COMPUTER AIDED OPTIMISATION OF CUTTING CONDITIONS IN MULTICUT TURNING OPERATIONS

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By
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ABSTRACT

COMPUTER AIDED OPTIMISATION OF CUTTING CONDITIONS IN MULTICUT TURNING OPERATIONS

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In this study, a computer program is developed for the optimisation of cutting conditions in turning operations such as; roughing, boring, facing, drilling, threading, grooving and parting-off.

By using minimum cost criterion as the objective function a direct search procedure is used for the optimisation of cutting conditions in turning operations namely; roughing, boring and facing. For the other operations which are drilling, threading, grooving and parting-off feasibility check methods are used for the optimisation of cutting conditions. The following costraints were considered in the optimisation: maximum and minimum depth of cuts and feeds for the tool and workpiece materials, maximum allowable tool force, holder strength and rigidity, spindle and feed-drive motors torque-speed characteristics, work holding limitations, deflection of the workpiece, geometrical accuracy, bearing design loads, cutting tool velocities, tool wear and surface roughness.

The program is written in Turbo C++ and CLIPPER programming languages on an IBM compatible personal computer. The use of the system is illustrated with practical examples.

Key Words: Metal cutting in turning, Optimisation, Cutting Conditions

ÖZET

BİLGİSAYAR YARDIMI İLE ÇOK PASOLU TORNALAMA İŞLEMLERİNDE KESME ŞARTLARININ OPTİMİZASYONU

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Bu çalışmada, kaba dış tornalama, boşaltma, alın tornalama, delme, diş açma, kanal açma ve kesme işlemlerinde kesme şartlarının optimizasyonu için bir bilgisayar programı geliştirilmiştir.

En az maliyet kriterini objektif fonksiyon olarak kullanıp, tarama metodu yardımı ile kaba dış tornalama, boşaltma ve alın tornalama işlemlerinde kesme şartlarının optimizasyonu yapılmıştır. Delme, diş açma, kesme-kanal açma işlemlerinde kesme şartlarının optimizasyonu için kısıtlayıcı kontrol metodları kullanılmıştır. Kesici-iş parçası malzemesi için kullanılabilecek maximum ve minimum talaş derinliği ve ilerleme oranları, kesici takım için maximum yük, tutucu için maximum yük, fener mili ve sürücü motorların tork-hız karakteristikleri, tutturma limitasyonları, parçanın sapması, parçanın toleransı, rulmanların dizayn yükleri, kesici takım hızları, kesici takım aşınması ve yüzey kalitesi kısıtlayıcılar olarak kullanılmıştır.

Program, IBM uyumlu bir kişisel bigisayarda Turbo C++ ve CLIPPER dilleri kullanılarak hazırlanmıştır. Programın kullanılışı pratik örneklerle gösterilmiştir.

Anahtar Kelimeler: Tornada talaş kaldırma, Optimizasyon, Kesme şartları.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

Item	Description
A	Constant for tool life equation
AVG	Avarage number of cutting edges per insert
B	Width of tool holder (mm)
C	Constant in tool-chip temperature equation
CAD	Computer Aided Design
CAPP	Computer Aided Process Planning
CAM	Computer Aided Manufacturing
C_T	Total machining cost (TL)
C_m	Constant in drilling moment equation
C_p	Constant in thrust force equation
C_v	Constant in drill tool life equation
CNC	Computer Numerical Control
D	Drill diameter (mm)
d	Depth of cut (mm)
d_1	Infeed for first pass (mm)
d_m	Mean diameter of thread (mm)
D_{eq}	Equivalent diameter of the drill (mm)
d_{maxt}	Maximum value of depth of cut for the tool-workpiece material (mm)

d_{mint}	Minimum value of depth of cut for the tool- workpice material (mm)
d_t	Total depth of the threat (mm)
e	Exponent in tool life equation
F_{bdload}	Bearing load (N)
F_{co}	Clamping force at zero speed (N)
F_c	Clamping force (N)
F_R	Resultant cutting force (N)
F_t, F_a, F_r	Tangential, feed and radial components of cutting force (N)
Ftmax	Maximum allowable force for the tool (N)
Ftp	Maximum allowable force for the tool holder (N)
Ftr	Maximum allowable force for the rigidity of the tool holder (N)
F_j	Clamping force exerted by each jaw of the chuck (N)
f	Feedrate for tool (mm/rev)
f_{maxt}	Maximum value of feed for the tool- workpiece material (mm/rev)
f_{mint}	Minimum value of feed for the tool- workpiece material (mm/rev)
f_{s1}, f_{s2}	Factors of safety for drill
K_1, K_2	Constants in tool-work temperature equation
L	Drill length (mm)
L_f	Free length of workpiece (mm)
l_g	Component gripped length (mm)
le	Cutting edge length (mm)
M	Drilling moment (N.m)
m_1, m_2, m_3	Exponents in tool-chip temperature equation
M_j	Resisting moment of chuck (Nm)

m_j	Mass of chuck jaws (kg)
n, n_1, n_2	Exponents in tool life equation
N	Rotational speed of chuck (rpm)
N_a	Maximum allowable speed to avoid axial slip in chuck (rpm)
N_c	Maximum allowable speed to avoid circumferential slip in chuck (rpm)
N_t	Maximum allowable speed to avoid component throw-out (rpm)
h	Surface roughness (mm)
H	Height of tool holder (mm)
h_{all}	Allowable value of surface roughness (mm)
p	Pitch of thread (mm)
U, J	Constants in crater wear equation
P_{sp}	Lead of ball screws in feed drives (mm)
P_a	Plain angle factor
P_{max}	Maximum available power from machine (kW)
P_{req}	Power required for machining (kW)
q_1, q_2, q_3	Exponents in tool-work temperature equation
r	Working radius (mm)
R_1, R_2, R_3	Constants in cutting force equations (mm)
r_n	Tool nose radius (mm)
r_g	Component gripped radius (mm)
r_j	Radial distance of jaws (mm)
r_n	Tool nose radius (mm)
T_{ac}	Actual cutting time (min)
T_d	Tool change time (cutting edge) (min)

T	Tool life (min)
T_m	Actual machining time (min)
T_{max}, T_{min}	Maximum and minimum allowable tool lifes (min)
T_L	Non-productive time (min)
x	Cost rate of machine (cost/min)
x_1, x_2, x_3	Exponents in cutting force equations
x_p, y_p	Exponents in drilling moment equation
x_0	Depreciation rate of machine tool
x_v, y_v, m	Exponents in drill tool life equation
V	Cutting speed (m/min)
V_{tmin}, V_{tmax}	Maximum-minimum speeds for workpiece-tool material (m/min
w_{min}	Minimum spindle speed (rad/sec)
w_c	Crater wear (mm)
w_f	Flank wear (mm)
w_0	Operator cost rate
y	Tool cost per cutting edge
y_1, y_2, y_3	Exponents in cutting force equations
Z, G, X, I	Constants in flank wear equation
δ_f	Total deflection of workpiece (mm)
δ_p	Permissible error on workpiece (mm)
δ_{Tw}	Total error on workpiece due to flank wear (mm)
δ_w	Flank wear in radial direction (mm)
τ	Shear strength of drill material (Pa)
α	Lip angle of cutting tool (Degree)
θ_f	Tool-work temperature (C°)

θ_c	Tool-chip temperature (C°)
α_r	Tool nose angle (Degree)
σ_t	Bending strength of holder material (Pa)
μ_a, μ_c	Coefficients of friction of jaw.
η	Efficiency of lead-screw mechanism in feed-drive

CHAPTER 1

INTRODUCTION

CAPP (Computer Aided Process Planning) can be treated as a link between CAD (Computer Aided Design) and CAM (Computer Aided Manufacturing) studies. It consists basically the determination of processes and parameters required to convert a block into a finished component. Optimisation of cutting conditions namely; depth of cut, feed rate and cutting speed is an important step in CAPP applications, since economics of the machining operation depend on the determination of optimum cutting conditions. The place of the determination of cutting conditions in a typical CAPP study is shown in Figure 1.1.

It is not sufficient to devise a feasible procedure to manufacture a desired component. The procedure must be economically justified too. Cutting conditions which give a saticfactory result may be established very rapidly. However, this may result in rapid tool wear and hence require frequent changes or resharpening of the tool. Thus, there is a need to relate

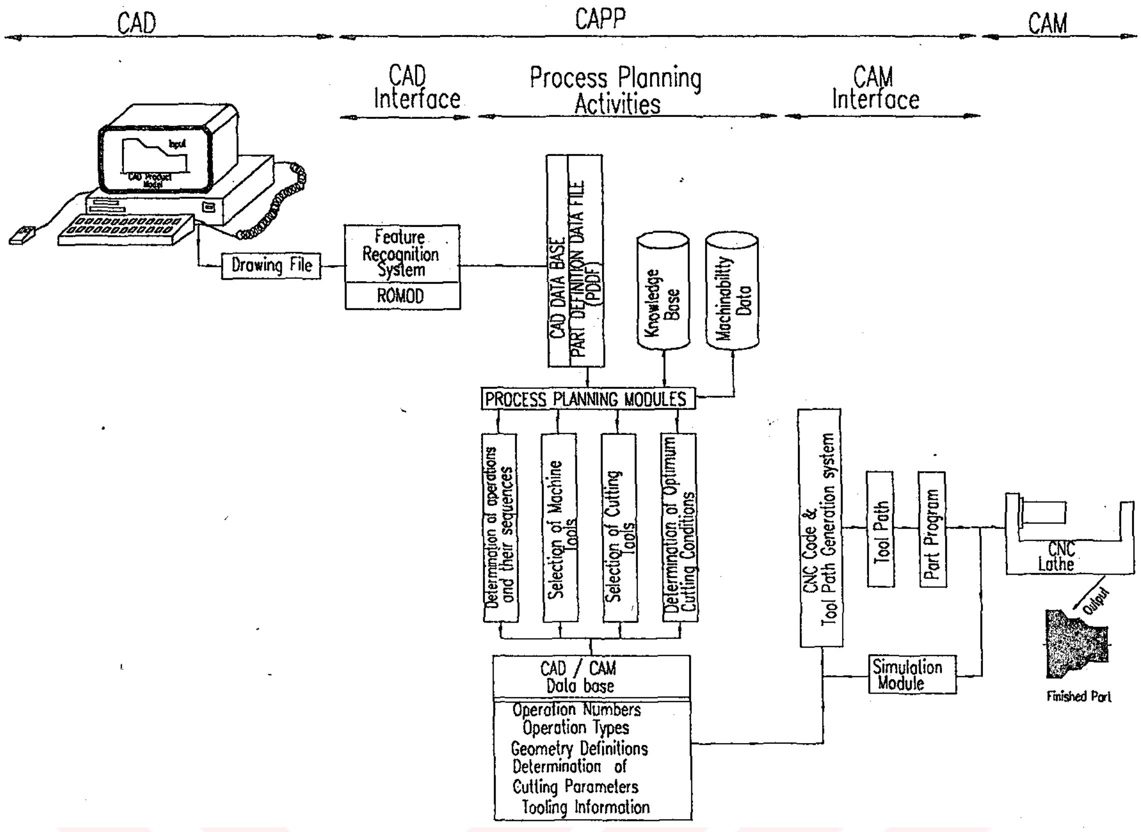


Figure 1.1 The CAD/CAPP/CAM Integration[1,2].

the technological factors involved in the cutting process to the economic situation. The variables affecting the economics of machining are numerous and include the tool material, machine tool capacity and cutting conditions [3]. As these variables are readily accessible on the machine tool, their selection has traditionally been considered as part of the machine operator's duties. However, the economical selection of the cutting conditions involves technical and cost data not readily available to the operator, so that an optimum selection can seldom be achieved by this approach. Additionally, the usage of optimised cutting data becomes a necessity if CNC machines are used in production. Since these machines are very expensive when compared with traditional ones and same results will be obtained if same cutting data are used in both types of machines.

Finding the economically optimum machining conditions in a manufacturing operation is seldom the only operation carried out on a component. Further, a full automation taking all process interactions and constraints is very difficult. A practical way which is often adopted is to select conditions for each separate operation in order to determine optimum values at that point in the overall production process.

Two criteria frequently used in the optimisation of machining operations are; the minimum cost per component criterion and the maximum production rate criterion. These two always give a different cost and production rate[4]. The minimum cost criterion gives a lower production rate, while the maximum production rate criterion has a higher cost per component. An alternative criterion is the maximum profit rate for the operation, and the results obtained from this approach lie fairly close to the conditions established by the other two criteria, usually somewhere between the two[5].

In a system capable of optimisation, there are controllable variables and uncontrollable parameters. Once workpiece material to be machined, the cutting tool, and operative worker have been reasonably determined, these are considered as un-controllable parameters. Controllable variables are cutting conditions; namely, depth of cut, feed rate and cutting speed.

In this thesis, constrained optimisation of cutting conditions for turning operations has been performed by using the minimum production cost criteria. For this purpose, a menu driven IBM PC compatible software has been developed.

Although several optimisation techniques are presented in the literature, Such as Linear programming, Dynamic programming, Geometric programming, Integer programming etc., In this thesis, a direct search procedure is adopted which has been used previously by few investigators such as Hinduja, et. al.[6] and Arsecularatne, for the optimisation of multi-pass turning operations; namely, roughing, boring and facing. For other operations (drilling, threading, grooving and parting) feasibility check methods are used. Maximum and minimum depth of cuts and feeds for the tool and workpiece materials, maximum allowable tool force, holder strength and rigidity, spindle and feed-drive motors torque-speed characteristics, work holding limitations, deflection of the workpiece, geometrical accuracy, bearing design loads, cutting tool velocities, tool wear and surface roughness are taken as restrictions acting on the process.

The thesis is organised as follows; the most relevant works are reviewed in Chapter 2. General theories about metal cutting in turning are discussed in Chapter 3. Optimisation methods used in the study and the restrictions used in the optimisation program are discussed in Chapter 4. Explanation about the program and examples are given in Chapter 5. Discussion and Conclusion are given in Chapter 6.

CHAPTER 2

LITERATURE SURVEY

2.1 INTRODUCTION

This chapter presents a brief survey of the most relevant literature related to the study reported in this thesis.

2.2 OPTIMISATION STRATEGIES

To machine a given workpiece in the most economic way, two distinct strategies are used to determine the optimum cutting conditions[7]. They are:

1. Adaptive control systems.
2. Steady state optimisation systems.

2.3 ADAPTIVE CONTROL SYSTEMS

An adaptive control system is designed to operate in a time varying environment. Thus, the adaptive control systems attempt to compensate for the changing environment by monitoring its performance through on-line measurement and changing some control parameters to achieve optimal performance.

Adaptive control systems are studied by many researchers some of which are discussed below.

Ermer[8] developed an optimisation technique based on adaptive control. The method works as follows: given the cost and time and tool parameters, cutting speed giving the minimum cost is calculated and operation is started at this speed. As operation continues, tool wear is measured periodically and parameters in Taylor's tool life equation are calculated. Then, new cutting speed giving the minimum cost is determined from the calculated parameters. Hence, cutting speed is continually updated for adaptive control and optimisation of the process as the operation continues.

