AND SWIVELING SPINDLES ON MACHINING CENTERS

The use of rotary tables and/or swiveling spindles not only allows complex geometries to be produced but also enables access to up to 5 sides of a workpiece. Such ability greatly reduces the proportion of time spent setting up the machine tool.

Figure A.3. shows a palletised component being machined on an N.C. Travelling Column Horizontal Boring Mill. In this case the machine has an independent W. axis on the table, as the component being machined has a close tolerance on parallelism of the two end faces then the table used incorporates wedges at the 90 deg. positions, thus enabling higher machining forces to be applied at these positions and much more accurate location than would normally be the case with a continuous rotary axis. The observant reader will also notice a heavy duty chain type tool changer on the far side of the machine column.

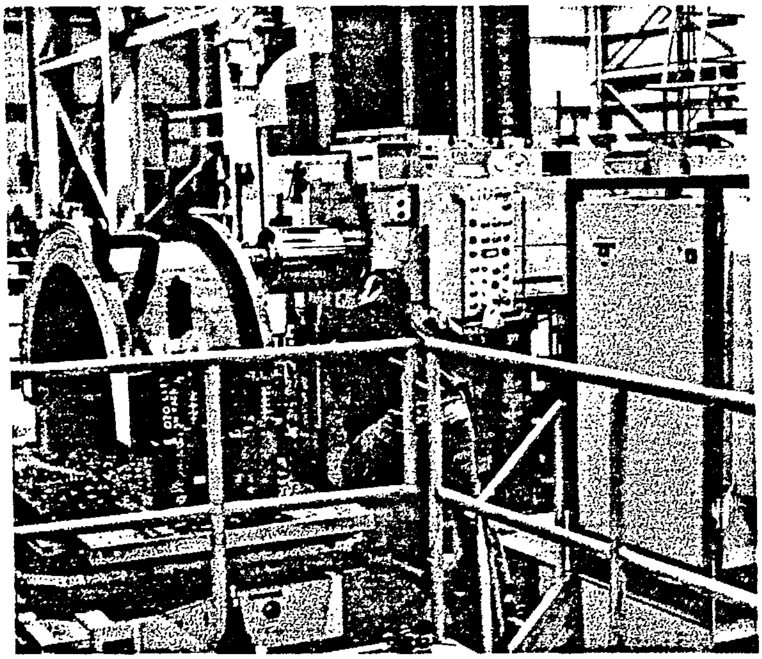


Figure A.3.
N.C. Horizontal Boring Mill (Travelling Column)
Photograph Courtesy of Westinghouse Canada

Figure A.4. shows the use of a rotary table to reduce tool positioning times and machine set up times on an N.C. Horizontal machining centre through the double loading of components.

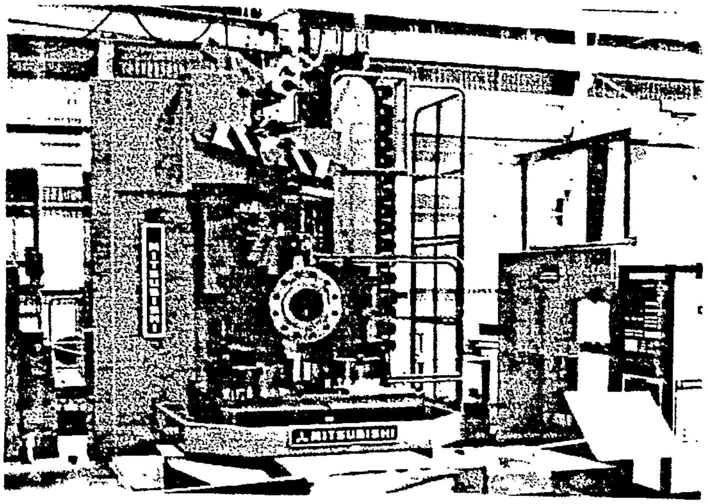
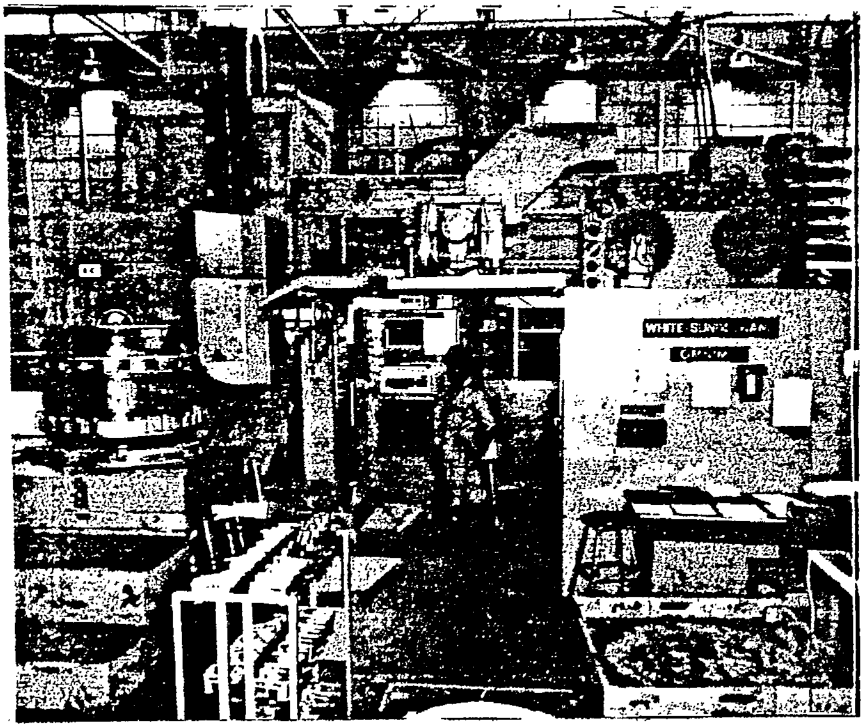
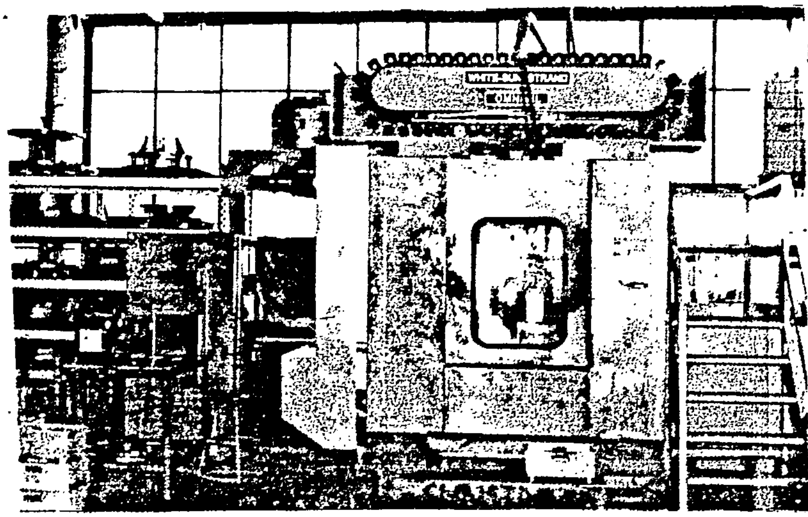


Figure A.4. Horizontal Machining Centre

Photograph Courtesy of Westinghouse Canada)

Figure A.5. shows various sizes and alternate arrangements of five axis N.C. machining centers, used in the manufacture of close tolerance complex mechanical components. In each case the spindle has effective access to five sides of the work and the machines are all equipped with high capacity tool changers.