Ropert P.Davis et al. [9] developed an optimisation method which is similar to Ermer's method, but they prepared a system which also senses thrust and power, and converts these to digital signals.

2.4 STEADY STATE OPTIMISATION SYSTEMS

In steady state optimisation, it is assumed that there are sufficient knowledge about the process which will behave in a predictable manner. The continuous performance feedback is, therefore, considered to be unnecessary i.e., an open loop configuration is used.

Since the beginning of this century, the selection of economic cutting conditions has been recognised as a major factor in the field of metal cutting. In 1907, Taylor[10] investigated the relation between the cutting speed and the tool life and he formulated an equation which is still used. Although, many other equations are later proposed in the literature[11,3], the modified Taylor's equation, which also includes the effect of feed rate and depth of cut , is most widely used. Taylor's tool life equation has the form:

$$VT^{e}=C$$

Where V is cutting speed, T is tool life, e is the exponent of tool life and C is constant. When other factors held constant, the production rate can be increased by increasing the speed. But according to the above equation the tool life decreases and cutting edge has to be replaced. Thus, there is an optimum speed beyond which the high frequency of tool changing will reduce the production rate. The same is true for the production cost of a component. Considering the extended Taylor's tool life equation (3.8), it can be shown that similar trends exist with other principal cutting variables, namely feed and depth of cut. Various procedures have been used to determine optimum cutting conditions. The techniques for handling the constraints in these procedures can be divided into two broad categories. The first category is that of feasibility check methods. In this case, unconstrained optimisation methods are used except that a check section is added to find out whether a constraint is violated or not. If this occurs, the current point is relocated inside the feasible optimisation region in a prescribed manner. The second category is that of the modified objective function method. In this method, the constraints are incorporated into the objective function which produces an unconstrained problem. Penalty functions are used in order to apply a penalty to the objective functions at non-feasible points, thus forcing the search process back into the feasible region. Brief descriptions of some widely used methods of optimisation are given below;

Geometric programming: It is one of the best method recently developed in optimisation theory. It is capable of solving certain problems involving non-linear terms in both the objective function and constraints. Instead of seeking the optimum values of the optimisation variables geometric programming first finds the optimal way to distribute the total cost among the various terms of the objective function. After the optimal allocations are found, the optimal cost can be obtained by simple calculations and then the values of optimisation variables for the optimal cost are determined.

Dynamic programming: Dynamic programming is an optimisation method used for making a series of interrelated decisions. This method starts with a small portion of the problem and finds its optimal solution. Then gradually enlarges the problem, finding the current optimal solution from the previous one, until the entire problem is solved.

Linear programming: It consists of methods for solving optimisation problems with constraints in which the objective function F is a linear function of the control variables x1,x2,..........xn, and the domain of these variables is restricted by a system of linear inequalities. Guy L. Curry, B. L. Deuermeyer[12] used this method for the optimisation single and double pass turning operations.

Penalty function method: This technique uses problem constraints and the original objective function to form an unconstrained objective function which is minimised by any appropriate unconstrained, multivariable technique, where several options are available. In this method, the objective function is modified by adding severe penalty to it whenever a constraint is violated in such a way that the unconstrained optimisation technique is forced to find the minimum in the feasible region. D. I. Kimbler, R. A. Wysk and R. P. Davis [13] used this method for the optimisation of multipass turning operations.

Search method: In this method, chip breaking area specified for each cutting tool(insert) is used as the main input for the optimisation. This area is divided into certain number of grids which depend on the sensitivity of the machine tool. Then, all the grid points are tested for feasibility by using constraints. Among these points, the optimum one for each machining operation is determined by taking the objective function into consideration. Minimum cost per operation is usually considered as the objective function.

The other methods which are used in the optimisation of cutting conditions are: Graphical techniques, Performance envelope, Integer programming etc.

Agapiou [14] used dynamic programming method for the optimisation of cutting conditions for multi-pass operations, where a given total depth of cut is to be removed from a workpiece. He assumed that the number of passes in metal cutting corresponds to the number of decision stages in dynamic programming and the cutting conditions at each pass correspond to the decisions at that stage. The stage state is the diameter of the workpiece at each stage.

J. Somlo, J. Nagy[15] stated that geometric programming method is more powerful than other optimisation methods in determining the optimum machining conditions when the solution is restricted by one or more inequality constraints. But they also pointed out that as the number of constraints increases another optimisation method should be employed together with the geometric programming.

S. M. Nişli [16] applied the geometric programming to single-pass turning operations for selecting the optimal machining conditions; cutting speed and feed rate. The minimum unit production cost and time criteria were handled together with constraints. It was stated that the optimal cutting speed and feed rate are restricted by atmost two constraints, and the optimal point is obtained by the intersection of the constraints with the unit production cost and the unit production time contours.

Another approach was introduced by M.P. Groover[17]. It is based on Monte Carlo simulation technique. This technique based on a mathematical model which is described by some assumed probability distribution. The actual machining process is replaced with its mathematical model. Then the variables in the mathematical model are sampled by means of a random number generator.

M. A. El Hakim et al.[18] prepared an algorithm which makes feasibility checks for the constraints. In this algorithm, the depth of cut is equated to the maximum depth of cut value for the tool and checked for the constraints if it violates any one of them, depth of cut is then reduced in steps until it satisfies the constraints. Cutting speed is calculated by using the selected criteria is then checked for the constraints. The procedure continues until total depth of cut is removed.

Hsu-Pin Wang et al.[19] used Expert System approach and Artificial Intelligence techniques for the machining data selection.

G. L. Ravigani et. al.[20] used graphical methods for the determination of cutting conditions. They said that cutting conditions can be optimised by applying graphics methods whereby tool-life test points can be directly used.

S.S. Rao and S.K. Hati [21] applied mathematical programming techniques to the determination of optimum cutting conditions by using both deterministic and probabilistic approaches. Three objectives; the unit production cost, the production rate and profit rate are considered for the optimisation.

Brewer[22] attempted to optimise the speed and feed for minimum cost per component produced considering the maximum available power. He presented graphs of feed versus speed with minimum cost loci to select the optimum feed and speed. He also included curves of constant power so that it is possible to check whether there is sufficient power available to realise the optimum feed and speed.

Kals et al [23] developed an algorithm for multipass roughing operations which involve the following steps:(1)All necessary data is obtained from data files.(2) The maximum allowable feed is selected based on the strength of the tool.(3)The number of passes required to remove the stock of material is calculated using the maximum depth of cut which is obtained from the chip breaking constraint and the maximum feed. The depth of cut for each pass is then determined by dividing the material to be removed equally among the passes.(4) The optimum tool life for minimum cost or maximum production rate is calculated. Using the equivalent chip thickness from the extended Taylor equation, the optimum cutting speed is then calculated for all passes.(5) The cost and time for each pass is calculated using the speed, feed and depth of cut. Feed and speed are checked for the constraints on the process. If the speed is less than the minimum recommended value for the tool, the feed is reduced by %5 and speed is recalculated. If speed is greater than the maximum recommended value, it is set at the maximum. If the feed is less than the minimum recommended value for the tool then the number of passes are increased by one, in which case the new depths, feeds and speeds for all the passes are recalculated. In this approach, to predict the force components empirical relations which use the equivalent chip thickness are employed. If the maximum power is exceeded the velocity is reduced. If the constraint is still violated then the feed is reduced by %5. Finally, if the depth of cut exceeds the critical value then the number of passes is increased by one to prevent the dynamic instability. New values for depth of cut, feed and speed are then calculated and rechecked for the constraints.

N. K. Jha [24] used a method called "Nonlinear mixed integer programming" for the optimisation of cutting conditions.

Van Houten[25] further improved the treatments of constraints. To predict the deflection of the workpiece he used equations and considered limitations due to chucking and this enabled him to take into consideration axial and rotational slip. For torque, he used power/speed characteristics of a DC motor, which gives the actual power available within the speed range. The constraints developed by Van Houten was used by some researches like Arsecularatne[7]. These constraints are also used in this study.

An analytical method applying a change-constrained programming concept is proposed by K.Iwata et al [26]. This method is used to determine the optimum cutting conditions considering the probabilistic nature of the objective function and the constraint function. They proposed a procedure for selecting the machining conditions so as to produce workpieces not only of the required accuracy but with maximum productivity and at a minimum cost.

M.Y. Friedman and V.A.Tipnis [27,28] have introduced a new concept called R-T characteristic functions which opens a new field in economic optimisation of cutting conditions. The concept views all metal removal processes in terms of two basic parameters; the cutting rate (material removal rate) R and the tool life T. The advantage of this method is that, even in the absence of cost data, if the R-T characteristic curve is known, it is always possible to approach the economically optimum point by merely moving the operation points on the R-T characteristics curve within the practical working region.

D.S. Ermer and B.V. Shah [29] presented an analytical method for sensitivity studies in the determination of optimum machining conditions for various processes assuming minimum cost criterion or maximum production rate criterion. The idea is that, instead of an optimum range of cutting conditions an optimum point, should be determined in order to exploit the sensitivity of the optimising response function; and thus help to solve the difficulties of non uniformity and variability as well as the constraints of an actual production operation. It is claimed that such an application of the concept of sensitivity can be very useful for approaching full optimisation. After obtaining the optimum range of machining conditions for each operation, the machining conditions can be varied in the optimum range while considering the full optimisation.

Hinduja et al.[30] and Arsecularatne [7] used a direct search procedure in the depth -feed plane to determine optimum point. The region in the depth-feed plane which gives the depth/feed combinations for chip control is approximately divided into a 20x20 grid. Then starting from the maximum depth, all the points on the grid are checked for the constraints applicable. The procedure takes into consideration a number of constraints such as motor power, tool strength etc. and determines the optimum depth of cut, feed and speed for each pass in multipass turning. A similar approach is used in this work by taking into account some extra constraints for the multipass operations. Such constraints are; cutting tool temperatures, tool wear, motor power of feed-drive motors etc.

2.5 CONCLUSIONS OF THE LITERATURE SURVEY

The following conclusions can be drawn from the above-mentioned investigations;

a) Taylor's modified tool-life equation is used in almost all of the related studies.

b) The number of studies concerned with multipass operations are relatively less than the single-pass operations.

c) A few researches used the maximum production rate criterion whereas the minimum unit production cost is used extensively by the researches.

d) Number of restrictions considered in the previous studies are limited. Some of the mostly used restrictions are; Spindle motor power restriction, Maximum and minimum values of feed and depth of cut for machine tool and tool-workpiece material combination, Maximum speed for machine, Tool life restriction, surface quality, Tolerance on workpiece, Tool wear.

e) There are very limited number of works which consider optimisation of cutting conditions in all turning operations.

In this study, optimisation of roughing, boring, facing, threading, drilling, grooving and parting-off operations are performed. For the optimisation problem some new constraints are considered. These constraints are holder strength and rigidity, feed-drive motors torque-speed characteristics, deflection of the workpiece, bearing design loads on the feed-drive mechanisms.

CHAPTER 3

METAL CUTTING IN TURNING

3.1 INTRODUCTION

The purpose of this chapter is to present main theories and rules related to metal cutting in turning by using single point cutting tools.

3.2 BASIC TURNING OPERATIONS ON A CNC LATHE

Machining operations that can be performed on a CNC turning lathe can be classified as[7] ; turning, drilling, grooving, threading and parting-off. Turning operations are roughing, boring and facing, These operations can also be classified as internal-external, right-hand, left-hand, inward-outward (in the case of facing). All these operations are shown by Figures 3.1 to 3.7.

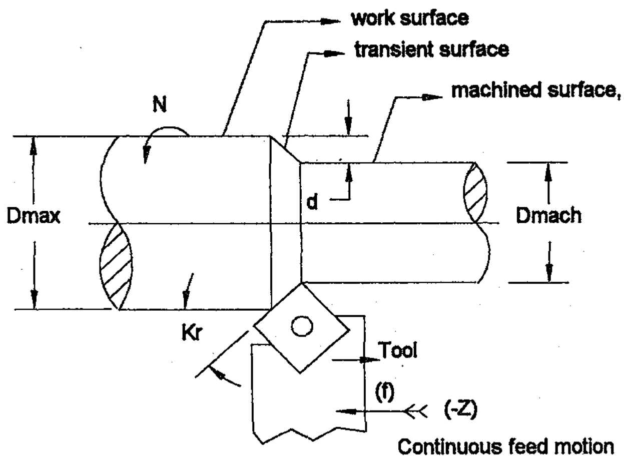


Figure 3.1 Cylindrical turning (Roughing and Finishing)