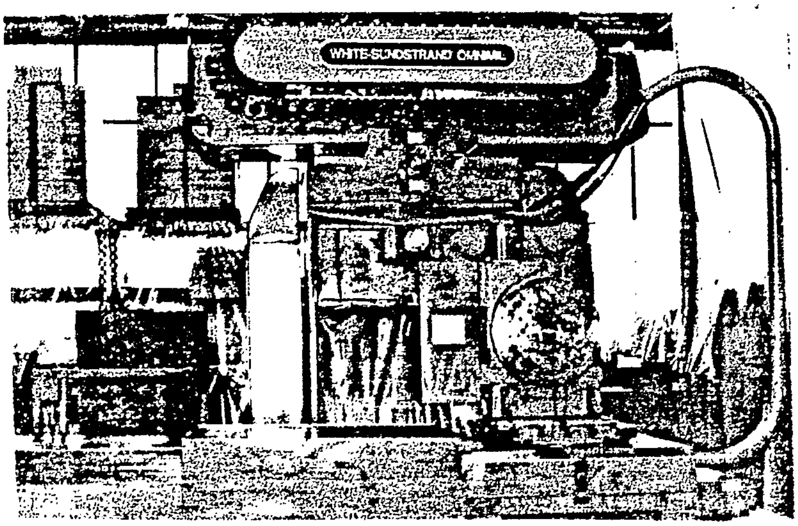


Figure A.5. 5 Axis N.C. Machining Centers

(Photographs courtesy of Bristol Aerospace)

A.4. THE USE OF INNOVATIVE HOLDING TECHNIQUES ON N.C. LATHES

In many cases the number of operations on a lathe may be reduced by the use of innovative holding devices. Figure A.6. shows a slant bed lathe equipped with program controlled tailstock and self centering steady. This configuration allows both internal and external operations to be performed in a single setting. Figure A.7. shows the use of a face driver on a relatively simple component. In many cases the use of this form of holding device will reduce loading time and preclude the need for a second set up with the component reversed in a conventional chuck.

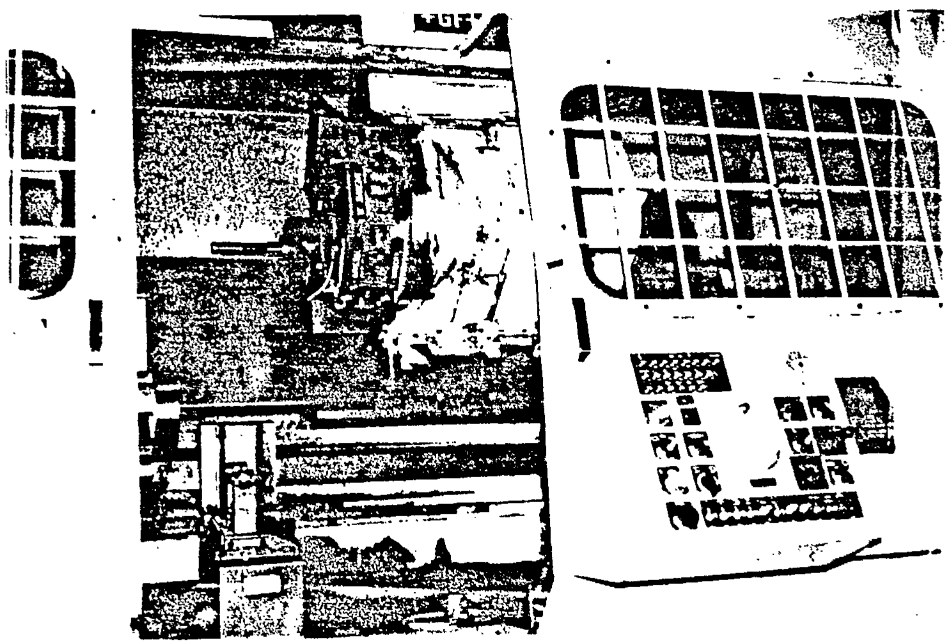


Figure (A.6.) Self Centering Steady

(Photograph courtesy Westinghouse Canada)

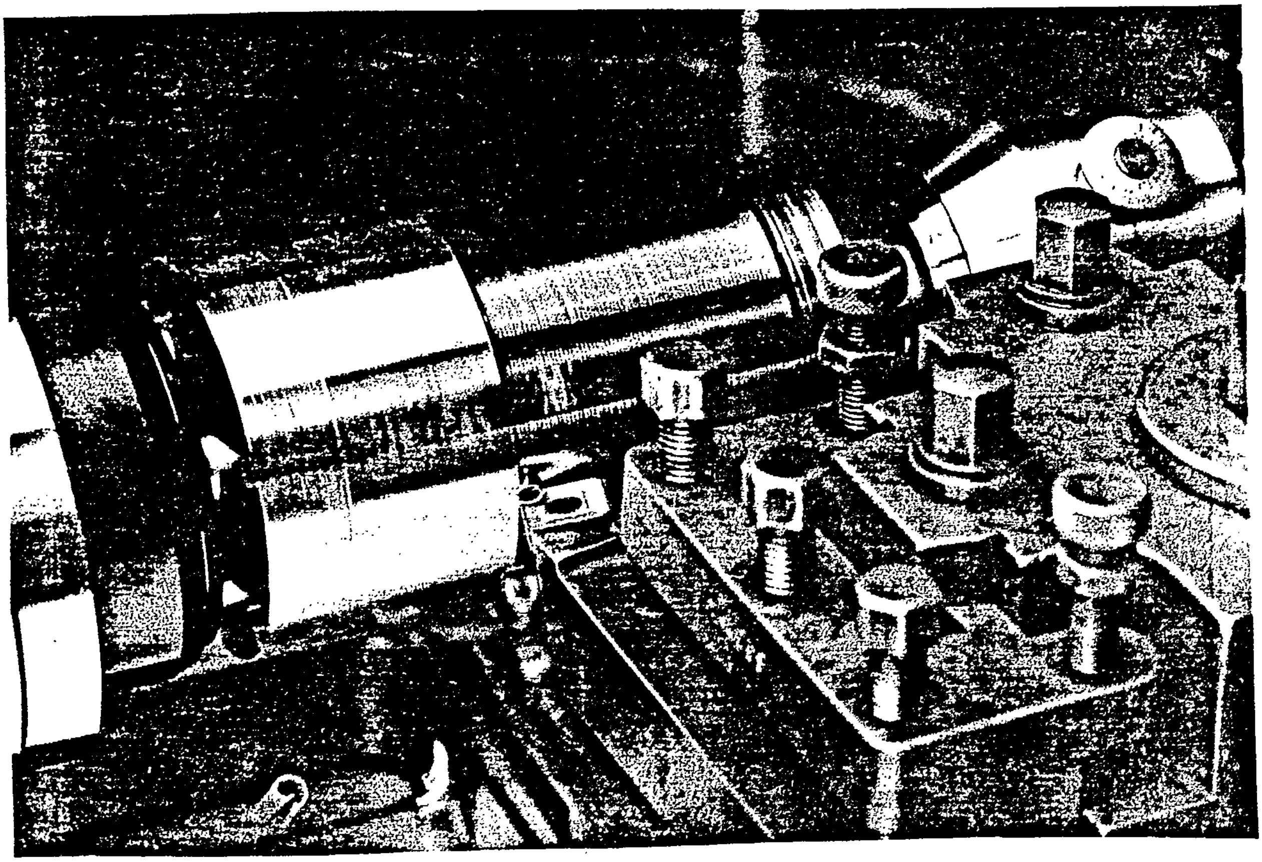


Figure (A.7) Face Driver

(Photograph courtesy Sandvik Canada)

A.5. THE USE OF AUTOMATIC TOOL CHANGE AND MEASURING PROBES ON N.C. LATHES

Measuring probes may be used to measure both component dimensions and tool offsets. Figure A.8. shows the use of a probe in the latter mode. The reader in this case should also notice the unit tool heads employed which may be exchanged automatically under program control. The body of the tool in the Sandvik block system will also accept probing heads to measure the workpiece.