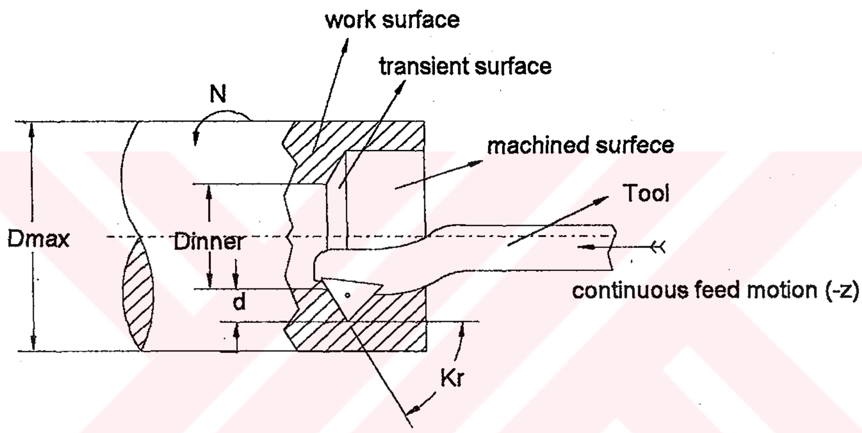


Figure 3.2 Boring operation

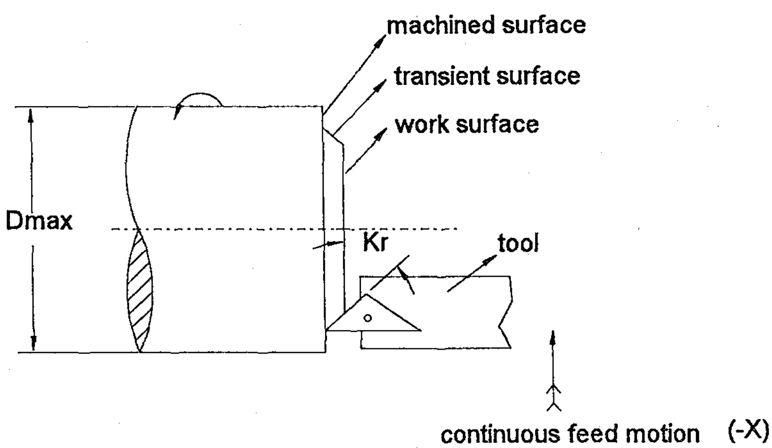


Figure 3.3 Facing operation

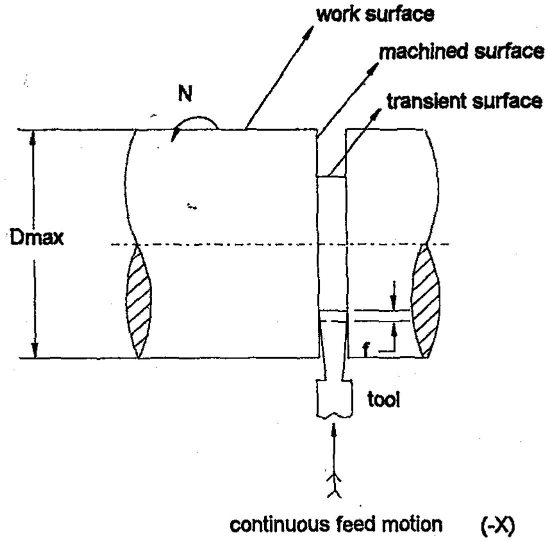


Figure 3.4 Grooving and Parting-off operations

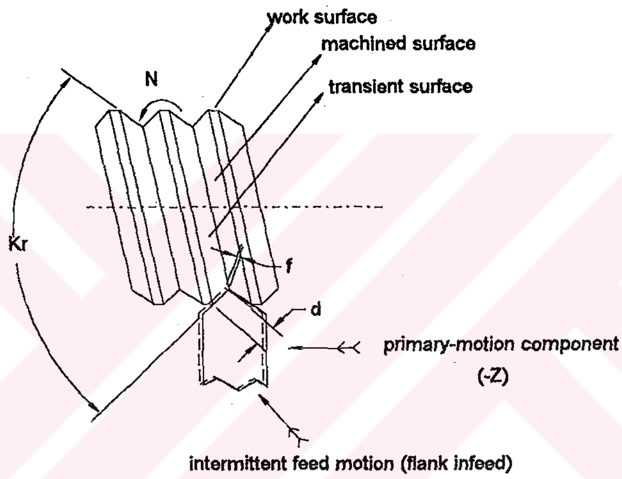


Figure 3.5 Threading operation

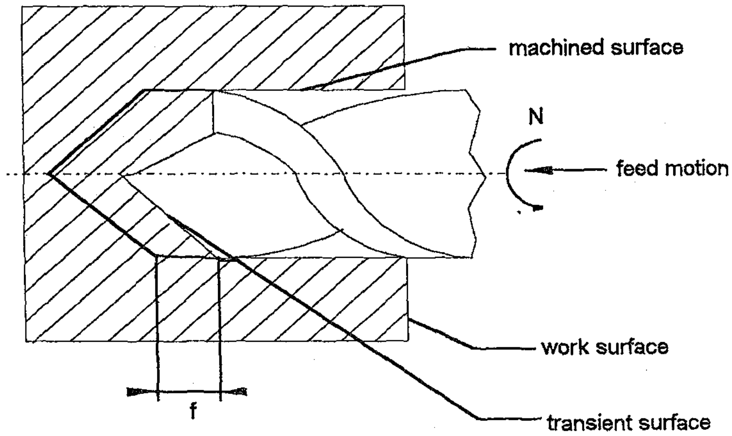


Figure 3.6 Drilling operation

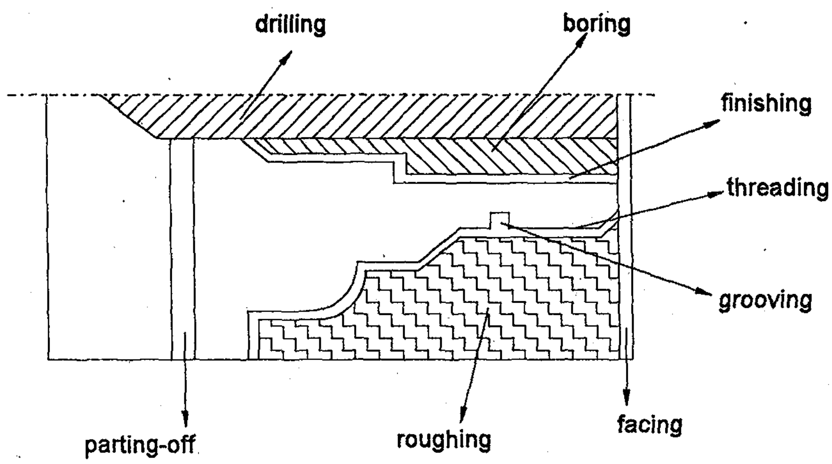


Figure 3.7 A component which shows all basic operations

3.3 TURNING TOOLS

Today, about 70 percent of cutting tools that are used in turning applications are carbide inserts[3]. Their holders and shapes are standardised by ISO. In this study, these codes are used for specifying the cutting tools. However, for grooving tools there are no such standards, hence manufacturer's codes are used [53,54]. A brief explanation for these codes are given below. For detailed explanation see Appendix C.

3.3.1 Indexable Inserts

ISO identification system for insert uses about 10 alphanumeric characters to specify the shape, clearance angle, tolerance, type, size, thickness, cutting point configuration, cutting edge definition, left/right hand operation and other conditions (see Table 3.1)

Table 3.1 Specification system for indexable inserts

Place	1	2	3	4	5	6	7	8	9	10
Example	C	N	M	G	12	04	12	F	F	QM

The first character indicates the shape of the insert, e.g. (C) for 80° parallelogram, (R) for round etc.

The second character is for denoting clearance angle on major cutting edge, e.g. (N) for 0°, (P) for 11° etc.

The third character indicates the tolerance on the size, e.g. letter (M) for tolerance equals to ±0.05 mm on both the nominal size and thickness.

The type of the insert is specified by the fourth character, e.g. (A) for hole,(W) with hole and countersink etc.

The digit (or digits) in the fifth place are for specifying the size of the insert.

The digit in the sixth place is for indicating the thickness of the insert.

The cutting point configuration is specified by a numerical value in the seventh place, e.g. 12 for 1.2 mm nose radius etc.

The eighth position is used for specifying the cutting edge condition, e.g. (F) for sharp cutting edge etc.

The letter in the ninth position indicates tool style feed direction, e.g. (R) for right hand, (L) for left hand and (N) for normal.

The digit ten is left for manufacturer's option, e.g. (QR) for roughing operations only etc.

3.3.2 Tool holders for indexable inserts

The tool holders for indexable inserts are generally made from hardened steel. Accurate pockets are ground in the tool holder to provide seating for the insert. The seating surface of the holder can provide positive, negative or zero rake to insert. A typical ISO specification for such an indexable tool holder is given in Table 3.2. For detailed explanation see Appendix C.

Table 3.2 Specification system for tool holders

Place	1	2	3	4	5	6	7	8	9	10
Example	P	S	F	E	R	20	20	K	12	

The letter in the first position indicates the method of holding or clamping the insert, e.g. (P) for pin-lock in the case of insert with a hole in its centre. (C) for top clamping etc.

The shape of the insert which the holder can accommodate is denoted by a letter in the second position, e.g. (S) for square, (R) for round etc.

The letter in the third position is for indicating the style of the shank, e.g. (F) for straight shank with 90° side cutting edge angle etc.

The letter placed in the fourth position is for designating the clearance angle on major cutting edge, e.g. (E) for 20° etc.

The hand of the tool, (R) for right hand and (L) for left hand, is indicated in the fifth position.

The height and shank width of the tool are indicated in sixth and seventh places respectively.

The letter in eighth place denotes the length of the tool, e.g. (K) for 125mm tool length etc.

The cutting edge length is given in ninth place, e.g. 12 for 12 mm cutting edge length.

The last digit is left for manufacturer's option.

3.4 CHIP BREAKING IN TURNING

Many investigators have made various experiments for the determination of chip breaking capability of turning tools. The studies of S. Kaldor, A. Ber, E. Lenz, J.L. Andreasen, L.De. Chiffre, I.S. Jawahir [39,40,43,47], are summarised here.

3.4.1 The Optimal Form of Broken Chips

Disposal of chips: Different cutting conditions produce varying forms of chips, when chip breakers are not used, or not set in the proper way. Minato[47] has classified the chip forms according to the rate of disposal by suction. The higher the disposal rate, the better the chips geometry. He proposed a parameter T(sec/kg) defining the time needed to dispose one kilogram of chips by means of a vacuum cleaner. Minato's results show that the "C" shaped chips are the best one.

Volume of chips: The volume of the chips was defined by many investigators [43,47]. Lang [39], proposed the parameter R=Ratio between the chips volume and the volume of the same weight of block material. When 3<T<10, the chips are well broken.

According to the results of Minato[47] the best chips geometry bears when R=3.7.

Operator safety and productivity: These two different point of wives result in the same chips configurations. Only small chips bearing the geometrical forms "C" , "G" or "e" are acceptable. Long chips tend to tangle around the tool , tool holder and workpiece material. The spinning long chips may cause harm to the operator who carelessly continues with the cutting, or stops the machining in order to remove the chips by hand. Unavoided stoppages is a loss of manufacturing time that decreases the productivity. Two further aspects could be noted; the possibility to cause an unexpected tool breakage and/or a ruined surface finish.

As a result of the above mentioned factors, the chips bearing the geometry "C" or "G" were chosen to be the "optimal chips" or "acceptable" by many investigators[39,47]. The classification of the chips is defined by the following signs: The acceptable chips sign is (+), and the unacceptable chips are signed as follows:

(-) For spiral or helical type, long chips (more than one turn)

(±) For small helical or spherical chips (two turns)

(T) For tied and condensed chips (more than two tied segments)

These are illustrated in Figure 3.8.

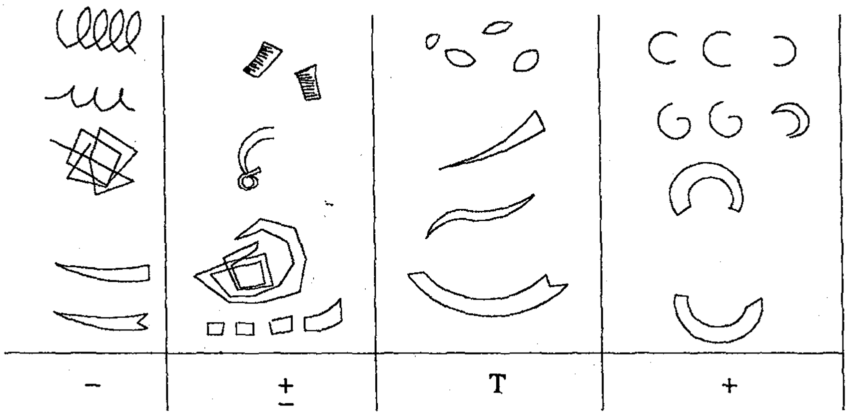


Figure 3.8 Classification of the various chip forms. "Plus" (+) sign indicates acceptable broken chips [39]

3.4.2 Graphical Representation of the Chip Breaking Ability of a Tool

There are some ways to record chip breaking results, shape and designation, obtained by machining tests. A common way is to represent photographically the picture of every chip according to machining conditions at every point, i.e.:(velocity-V, feed,-f, depth of cut-d)[47,55].

The presentation is done on a graphical plan describing the depth of cut-d, versus the feed-f, for the following ; tool- work material, velocity, cutting geometry and coolant. Every point on this plan defines (by its picture) the chip geometry, as a function of the machining parameters.

An easier way is to mark on the d versus f plan the predefined signs (+,±,-,T). Although cutting speed has an effect on chip breaking, it is very small [43,47] when compared with feed and depth of cut so, it is not used for denoting the chip breaking capability of a turning tool by manufacturer's [53,55], (see Figure 3.9)

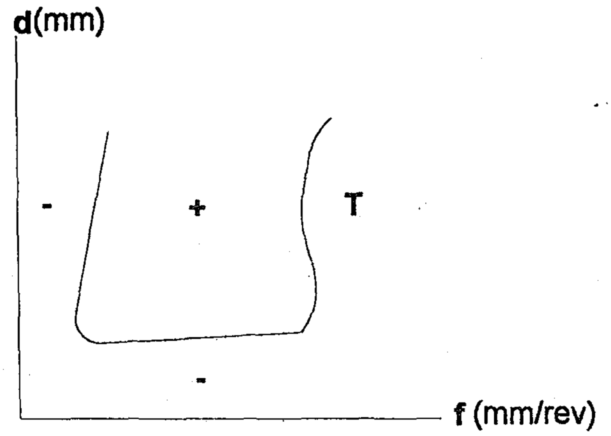


Figure 3.9 A schematics of chip breaking diagram, depth of cut(d) versus feed(f) [47]

3.4.3 Explanation of Chip Breaking Diagrams

A chip breaking diagram that shows clearly three different regions of chip breaking is shown in Figure 3.10.

As each of these regions has its own mechanism of chip breaking, they may represent the basic three modes [43,47].

Mode A(Orthogonal): Represented by a wedge-shaped zone in the upper and left-hand part of the diagram. The chips covered in this zone have a two-dimensional geometry as a common property.

Mode B(Oblique): Represented on the chip breaking diagram by a narrow strip along the feed axis. The (helical or three dimensional) chips are typical of small depth of cut and relatively high feeds.

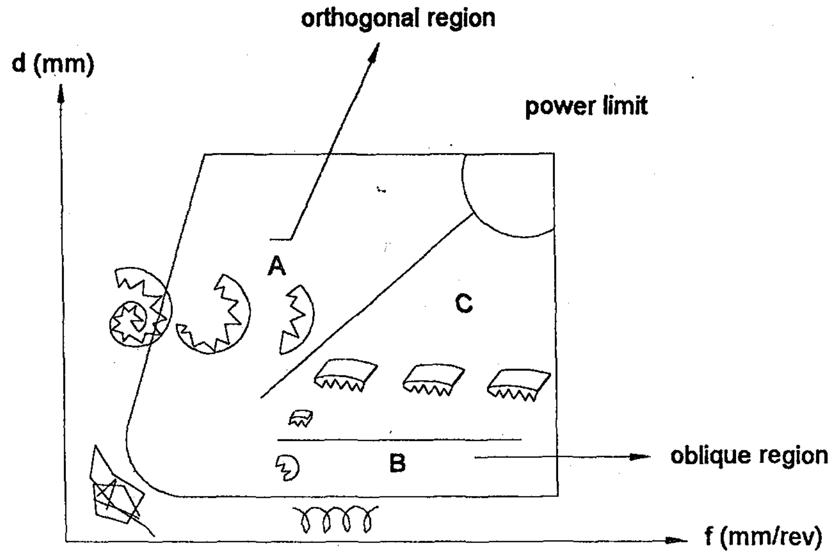


Figure 3.10 The different chip breaking regions: the orthogonal (A), the oblique (B), and the transition one (C) [47]

Mode C(Mixed): Represented by the intermediate wedge between the two above zones. Both chip mechanisms are involved in this region.

3.5 POWER AND FORCES IN TURNING

The forces acting on the cutting tool are influenced by the parameters involved in chip formation process i.e.[3]

- Workpiece material
- Tool material
- Cutting fluid
- Depth of cut
- Feed rate
- Cutting speed

The cutting force can be resolved into three components, as shown in Figure 3.11, namely;

- Tangential component (F_t)
- Radial component (F_r)
- Axial component (F_a)

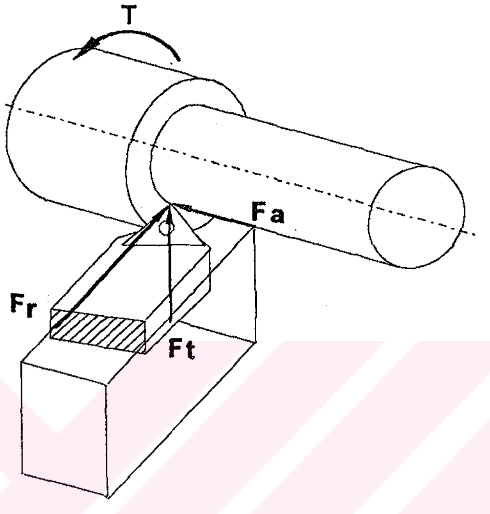


Figure 3.11 Force components in turning

The tangential component F_t is in the direction of cutting velocity vector. The radial component, as the name denotes, is in the direction of the radius of the workpiece. The third component is parallel to the axis of the workpiece, i.e. in the direction of longitudinal feed.

The force components in turning may be represented in exponential form involving feed and depth of cut.

$$F_t = R_1 f^{x_1} d^{y_1}$$
$$F_r = R_2 f^{x_2} d^{y_2} \qquad 3.1$$
$$F_a = R_3 f^{x_3} d^{y_3}$$

where, R_1, R_2, R_3 are constants which indicate the effects of workpiece material, cutting fluid, etc. $x_1, x_2, x_3, y_1, y_2, y_3$ are exponents. Values for these constants and exponents can be found in Appendix A.

As seen in the above equations, the effect of cutting speed has been neglected because, Tobias et al.[51] showed that relatively high speeds are used in practice, and the cutting speed has a very small effect on cutting force (see Figure 3.12).

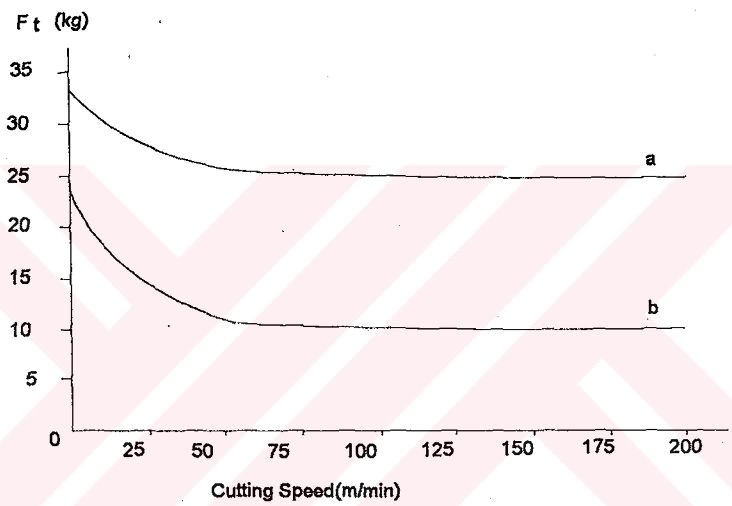


Figure 3.12 Tangential cutting force component as a function of cutting speed. Material: Mild steel, chip width 0.38mm, (a) feed 0.317mm/rev, (b) feed 0.159mm/rev [51]

In this work, the equations given above are used for calculating the cutting forces. But there are other methods for calculating them [10,11,50], which use specific cutting pressure or chip breaking angle relationships. However, these type of equations are suitable for the tangential force component. They are not applicable for the feed and radial force components, because some percent of tangential cutting force are taken for the feed and radial force component (%50 for feed, %25 for radial component [55]) ,but this contradicts with the real case [7].

Since there is no radial movement, there is no work done by the radial component of force. The other two components do the work. However, the feed speed is so small and hence the product of the feed force and feed speed is negligible[5] as compared to that of tangential force and cutting speed. Therefore,

$$\text{Rate of doing work in turning} = \text{Tangential force} * \text{Cutting speed}$$
$$\text{Power needed (W)} = F_t * V/60$$

where, F_t is in (N) and V is in (m/min).

3.6 DETERMINATION OF TOOL WEAR AND CUTTING TEMPERATURES

3.6.1 Heat and Temperature During Cutting

The mechanical work of cutting causes energy conversion to heat, and results in high cutting temperatures. The main sources of heat in cutting shown in figure below are:

- The shear zone (I), where the primary plastic deformation, q_S, takes place.
-The tool/chip interface (II), where secondary plastic deformation, due to friction, q_C, takes place.

- The tool/work interface (III), at flank where frictional rubbing, q_f, occurs.

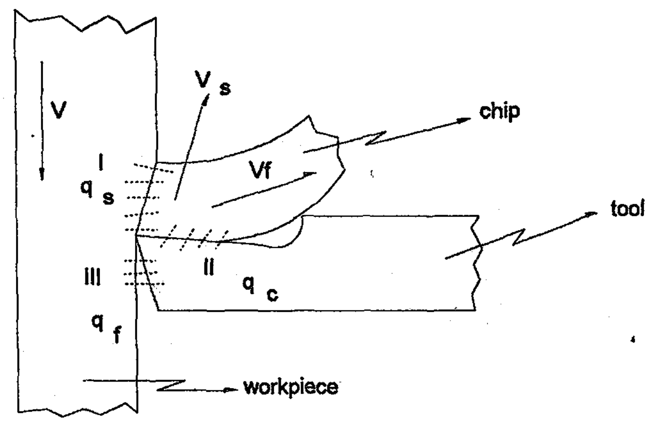


Figure 3.13 Sources of heat in metal cutting [10]

$$q_{total} = q_s + q_c + q_f \qquad 3.2$$

Several methods have been developed for measuring cutting temperatures [31]. Since cutting temperatures have a detrimental effect on tool wear and can cause tool failure [10]. The relative heat distribution among the work, tool and chips has been determined experimentally[31]. As shown in Figure 14, 50-80 percent of heat is removed by chips, 10-20 percent are taken by the tool and 10-20 percent are taken by the workpiece.

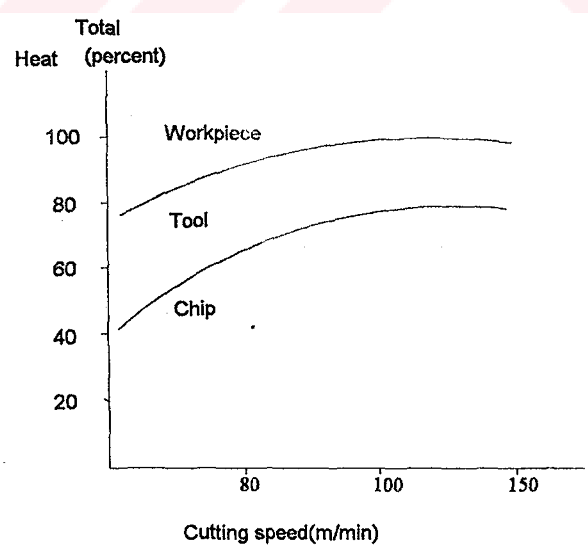


Figure 3.14 Distribution of heat between chip, tool and workpiece during metal cutting [10]

These results show that chip-breaking capability of the tool is very important in any cutting operation because the great amount of heat is removed by chips.

Chao and Trigger[31] have investigated the effect of different variables on tool-work temperature. The following relationship represents the form of their results.

$$\theta_f = K_1 V^{q_1} f^{q_2} + K_2 w_f^{q_3} \qquad 3.3$$

where, K_1 and K_2 are constants, q_1,q_2,q_3 are exponents whose values can be found in Appendix A, V is cutting speed(m/min), f is feed(mm/rev), w_f is flank wear(mm).

Koren and Lenz [31] developed the following relationship for the temperature at the tool-chip interface.

$$\theta_c = CF V^{m_1} f^{m_2} d^{m_3} \qquad 3.4$$

where, C is a constant, m_1,m_2,m_3 are exponents whose values can be found in Appendix A, F is cutting force(N), V is cutting speed(m/min), f is feed(mm/rev) and d is depth of cut(mm).

3.6.2 Tool Wear in Turning

The primary cause of tool failure under normal cutting conditions is usually the gradual wear[11]. The useful life of a tool, called "tool life" is limited by tool wear . Wear which can be described as the total loss of weight or mass due to the friction of the sliding pairs. This friction can be caused by five basic mechanisms: (1) Abrassive wear, (2) Adhession wear, (3) Diffusion wear, (4) Chemical and electrolytic wear, (5) Oxidation wear[3].

Abrassive Wear: Abrassive wear is caused by hard constituents of the workpiece material, including fragments of built-up edge, plowing into the tool surfaces and they sweep over the tool as shown in Figure 3.15.

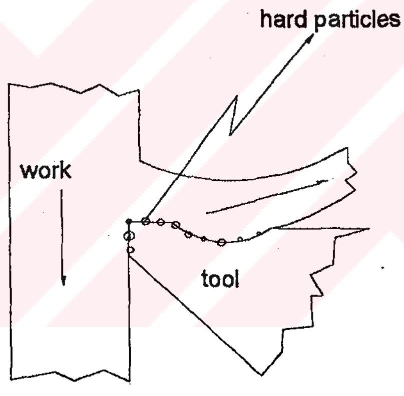


Figure 3.15 Abrassive wear

Adhession Wear : When two surfaces are brought into contact under loads, and subjected to friction, adhession may occur at the high temperatures generated by plastic deformation and friction.

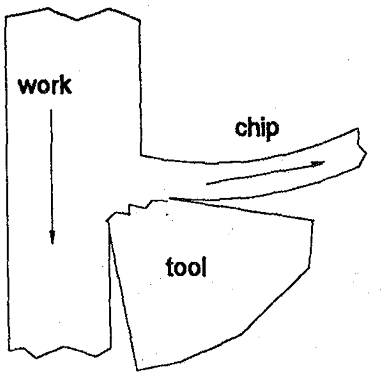


Figure 3.16 Adhession wear

Diffusion Wear : Solid state diffusion is the mechanism by which atoms in a metallic crystal shift from one lattice point to another causing a transfer of the element in the direction of the concentration gradient. Diffusion wear is caused by the process of surface and interstitial diffusion. The mechanical process involved in adhession is capable of increasing the localised interface temperature of the actual contact area between the tool and workpiece.

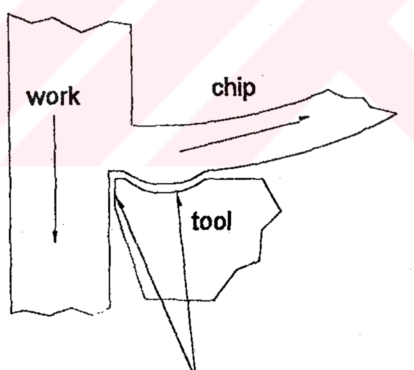


Figure 3.17 Wear by diffusion

Chemical and Electrolytic Wear : Chemical wear is caused by interaction between the tool and workpiece in a chemically active cutting fluid environment. Electrolytic wear is caused by possible galvanic corrosion between the tool and workpiece.

Oxidation Wear : Oxidation also causes tool wear at high cutting speeds, i.e., in the high cutting temperature range. The oxidation of the carbide in the tool material weakens the tool matrix and therefore the strength of the cutting edge.

3.6.2.1 Criterion and Geometry of Tool Wear

Tool wear progresses as the cutting operation progresses; the wear land extends from the cutting edge up the flank of the tool. In addition, a characteristic cavity, known as a "crater", forms at a certain distance from the cutting edge on the tool face as illustrated in Figure 3.18.

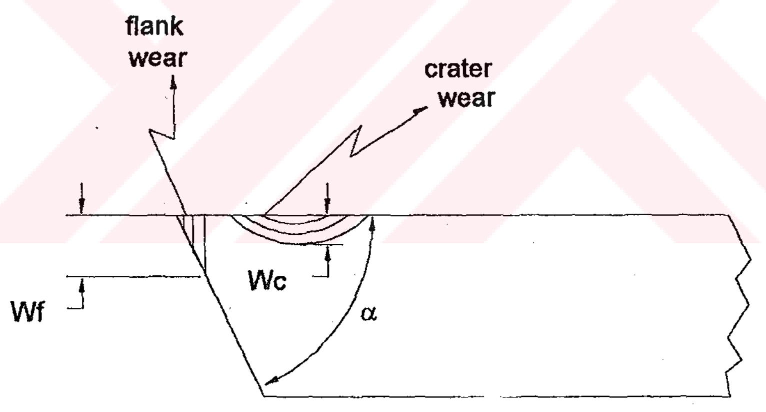


Figure 3.18 Schematic representation of tool wear in turning

Flank wear has been studied by several researchers. Perhaps the simplest model so far has been presented by Koren and Lenz [31] who assume abrassion and diffusion as the predominant wear mechanism. They separate the flank wear into two components; one caused by abrassion (w_{f1})

and the other by diffusion (w_{f2}). The relationships representing these components have the form;

$$w_{f_1} = (Z\cos\alpha_r F/(f\,d))/(1+I/V)$$
$$w_{f_2} = X\sqrt{V}\,e^{(-G/(273+\theta_f))} \qquad 3.5$$
$$w_f = w_{f_1} + w_{f_2}$$

where, Z,G,X,I are constants, α_r is tool nose radius(mm), f is feed(mm/rev), d is depth of cut(mm), F is cutting force(N) and V is cutting speed(m/min)

Crater wear is generally believed to be caused by diffusion as a result of high temperature at tool-chip interface[3]. The relationship used to represent crater wear is developed by Usui [46].

$$w_c = J\,F\,V\,e^{(U/(273+\theta_c))} \qquad 3.6$$

where, J, U are constants, F is cutting force(N), V is cutting speed(m/min).

The following flank wear values are recommended as the criteria for the carbide tipped tools by ISO.

1- 1.0 to 1.4 mm for roughing steels.
   0.4 to 0.6 mm for finishing steels.
2- 0.8 to 1 mm for roughing cast irons.
   0.6 to 0.8 mm for finishing cast irons.
3- 0.8 to 1 mm for carbide tipped cut-off tools.

For crater wear ISO recommends values which lie between 0.8 to 0.4 mm for both carbide and HSS tools.

3.7 DETERMINATION OF TOOL LIFE IN TURNING

Tool life is measured by considering several criteria depending upon the cutting conditions and the requirements of the operation. The most common measures of tool life are: Complete failure, predetermined wear limit, surface finish limit, size failure, cutting forces and power limit [50].

The objective of a particular machining operation determines which criterion should define the tool life. In practice, a wear limit is the most commonly used for machining operation[3]. Whichever criterion is chosen, tool life is that time elapsed between two successive grindings of a cutting tool, or between a replacement of a new tool or tip. Various ways of expressing tool life include: Time of actual operation, volume of metal removed, total length of cut, number of pieces machined [11].