Figure A.9. shows the application of exchangeable tooling on a four axis lathe, the component being driven between centers by a face driver. The reader should realize that the application of either three or four axis lathes will often bring significant economic gains through the possibility of overlapping cutting operations.

7.

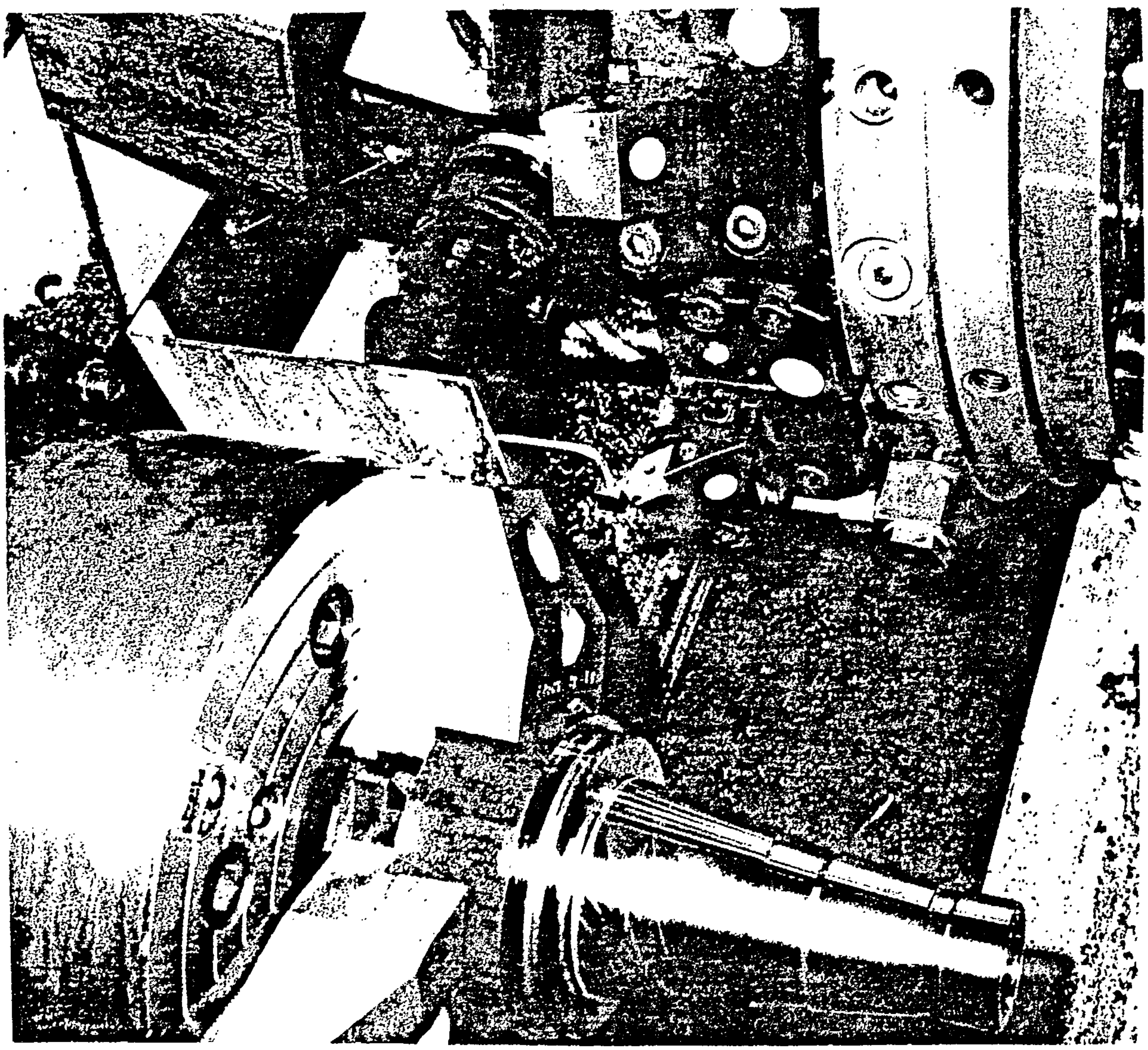


Figure A.8. Setting tool offsets with a Measuring Probe

(Photograph courtesy Sandvik Canada)