Taylor has proposed the relationship between cutting speed, V, and tool life, T, in minutes as follows:

$$VT^{e} = C \qquad 3.7$$

where, e is an exponent and C is a constant which depend upon tool material, workpiece material, cutting conditions, and environment.

Equation 3.7, often called "Taylor's tool life equation". It can be expanded to add the effects of feed(f) and depth of cut(d);

$$TV^n f^{n_1} d^{n_2} = A \quad 3.8$$

where, n, n_1, n_2 are exponents and A is a constant.

3.8 SURFACE ROUGHNESS IN TURNING

When chip formation occurs without a built-up edge, the tool profile is etched or reproduced on the machined surface (Figure 3.19). Geometry of feed marks depends on feedrate, side cutting edge angle, nose radius and end-cutting edge angle.

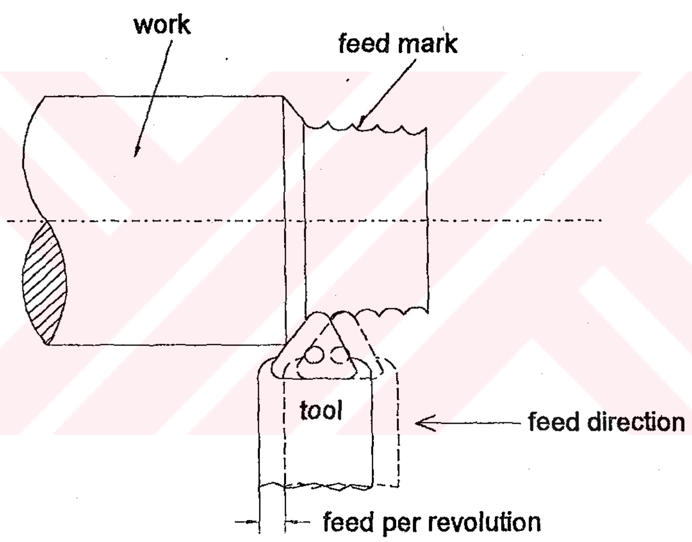
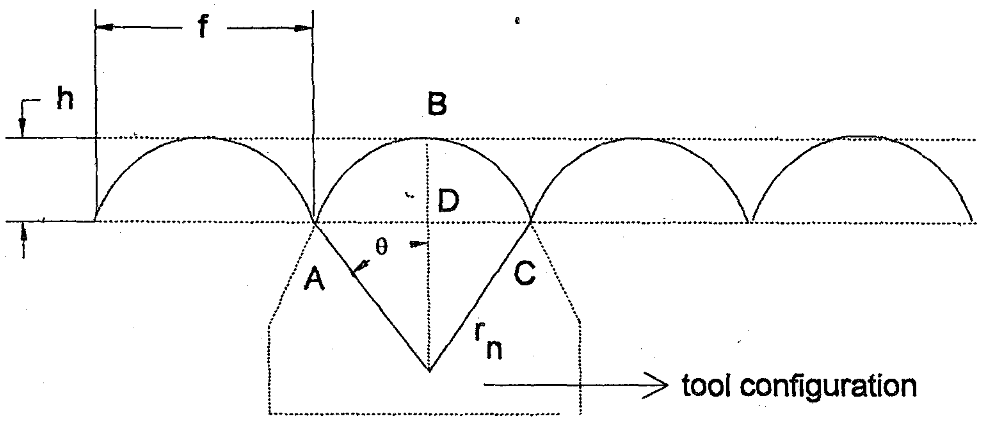


Figure 3.19 : Feed marks during turning

At medium feed values, which is the general case, cutting takes place entirely on the radius nose (see Figure below), one can find that:



$$h = r_n - r_n\cos\theta = r_n(1-\cos\theta) = r_n(1-\sqrt{1-\sin^2\theta})$$

$$\cong r_n(1-(1-0.5\sin^2\theta)) = r_n\sin^2\theta/2$$

But

$$\sin\theta = f/2r_n$$

so

$$h = f^2/8r_n \qquad 3.9$$

CHAPTER 4

OPTIMISATION OF CUTTING VARIABLES IN TURNING OPERATIONS

4.1 INTRODUCTION

In this chapter, economics of metal cutting, optimisation of cutting conditions for turning operations namely; roughing, boring, grooving, parting-off, threading, drilling and restrictions related on these operations are explained.

4.2 ECONOMICS OF METAL CUTTING

In metal cutting operations, the economics or cost of operation plays a vital role in determining the rate of production and/or speed of operation. If one cuts or machines the unwanted material at a very slow speed, the completion time of operation would increase, and with it, the cost of labour, the cost of machining operation, and the overhead costs would increase

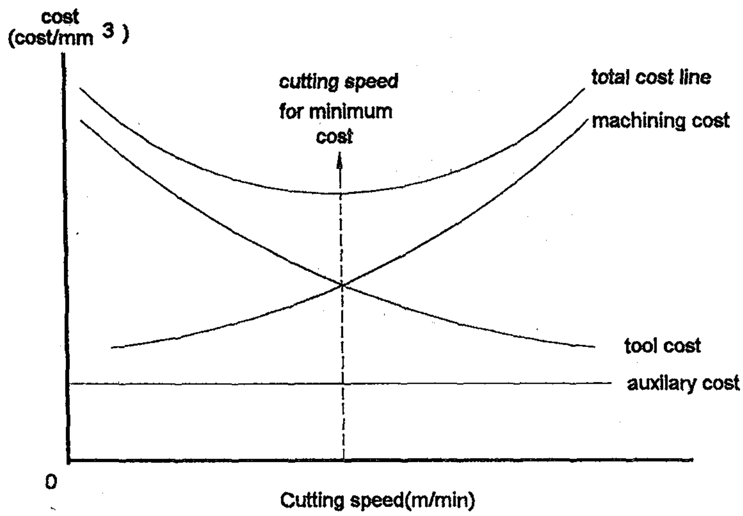


Figure 4.1 Machining costs

and make the operation costlier. If the same operation is done at very high speed, the wear of cutting would be accelerated. The operator will have to regrind or change the tool and reset it on the machine more frequently. Thus, it would increase the tool cost, the tool resetting cost and machine downtime. All these would make the operation costlier. The effect of speed on various costs is illustrated in Figure 4.1, which shows that only at some particular speed, the operation is most economical.

4.3 CUTTING CONDITION DETERMINATION METHODS

Cutting conditions in any machining operation are described by the depth of cut, the feed and the cutting speed. The following three methods may be used to determine these parameters:

- Experience of the foreman, operator or process planner.
- Handbook recommendations.

Computerised machinability data system (optimisation of cutting conditions)

The first method is based on the experience and has some risk to obtain valuable results since the experience may change from one person to another. The recommendations given in almost every machining handbook take only the effects of the workpiece and cutting tool material into account. The other intrinsic factors to be taken into account in conjunction with the economy of machining are disregarded. The depth of cut is specified by the user while using the handbook data which requires continuous interactions between the user and the computer. This is a time consuming and an iterative job, which is another disadvantage of this system. Therefore handbook suggestions are applicable to some extent, reasonable but not the best one. However, all effective factors(i.e.,tool life, chucking, machine power, etc.) are considered to determine the optimum cutting conditions in the computerised machinability systems although their effects are small.

4.4 OPTIMISATION OF CUTTING CONDITIONS IN TURNING OPERATIONS

The tool life for a turning operation is given by the equation(3.8), i.e.,

$$T = \frac{A}{V^{n} f^{n_1} d^{n_2}} \qquad 4.1$$

The cost of an operation can be expressed as:

$$C_T = xT_L + xT_m + xT_d\left(\frac{T_{ac}}{T}\right) + y\left(\frac{T_{ac}}{T}\right) \quad 4.2$$

where, x is machinig cost rate and it is given by:

$$x = w_0 + \left(\frac{\text{percentoperatoroverheads}}{100}\right) w_0 + x_0 + \left(\frac{\text{percentmachineoverheads}}{100}\right) x_0 \quad 4.3$$

In this equation, w_0 is the operator's wage rate and x_0 is the depreciation rate of the machine tool. Machine depreciation rate can be calculated by using the following expression:

$$x_0 = \frac{\text{Initial Cost of Machine}}{\text{Number of Working Hoursper Year * AmortizationPeriod}} \quad 4.4$$

Td is tool change time (min) and it is given by:

$$T_d = \frac{\text{time to index insert ((AVG}-1)+\text{time to replace insert)}}{\text{AVG}} \quad 4.5$$

In this equation, AVG is average number of cutting edges per insert. The number of tool changes depends on the actual cutting time per component, T_{ac}, and the tool life, T.

y is tool cost per cutting edge. It depends on the type of tool used. For a carbide tool tip the cost per cutting edge is given by:

$$y = \frac{\text{Cost of insert}}{\text{AVG}} + \frac{\text{Cost of holder}}{\text{Number of cutting edges used during life of holder}} \quad 4.6$$

By considering minimum cost criterion the depth of cut , speed, and feed must be chosen to minimise the cost. The tool life is given by equation(4.1) and machining time T_m ,generally, is taken to be equal to the actual cutting time[7] T_{ac} and is found from;

$$T_m = \frac{L}{fN} = \frac{L}{\lambda V f} \approx T_{ac} \qquad 4.7$$

where, L is the distance travelled by the tool in making a pass(mm), N is the spindle speed(rpm), $\lambda = 1000/\pi D$, D is the diameter of workpiece(mm).

Substituting equations (4.1, 4.7) into equation(4.2) gives the cost in terms of speed, depth of cut and feed, i.e.,

$$C_T = xT_L + x\frac{L}{\lambda Vf} + xT_d \frac{L}{\lambda A} V^{(n-1)} f^{(n_1-1)} d^{n_2} + \frac{yL}{\lambda A} V^{(n-1)} f^{(n_1-1)} d^{n_2} \qquad 4.8$$

The cutting conditions for minimum cost are;

$$\frac{\partial C_T}{\partial V} = 0 \quad , \frac{\partial C_T}{\partial f} = 0 \quad , \frac{\partial C_T}{\partial d} = 0 \qquad 4.9$$

i.e.,

$$\frac{\partial C_T}{\partial V} = 0 \quad \text{when} \quad 1 = (n-1)\frac{V^n f^{n_1} d^{n_2}}{A}\left(\frac{xT_d + y}{x}\right) \qquad 4.10$$

$$\frac{\partial C_T}{\partial f} = 0 \quad \text{when} \quad 1 = (n_1-1)\frac{V^n f^{n_1} d^{n_2}}{A}\left(\frac{xT_d + y}{x}\right) \qquad 4.11$$

$$\frac{\partial C_T}{\partial d} = 0 \quad \text{when} \quad 1 = (n_2-1)\frac{V^n f^{n_1} d^{n_2}}{A}\left(\frac{xT_d + y}{x}\right) \qquad 4.12$$

Equations (4.10), (4.11), (4.12) can not be simultaneously satisfied and a unique minimum does not occur. This is because $n_2 < n_1 < n$ hence for any value of feed or depth of cut, the cutting speed required to satisfy equation (4.12) is lower than the one found from equation (4.10) and equation (4.11). The loci of these equations are shown in Figure 4.2, The cost axis is perpendicular to the f-V-d plane.

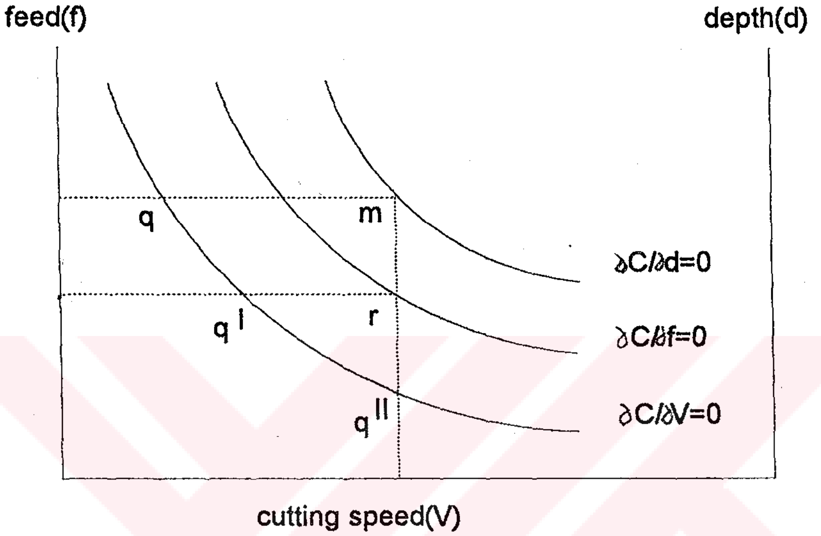


Figure 4.2 Cost curves

Since a unique minimum does not occur it is necessary to determine a method for selecting the feed, depth of cut and speed which will give the permissible minimum cost. Considering equations (4.10), (4.11), (4.12), it can be shown that, since $n_2 < n_1 < n$, the cost at point q, in Figure 4.2, is lower than that at point m, and the cost at point m is lower than that at points r and q^{II}. Similarly the cost at point q^{I} is lower than at point r, and the cost at point r is lower than that at point q^{II}.Therefore, the cost is found by selecting the highest possible feed and depth of cut. The cutting speed is then determined from equation (4.1). Methods for finding highest possible depth of cut and feed for different turning operations for minimum cost criterion are explained in the next sections .

If the equation (4.10) is expressed in the form,

$$\frac{A}{V^n f^{n_1} d^{n_2}} = (n-1)(\frac{xT_d + y}{x}) = T_{opt} \qquad 4.13$$

where, T_{opt} is the optimum tool life for minimum cost. This equation shows that the tool life for minimum cost depends on the tool-life speed exponent (n) and the ratio of the tool costs to the labour and overhead cost rate. Reduced tool costs will give a lower T_{opt} and increased optimum speed. When the cutting conditions are found in terms of the tool life T_{opt}, the corresponding optimum speed V_{opt} is found from;

$$V_{opt} = (\frac{A}{T_{opt} f^{n_1} d^{n_2}})^{1/n} \qquad 4.14$$

4.4.1 Optimisation Procedure for Roughing and Boring Operations

Roughing and boring operations are the most important operations in turning applications, since they are the major contributors to the cost of machining in a turned component.

On numerically controlled machines the main problem that has to be considered is swarf disposal; it is essential that the cutting conditions selected are such that easily disposable chips are produced[6]. Cutting speed has less effect on chip breaking[43,48], when compared with feed and depth of cut. To determine the possible cutting region for satisfying the chip breaking requirement some researches made many experiments and they represented their results by a diagram which is called chip breaking (d-f) diagram [43,47,55] as explained in section (3.3.2), The d-f diagram is defined as those combination of depth of cut (d) and feed (f) which produces disposable chips easily. Such diagrams are now available from cutting tool manufacturer's catalogues and an example is shown below[54].