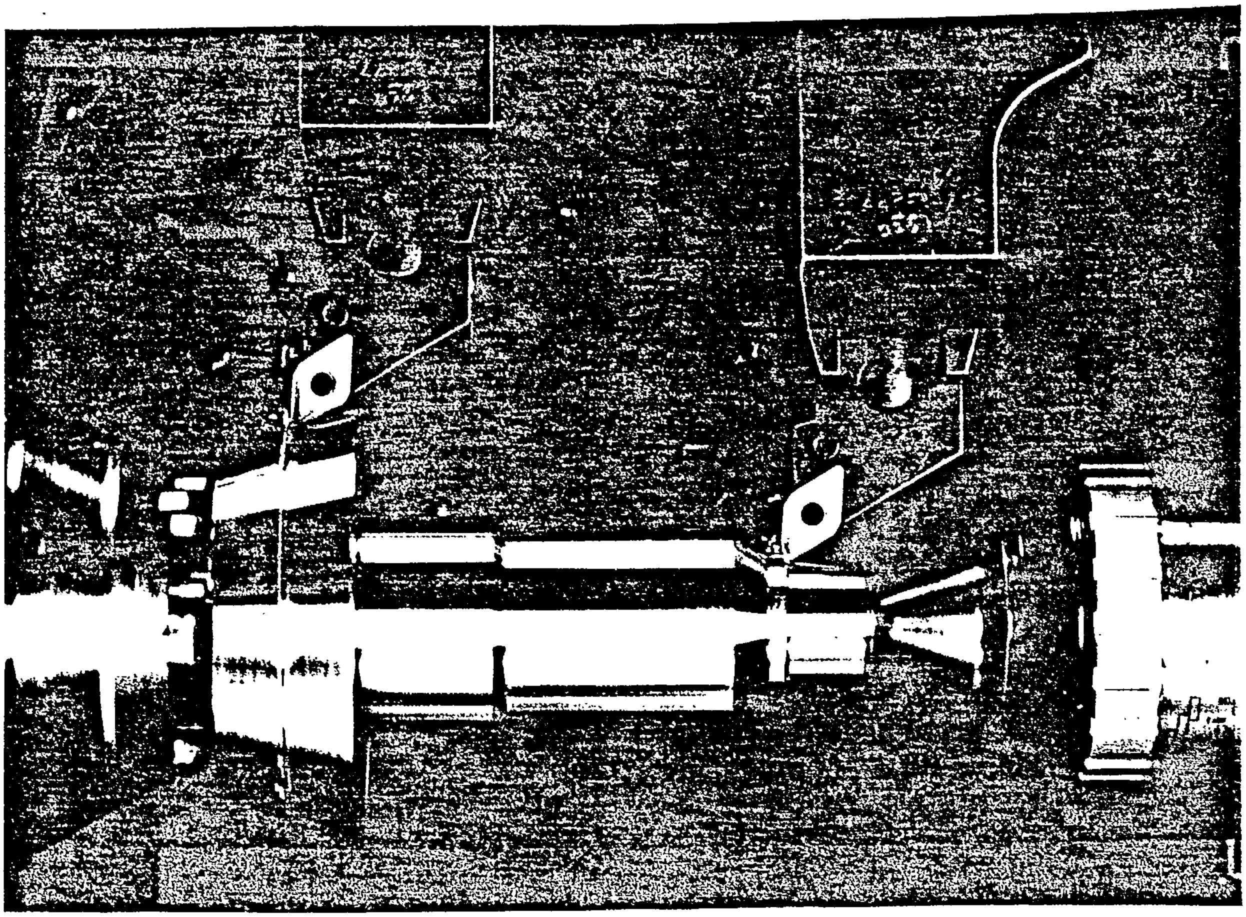


Figure A.9. The use of exchangeable Turning Tools and a Face Driver

(Photograph courtesy Sandvik Canada)

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INTRODUCTION

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There are many good sources of information which the reader will find available in most University Collections, the following two references however, are of such importance that the author has chosen to single them out from the remainder of the bibliography in the hope that those interested in this subject will acquire them for personal use.