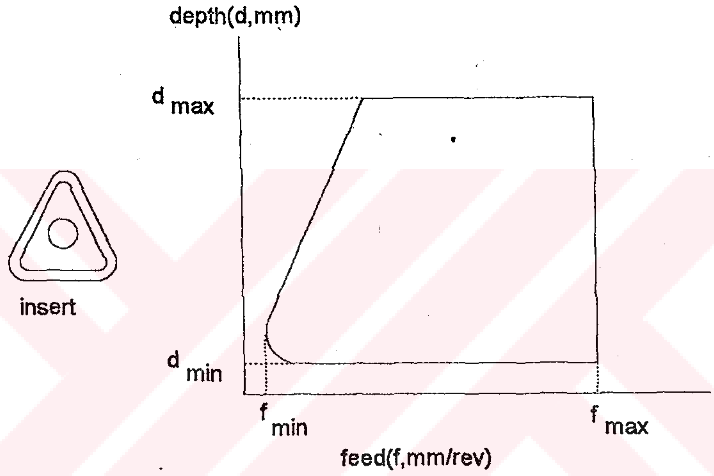


Figure 4.3 Chip breaking diagram for a specified insert [54]

By using this diagram a method which is similar to Arseculаratne's method[7] developed for obtaining optimum values of depth of cut (d_{opt}) and feed(f_{opt}).

The diagram is divided into certain number of grids. The number of grid points in the depth of cut and feed directions can be varied depending upon the accuracy to which the optimum depth and feed values are required. One should also take the sensitivity of machine tool into consideration when obtaining exact values of the depth of cut and feed. In this study chip breaking diagrams are divided into 20x20 grids. It is considered that some part of this diagram is feasible and other is non-feasible because of the constraints which will be explained in the next sections. It is obvious that the optimum values for feed and depth of cut can be found only in feasible region. As explained in section 4.3, they are the highest possible values which give the minimum cost. The feasible and non-feasible regions are separated by a curve as shown in Figure 4.4.

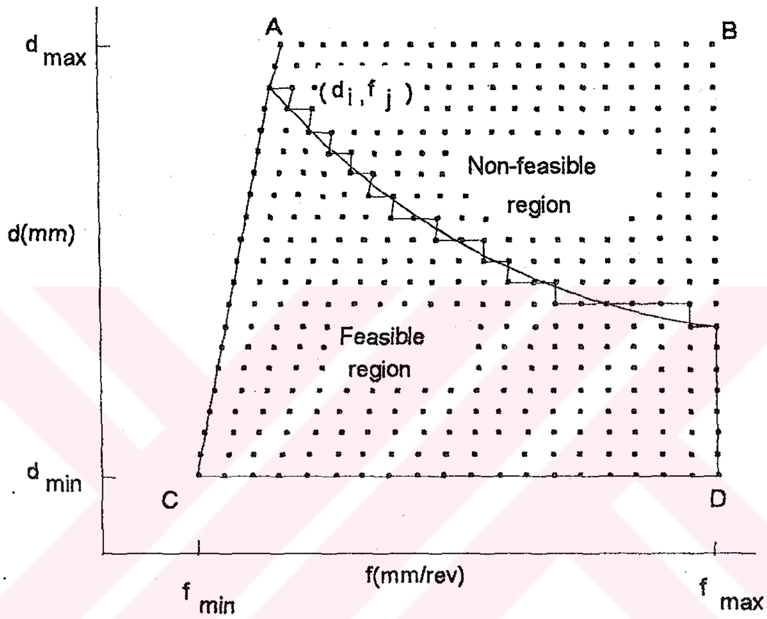


Figure 4.4 Chip breaking area

Highest possible values for feed and depth of cut lie on this line. A search procedure is used for finding these values. The search procedure starts from point A in figure 4.4 and the following steps are involved;

A grid point defined by (d_i,f_j) is tested for constraints (constraints are explained in section 4.4.3). If it is non-feasible (as shown in Figure 4.5 by (n)) then the point with the lower depth (as shown in Figure 4.5 by (y)) is tested for constraints. If this point is feasible the optimum cutting speed is calculated for this point by using equation 4.14. Optimum tool life is then calculated by using the objective criteria (minimum cost). The optimum cutting speed is then checked for constraints whether it violates any one of them, a sub optimum cutting speed is calculated which satisfies the constraints. The specific cost of machining is calculated for this point. The point with the same depth of cut but higher feed is considered next and the procedure continues until the first non-feasible point on the lowest depth line is met(point D in figure 4.4). The point which has the minimum cost is considered as optimum point for the pass. The program performs all these operations for the following passes until the sum of the optimum depth of cuts equals or exceeds the stock to be removed. If sum of the optimum depth of cuts exceeds the stock to be removed then, they are modified in order to remove the exact stock. There are some ways of carrying out this modification. Some of them are explained below[30].

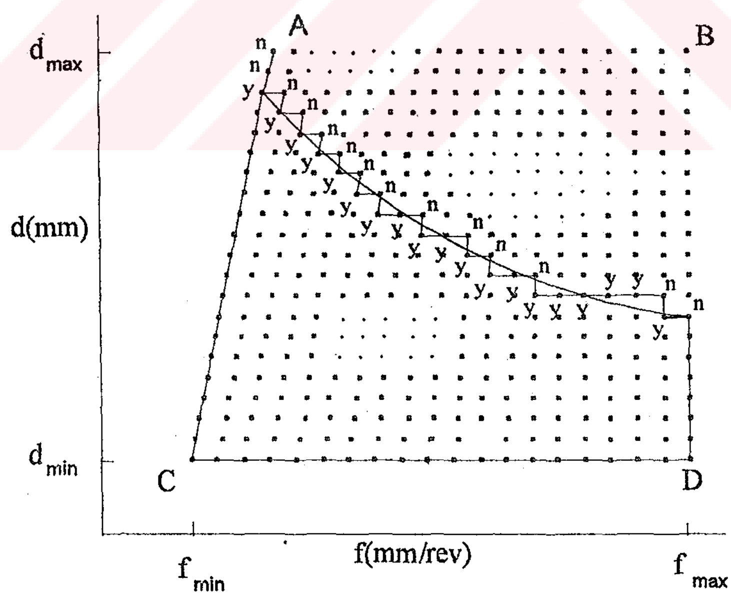


Figure 4.5 Chip breaking area

Method 1: In this method, the last pass is eliminated. The amount that would have been machined in this pass is labelled as estock in Figure 4.6. and it has to be redistributed between the other (n-1) previous passes. The amount added to a particular pass depends upon its relative magnitude.

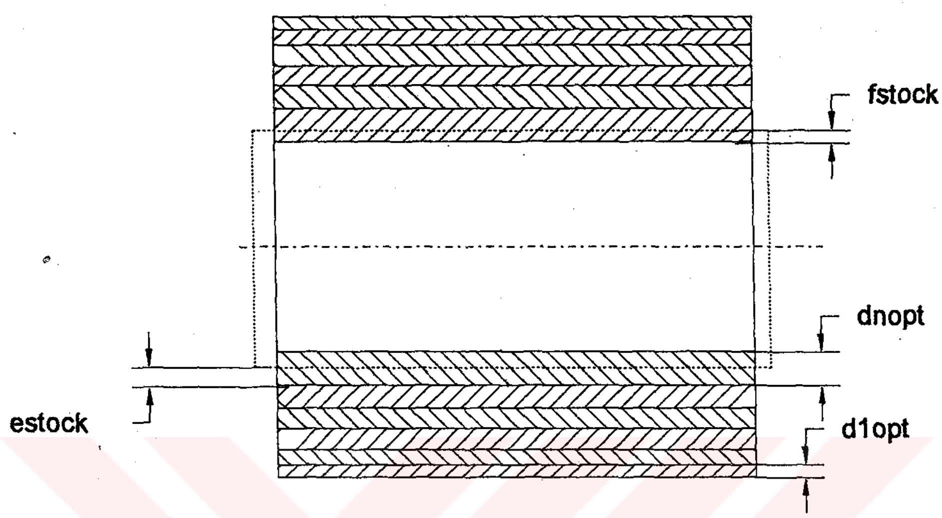


Figure 4.6 Modification of last pass

Method 2: In this method, the number of passes are kept the same but the amount which exceeds the stock to be removed (fstock in Figure 4.6) is subtracted from the previous depth of cuts as described in equation 4.15. The reduced depth of cut in the i^{th} pass is given by:

$$d_i = d_{i_{opt}} - (fstock / \sum_{i=1}^{n} d_{i_{opt}})\, d_{i_{opt}} \qquad 4.15$$

where;

$$fstock = \sum_{i=1}^{n} d_{i_{opt}} - d_{total}. \qquad 4.16$$

Method 3: In this method, the depth of cut in the last pass is made equal to estock. The depth of cuts in the other passes retain their optimum value.

Method 4: In this method, the last pass is eliminated and the amount that would have been machined in the last pass is added to the previous pass.

$$d'_{n-1} = d_{(n-1)_{opt}} + d_{stock} \qquad 4.17$$

This method cannot be used if d'_{n-1} becomes greater than the maximum permissible depth of cut for the $(n-1)^{th}$ pass.

In this study the 3rd method is used since it is practical and gives better results when compared with the others.

4.4.2 Optimisation Procedure for Facing Operations

Although facing is considered as a single pass operation in many works[32,42], in this study, it is considered as multi-pass operation. The optimisation procedure for determining the optimum cutting parameters for facing is the same as roughing and boring operations. But in a cylindrical turning operation (roughing, boring etc.) constant spindle speed gives a constant cutting speed, and the cutting speeds for minimum cost criterion can be calculated using equations previously developed. In a facing operation, however, a constant spindle speed results in a variable cutting speed.

A facing operation is shown in Figure 4.7. In this operation, the cutting speed varies linearly with the radius of the cut, r; the cutting speed is maximum at the periphery of the workpiece and minimum at the end of the operation.

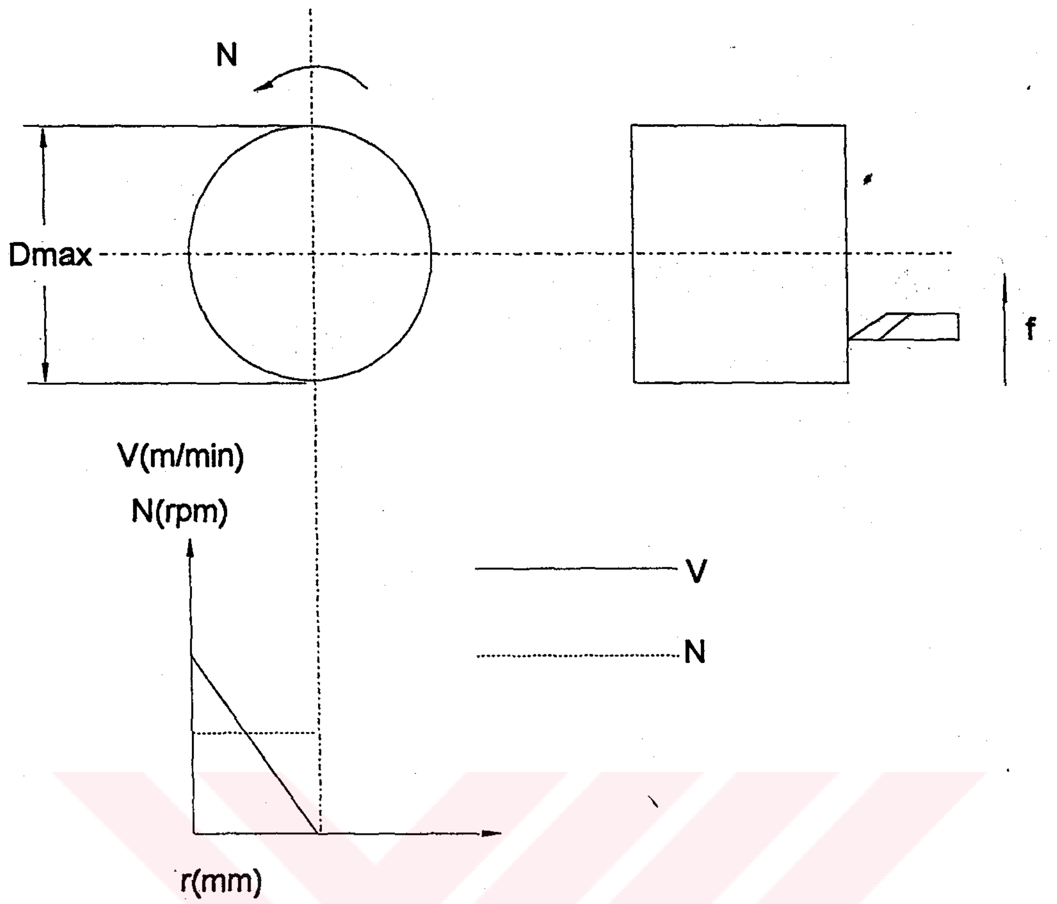


Figure 4.7 Relation between rotational and cutting speed in face turning

It is known that lathes without numerical control (conventional lathes) have stepwise drivers, which means that the cutting speed can only be changed only gradually. When using numerically controlled lathes it is possible to change spindle revolutions continuously. In that case, it is possible to keep cutting speed (V) constant by regulating spindle revolutions progressively.

In this study spindle revolutions are kept constant, because in the case of programming CNC lathes by using M-G codes it is not possible to input spindle speed as variable[35].

Optimum cutting speed is calculated by using equation 4.14. then the optimum spindle speed is given by the following equation:

$$N_{opt} = V_{opt} 1000/ \pi D_{max} \qquad 4.18$$

where, D_{max} is maximum facing diameter in (mm).

4.4.3 Constraints

Chip breaking area explained above is in itself a constraint for obtaining disposable chips. In addition to this the following constraints are also considered.

4.4.3.1 Maximum and Minimum Depth of Cuts and Feeds for the Tool and Workpiece Material

A point (di,fj) (in Figure 4.4) is tested for the allowable minimum and maximum values of feed and depth of cut for specified workpiece and tool material

$$d_{maxt} = (2/3)\,l_e \qquad 4.20$$

$$f_{maxt} = \min(0.8r_e, \quad P_a\, f_{max}) \qquad 4.21$$

where, l_e is cutting edge length(mm) and r_e is tool nose radius(mm).

4.4.3.2 Maximum Allowable Tool Force

Cutting forces can be calculated by using equations 3.1. Resultant cutting force can then be calculated as :

$$F_R = \sqrt{F_t^2 + F_r^2 + F_a^2} \qquad 4.22$$

The maximum force that tool can withstand is calculated as:

$$F_{tmax} = P_a \sqrt{F_{t_B}^2 + F_{r_B}^2 + F_{a_B}^2} \qquad 4.23$$

where, Pa is plane angle factor which is 1 for square insert, 0.7 for triangular insert, etc. as manufacturer recommends[55]. F_{tB}, F_{rB}, F_{aB} are the tangential, radial and feed components of cutting force corresponding to point B in f-d diagram (Figure 4.4).

If the resultant cutting force F_R at (d_i, f_j) is greater than F_{tmax}, then the point becomes non-feasible.

4.4.3.3 Holder Strength and Rigidity

i) Maximum force permitted by the shank at critical cross section is:

$$F_{tp} = \frac{BH^2 \sigma_t}{6L} \quad \text{for square cross-section.} \qquad 4.24$$

$$F_{tp} = \frac{\pi d^3 \sigma_t}{32L} \quad \text{for round cross-section.} \qquad 4.25$$

where, Ftp is maximum allowable force, B,H,L are width height and free length of the holder. d is diameter of the holder(in the case of round tool holder). σ_t is bending strength of the holder material.

If the tangential component of the cutting force (F_t) at (d_i,f_j) is greater than F_{tp}, then the point becomes non-feasible.

ii) Maximum load permitted for the rigidity of the tool is:

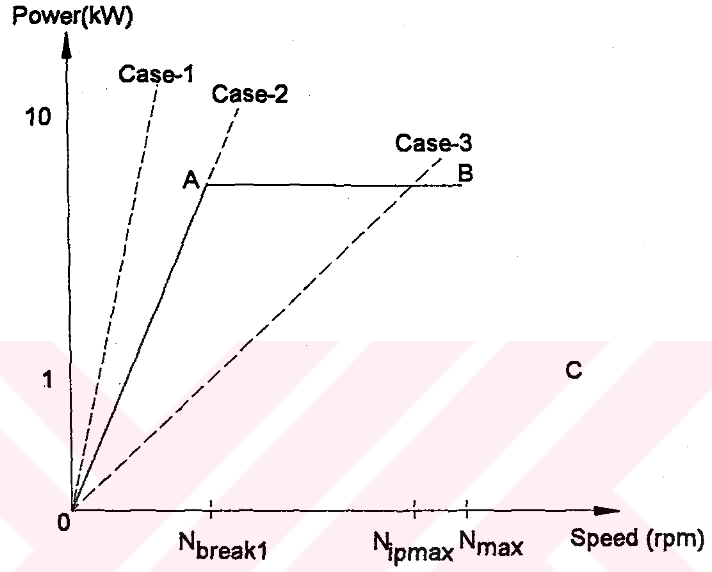
$$F_{tr} = \frac{3f\,EI}{L^3} \qquad 4.26$$

where, I is second moment of inertia of holder and it is equal to $BH^3/12$ for square cross-sections, $0.05d^4$ for round cross-sections. f is maximum allowable deflection of the holder and it is equal to 0.1 mm in roughing operations, 0.05 mm in finishing operations as tool manufacturer recommends[50]. E is the modulus of elasticity of holder material.

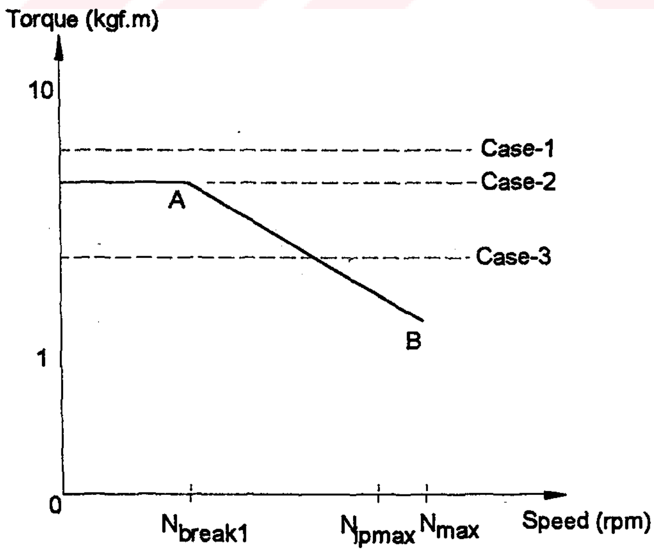
If the tangential component of the cutting force at (d_i,f_j) is greater than F_{tr}, then the point becomes non-feasible.

4.4.3.4 Spindle Motor Torque-Speed Characteristic

The torque and power speed characteristic of spindle motor is usually specified by machine tool manufacturer. The torque and power speed characteristic of a motor drive is shown in Figure 4.8.



(a) Power speed characteristic of the motor



(b) Torque speed characteristic of the motor

Figure 4.8 Torque and power-speed characteristic of a motor [56]

These characteristics are interrelated, since one can be driven from the other. Therefore, it will be sufficient if only one of the characteristic is considered as a constraint.

Torque due to the cutting force component F_t is calculated as (F_t*r) and rotational speed can easily be determined from torque-speed curve of the motor. If torque is greater than stall torque of the motor, then the point (d_i,f_j) is considered to be non-feasible (case 1 in the figure). Otherwise, corresponding speed is selected as rotational speed of the workpiece from which cutting speed could be determined as ($V_m=2\pi N/1000$) (case 2 and 3 in the figure). If this speed is less than Vopt calculated by the equation 4.14. then optimum speed to be used in the next steps is taken to be equal to V_m.

4.4.3.5 Work Holding Limitations

If the workpiece is gripped from their external surfaces and if there is no compensation in gripping mechanism, work holding becomes more critical. For these conditions, at any speed, the clamping force is expressed as:

$$F_c = F_{co} - \sum m_j r_j \left(\frac{2\pi N}{60}\right)^2 \qquad 4.27$$

The clamping force Fco at zero speed could be taken from handbooks or it may be calculated from the chuck hydraulic activating pressure. The component must be securely hold in the chuck in such manner that there must not exist axial slip, circumferential slip and component throw-out. The limiting speed values that can be used to prevent axial, circumferential slip and component throw-out are derived by many researchers[25,38,44].

In the case of internal gripping of the workpiece, the clamping force will not decrease while spindle speed increase, for this reason internal gripping situation is not considered.

Configuration given below can be considered when driving the restrictions.

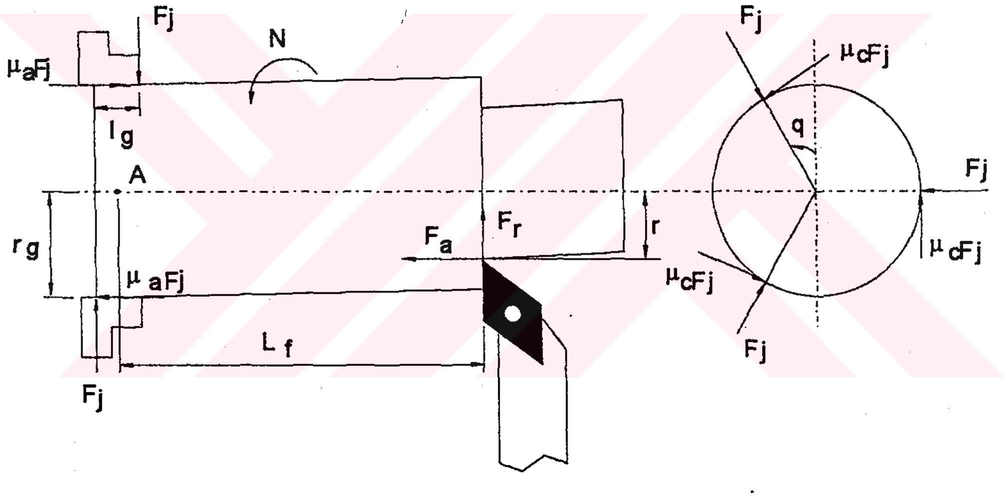


Figure 4.9 Chucking and cutting forces acting on a component

i) Axial slip: To prevent the occurrence of axial slip, the component of cutting force in the axial direction must be less than the frictional force (see Figure 4.9).

$$F_a < \mu_a F_c \qquad 4.28$$

By using equation 4.27, maximum spindle speed without risk of axial slip is calculated as:

$$N_a = \frac{60}{2\pi}\left(\frac{F_{co} - F_a/\mu_a}{\sum m_j r_j}\right)^{1/2} \quad 4.29$$

If the optimum spindle speed (N_{opt}) is greater than N_a then N_{opt} is taken to be equal N_a.

ii) Circumferential slip: To prevent circumferential slip, the torque due to tangential force component must be less than the frictional torque.

$$F_t r < \mu_c F_c r_g \quad 4.30$$

Maximum spindle speed without risk of circumferential slip is calculated as:

$$N_c = \frac{60}{2\pi}\left(\frac{F_{co} - F_t r/\mu_c r_g}{\sum m_j r_j}\right)^{1/2} \quad 4.31$$

If N_{opt} is greater than N_c then N_{opt} is taken to be equal to N_c.

iii) Component throw-out: Component throw-out is possible when the component is held using chuck only. The forces acting on a component at the point of machining and at the clamped end are shown in Figure 4.9.Considering moments about point A;

$$\begin{aligned} M_{horizontal} &= F_r L_f - F_a r \\ M_{vertical} &= F_t L_f \end{aligned} \quad 4.32$$

The resisting moment about point A is given by;

$$M_j = \frac{l_g}{2} F_j (\cos\theta + \cos(\theta+120) + \cos(\theta+240)) + \mu_a F_j r_g (\cos\theta + \cos(\theta+120) + \cos(\theta+240)) \qquad 4.33$$

M_j is minimum when θ =30°

$$M_{jmin} = (\frac{l_g}{2} + \mu_a r_g)\frac{F_c}{\sqrt{3}} \qquad 4.34$$

The component is held securely when;

$$M_{jmin} > \max(M_{horizontal}, M_{vertical}) \qquad 4.35$$

The maximum allowable speed is calculated as:

$$N_t = \frac{60}{2\pi}\left(\frac{F_{co} - \sqrt{3} M_{hv}/(l_g/2 + \mu_c r_g)}{\sum m_j r_j}\right)^{1/2} \qquad 4.36$$

where, $M_{hv} = \max(M_{horizontal}, M_{vertical})$.

If N_{opt} is greater than N_t then N_{opt} is taken to be equal to N_t.

4.4.3.6 Torque-Speed Characteristics of Feed-Drive Motors

Although Fa and Fr are smaller than Ft, feed axis motors must still be checked in a similar way as in the spindle motor. Maximum torque of z-axis feed drive motor must be compared with the torque resulted from axial cutting force (F_a). Considering the schematic representation of a feed drive mechanism given below;

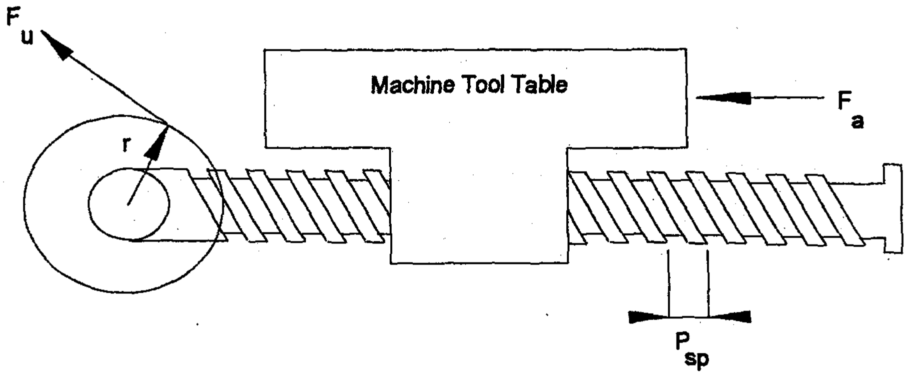


Figure 4.10 Schematic representation of feed-drive mechanism

torque resulted from feed force can be driven as:

$$F_u 2\pi r = F_a P_{sp} 1/\eta \qquad 4.37$$

where, $M = F_u r$

$$M = \frac{F_a P_{sp}}{2\pi\eta} \qquad 4.38$$

where, η efficiency of lead-screw assembly, P_{sp} is lead(mm), F_a is axial component of cutting force(N).

Maximum torque of x-axis feed drive motor is calculated in the same manner and it is especially important in grooving, facing and parting-off operations.

4.4.3.7 Deflection of the Workpiece

In the deflection analysis, a beam model is considered. In this model, beam structure is clamped at one end and free at the other; such a situation is identical to a workpiece mounted between the jaws of the chuck and free in the other end.

Only external operations are considered in the analysis since deflections during internal operations will be smaller than the deflections during external operations. By using geometry of the blank and sequence of operations data which is the output of the process planning program [36], The geometry of the part after each pass is recalculated (which may be a stepped beam) and stored as the geometry of the new part. In an operation, critical point for the deflection is taken as the point which has the largest distance from the chuck.

By using Castigliano's theorem, deflection at the critical point is calculated for each pass in related operation. The method of calculation is follows as:

$$\delta_i = \frac{\partial U}{\partial F_{r_i}} \qquad 4.39$$

Equation 4.39 is the statement of Castigliano's theorem as applied to problems where the force-deflection relation is linear.

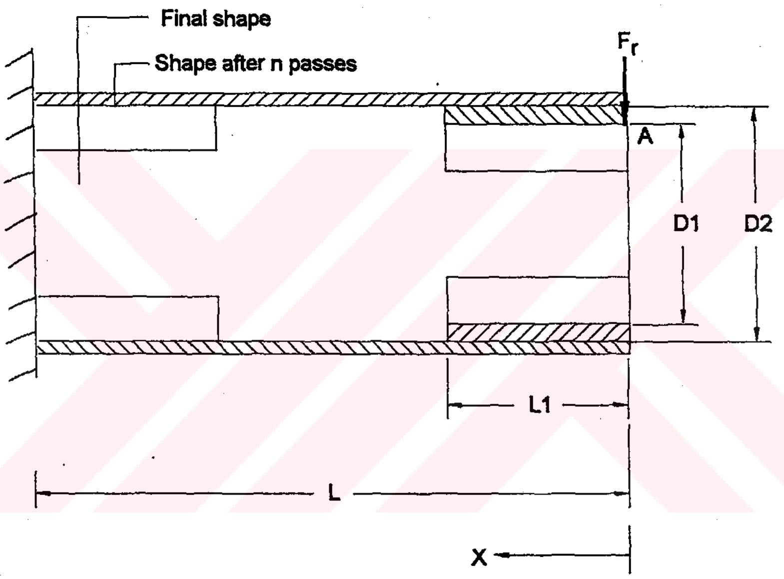
The elastic strain energy in bending is given by[52].

$$U = \int_L (M^2/2EI)\, dx \qquad 4.40$$

So equation 4.39 can be written in the form:

$$\delta_i = \int_L (1/EI)(M\, \partial M/\partial Fr_i)\, dx \qquad 4.41$$

If the stepped shaft given in Figure below is considered, deflection at the critical point A can be found as:



The bending moment is:

$$M = -F_r\, x \qquad 0 < x < L$$

Therefore;

$$\frac{\partial M}{\partial F_r} = -x$$

Since the moment of inertia (I) is a discontinuous function of x, the integration must be divided into parts. Thus;

$$\delta_f = 1/EI_1 \int_0^{L_1} (-F_r x)(-x)\, dx + 1/EI_2 \int_{L_1}^{L} (-F_r x)(-x)\, dx$$

$$\delta_f = \frac{F_r}{3EI_1} L_1^3 + \frac{F_r}{3EI_2}(L^3 - L_1^3) \qquad 4.42$$

where, E is modulus of elasticity of the workpiece material, $I_1 = \pi D_1^4/64$, $I_2 = \pi D_2^4/64$.

If the deflection (δ_f) is greater than the maximum allowable deflection, the radial cutting force must be reduced. This means the grid point (di,fj) is non-feasible.