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APPENDIX (B)

CAD/CAM MONOGRAPHS AND AUTHORS

Current Authors of the CAD/CAM Monograph Series

Monograph Number	Short Title	Author and Location
1	Introduction to CAD/CAM	(See note 1)
2	Economic Justification	
3	Computers, Graphics & CAD	M. Polis E.P./Mtl
4	CAD Analytical Techniques	J.R. Dickinson - UWO
5	Production, Material & Inventory Control	
6	Data base design, Group Technology	
7	NC Machine Tools	I. Yellowley - TUNS
8	Other NC Equipment	
9	Automated Testing & Inspection	
10A	Robots & Material Handling	P. Young - Hamilton
10B	Sensors & Robot Vision	H. Lowe - Pbo
11	Distributed Systems	D. Bonham - UNB
12	NC & Robot Programming Languages	
13	Project Management	(See note 2)
14	Systems Design & Integration F.M.S.	(See note 3)
15	Social Implications	
16	Applications	
16a	Automotive Industry	G. Prentice - Cam.
16b	Machinery & Equipment Mfg. Industry	S. Maclean - Cam.
16c	Aerospace Industry	R. Kunze - Cam.
16d	Electrical & Electronics Industry	G. Piri - Cam.
16e	Food & Beverage Industry	J. Williamson - Cam.
16f	Chemical & Plastics Industry	G. Prentice - Cam.
16g	Architecture & Construction	W. Bradley - Cam.
16h	Automated Warehousing	J. Williamson - Cam.
16i	Other	
17	Major & National Programs	

Abbreviations:
- E.P. - Ecole Polytechnique
- U.W.O. - University of Western Ontario
- TUNS - Technical University of Nova Scotia
- Pbo - Ontario Robotics Centre, Peterborough
- Cam - Ontario CAD/CAM Centre, Cambridge
- UNB - University of New Brunswick

Note 1 - The 1984 reprint "Computers in Industry", available from the Maclean Hunter Ltd. in Toronto provides a good general introduction to CAD/CAM technology. The Department of Regional Industrial Expansion will soon have available a reprint collection of approximately 30 published papers and articles on CAD/CAM technologies. This third reprint, for which members of the CAD/CAM council have assisted by reviewing and selecting appropriate material, will replace the DITC reprint #2 of 1981. The Maclean Hunter reprint mentioned above, together with this DRIE reprint #3, which provides more in-depth coverage than before, could be regarded as monograph #1, an "Introduction to CAD/CAM".

Note 2 - A doctoral thesis being undertaken by Ms. C.A. Beatty at the University of Western Ontario School of Business Administration is expected to also result in a report under the DRIE Technological Innovations Studies Program and possibly to be monograph #13.

Note 3 - Not surprisingly a count of the abstracts selected in 1983 shows that the highest CAD/CAM activity is in section 14 - 'Systems Design and Integration', including Flexible Manufacturing Systems. This suggests that a coordinated effort by more than one author in parallel, or a division into sub-sections would be warranted for the monograph(s) under this topic. Participation by a major user engaged in a system design study could be beneficial. Currently the following activity has come to attention.

- Ms. L. Quesnel, Department of Industrial Engineering at Ecole Polytechnique, has expressed interest in undertaking monograph #14, with emphasis on the simulation aspects of Flexible Manufacturing Systems.

- Prof. H.G. Wedderburn at Wilfrid Laurier University has proposed preparation of a monograph on Just in Time Production, particularly as applied to Flexible Manufacturing Systems.

- In addition, a report known as working paper #84-01 "Flexible Manufacturing Systems" by D. Gupta, S.P. Dutta and R.S. Lashkari is available from the Department of Industrial Engineering, University of Windsor.

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