Maximum allowable value of deflection can be taken as a criterion of chatter in turning operations. Rahman[45] showed that the deflection can be used effectively to determine the point of onset of chatter. In other words, chatter can be eliminated by limiting the deflection of the workpiece during cutting operation. Hinduja[6] used a value 0.04mm for the maximum allowable deflection to prevent the chatter. In this study the same value is used for the maximum allowable deflection.

4.4.3.8 Geometrical Accuracy of the Workpiece

The total dimensional error on the workpiece results mainly from the effects of the tool flank wear, system flexibility, geometrical errors and thermal deformations of the machine tool used. However, assuming that machine tool satisfies the standard geometrical acceptance tests and steady state thermal conditions are attained, the last two sources of errors can have only negligible effects on the accuracy of the machined workpiece compared with the first two sources. Therefore, only the effects of the first two will be taken into consideration.

i) Dimensional Error due to the Tool Wear: The flank wear (δ_W) is measured in radial direction w.r.t the workpiece and hence the dimensional error is given by:

$$\delta_w = \frac{w_f}{\tan\alpha} \qquad 4.43$$

The total error at the end of n passes can be written as:

$$\delta_{T_w} = \sum_{i=1}^{n} \delta_{w_i} \qquad 4.44$$

where, w_f is flank wear and it can be calculated by using the equations given in section 3.5.2.1, α is lip angle of the tool.

ii) Dimensional error due to deflection of the workpiece: The method for the calculation of deflection of the workpiece due to radial component of the cutting force in any pass is given in section 4.4.3.7.

Then the total error on the workpiece in a pass is:

$$\delta_t = \delta_{Tw} + \delta_f \qquad 4.45$$

The calculated dimensional error (δ_t) is compared with the maximum permissible error (δ_p) which is the %50 of the specified diametrical tolerance. For a point to be feasible the following inequality must be satisfied:

$$\delta_t < \delta_p \qquad 4.46$$

4.4.3.9 Bearing Design Loads

The preload resulted from axial cutting force component (F_a) must be smaller than the design load (allowable load to have proper function from preloading) of the bearing assembly in the spindle (see Figure 4.11) and bearing assembly in the feed drive mechanism (see Figure 4.12) which control the z-axis movements. The same check should be made for x-axis feed drive mechanism by controlling radial component (F_r) of the cutting force.

In an axially preloaded bearing assembly (thrust-ball bearing assembly see Figures 4.11, 4.12), preloads resulted from cutting force components (F_{pc1},F_{pc2} in the case of spindle and z-axis feed drive bearing assemblies, F_{pc3} in the case of x-axis feed drive bearing assembly) can be calculated by using equations[49].

$$F_{pc1} = \frac{F_a}{(1+r^n)^{1/n}} \qquad 4.47$$

$$F_{pc2} = \frac{F_a}{(1+r^n)^{1/n}} \qquad 4.48$$

$$F_{pc3} = \frac{F_r}{(1+r^n)^{1/n}} \qquad 4.49$$

where, r = M1/M2, M1 is the number of thrust bearings on right side and M2 is the number of thrust bearings on left side . n is a constant, which is equal to 2/3 for angular contact ball bearings and to 9/10 for tapered roller bearings.

Bearing configuration preloaded in axial and radial loading is not considered in this study.

$$\text{if} \quad F_{pc1} > (F_{bdload})_{spindle} \qquad 4.50$$

$$\text{if} \quad F_{pc2} > (F_{bdload})_{z-feed} \qquad 4.51$$

$$\text{if} \quad F_{pc3} > (F_{bdload})_{x-feed} \qquad 4.52$$

Then the point (d_i, f_j) is non-feasible.

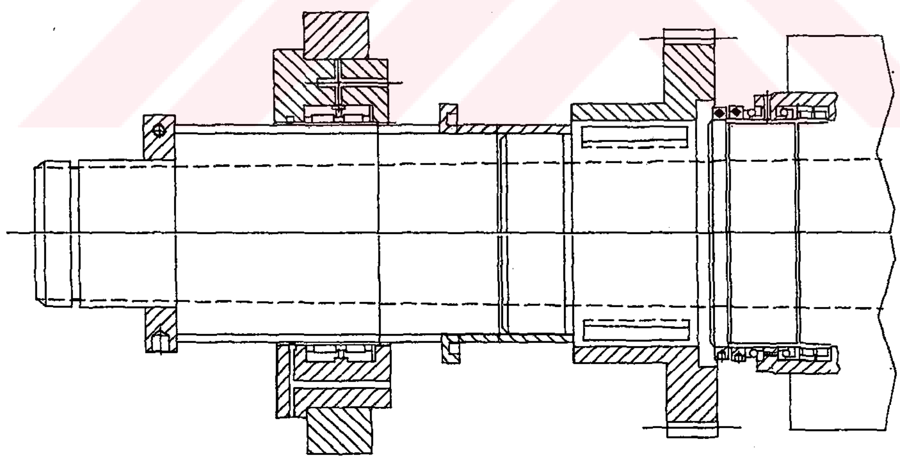


Figure 4.11 A lathe spindle with thrust and ball bearing arrangement [57]

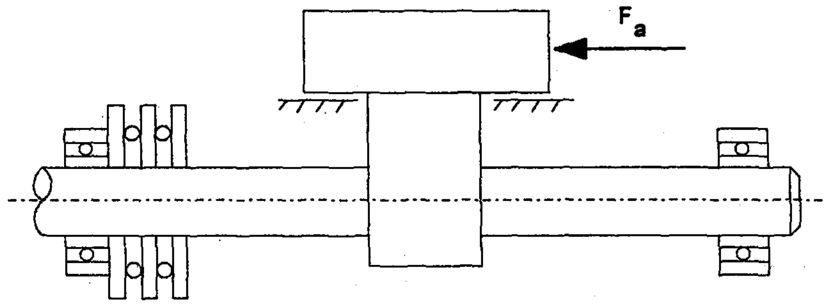


Figure 4.12 Schematic view of feed drive assemblies with thrust and ball bearing arrangement

4.4.3.10 Cutting Tool Velocities

The cutting speed must be within the range $V_{tmin} \leq V_{opt} \leq V_{tmax}$. Where, V_{tmin} is minimum allowable speed for the tool to avoid built-up edge, and V_{tmax} is maximum allowable speed for the tool to avoid tool burn-out. V_{tmin} and V_{tmax} are calculated by using maximum and minimum values of tool life (T_{max}, T_{min}) specified for the tool. Values for T_{min} and T_{max} are specified in manufacturer's catalogues.

$$V_{tmin} = \left(\frac{A}{T_{max} f^{n_1} d^{n_2}}\right)^{1/n} \qquad 4.53$$

$$V_{tmax} = \left(\frac{A}{T_{min} f^{n_1} d^{n_2}}\right)^{1/n} \qquad 4.54$$

If the optimum cutting speed at (d_i, f_j) is greater than V_{tmax} or smaller than V_{tmin} then the point is non-feasible.

4.4.3.11 Cutting Temperatures

The tool-work temperature (θ_f) and tool-chip temperature (θ_c) can be calculated by using equations (3.3) (3.4).

In a cutting process avoiding thermal failure, θ_f and θ_c must be smaller than the permissible value θ_p, specified for the tool-workpiece material combination[4]. If the temperatures calculated at a grid point (d_i,f_j) is greater than the permissible values, then the optimum cutting speed at that point is reduced to satisfy the temperature constraint. If this not possible then the point becomes non-feasible

4.4.3.12 Tool Wear Restriction

The values of flank wear (w_f) and crater wear (w_c) can be calculated by using equations given in section 3.6.2. If sum of the flank wear and crater wear is greater than the permissible values which are given in section 3.6.2.1., then the cutting speed is reduced in steps to satisfy the wear criterion, if this is not possible then the point (d_i,f_j) becomes non-feasible.

4.4.3.13 Surface Roughness

Neglecting the influence of cutting speed, the maximum permissible feedrate to achieve a given surface finish, can be found by using equation (3.9) which is driven in section 3.7.

$$f_{f_{max}} = \sqrt{8 h_{all} r_e} \qquad 4.55$$

Where r_e is tool nose radius, h_{all} is maximum allowable value of surface roughness.

If the value of feed in the last pass is greater than $f_{f_{max}}$ then the point becomes non-feasible.

4.4.4 Optimisation Procedure for Grooving and Parting-off Operations

4.4.4.1 Characteristics of Grooving and Parting-off Operations

These operations still remain one of the most problematic of all cutting operations[41]. The most important characteristics of these operations in comparison to other cutting operations in turning are:

i) During parting-off, the cutting speed changes from a maximum at the outer diameter of the workpiece and decreases to zero when reaching the center of the workpiece. This phenomenon is only true when a constant N(rpm) is maintained (see Figure 4.13). This situation is considered in this study for the reasons explained in section 4.4.2. The same situation is also true for grooving operations.

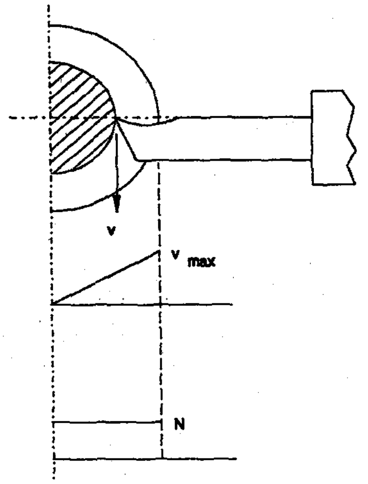


Figure 4.13 Cutting speed in parting-off and grooving

ii) The forces acting during parting-off and grooving namely; Cutting force(tangential) Ft, axial force Fa and radial force Fr are as shown in Figure 4.14.

Axial forces are effective only when cutting is done in three dimensional parting operations, meaning that the cutting edge is not parallel to the turning axis (i.e., the axis of the workpiece).

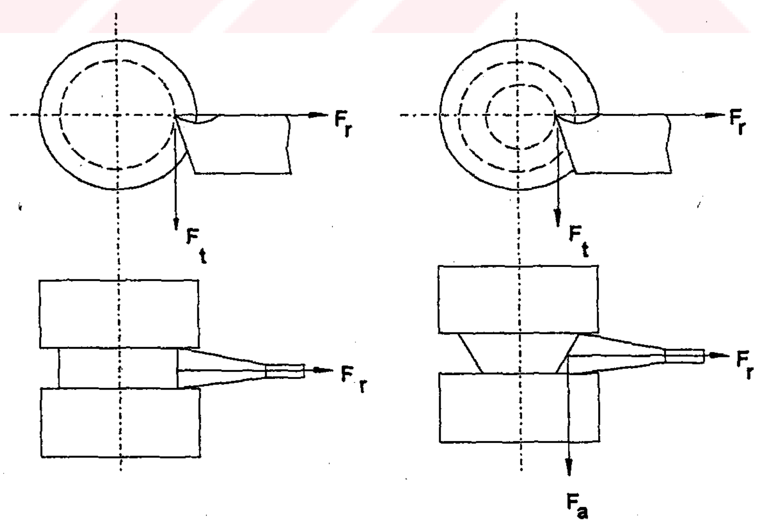


Figure 4.14 Forces acting during a) two dimensional parting-off and grooving b) three dimensional parting-off operations

4.4.4.2 Optimisation Method

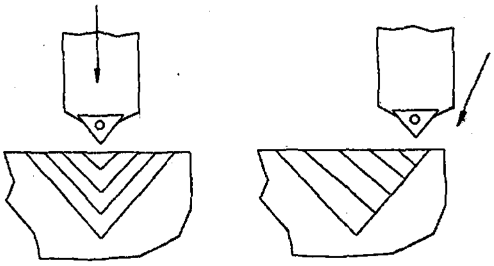
For these operations, width of cut is equal to the cutting edge width of the tool. The feed and cutting speed are the variables that must be considered in the optimisation problem. The steps that involved in the optimisation are:

The feed is first set to the maximum allowable value for the tool, whose values can be found in manufacturer's catalogues[54]. The feed is then checked for constraints as explained in section 4.4.3. If it violates any one of these constraints, then it is reduced in steps of 0.01 mm/rev, until the constraints are satisfied.

At the point where the feed satisfies all constraints, the optimum cutting speed is calculated by using equation 4.14. This speed is reduced to two-thirds as recommended by tool manufacturer[54]. This speed is then checked for constraints , if it violates any one of them then it is modified to satisfy the constraint as explained in section 4.4.3.5.

4.4.5 Optimisation of Threading Operations

If a single point tool is used for threading, the stock is removed in a number of passes for producing the final shape of the thread. The tool is fed in by the previously determined infeed depth. This is done generally by two methods; radially (straight infeed) or parallel to one of the flanks (flank infeed), as shown in figures given below.

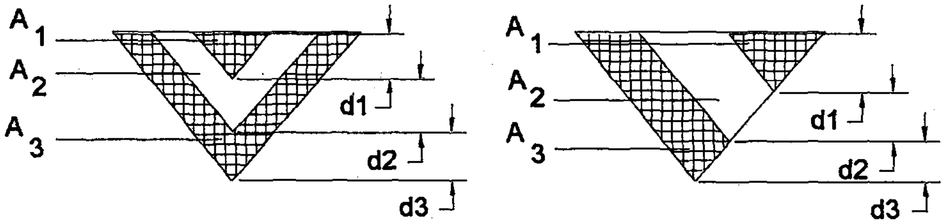


(a) (b)

Figure 4.15 Types of infeed (a) straight infeed, (b) flank infeed

If straight type infeed is used ,V-shaped chips are formed. These type of chips are not preferable because it is difficult to deform this chip and it causes problems in chip flow[55]. This method is generally used in short-chipping materials[55]. If flank type of infeed is used, the chips formation is similar to that of turning. The chips are easily formed and guided. Thus, this type of infeed has advantages in chip flow when machining long-chipping materials.

In order to apply a constant load on the cutting edge, the infeed depth for each pass is reduced as the engaged length of cutting edge increases. The chip thickness is thus reduced and chip area becomes a constant (see Figures below).



A1=A2=A3

Figure 4.16 Constant area criterion

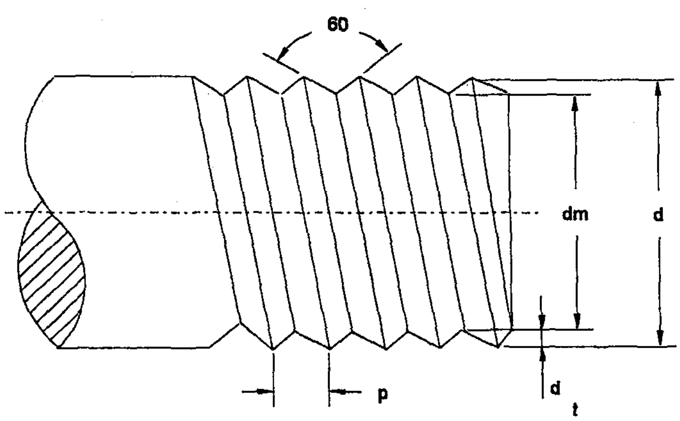
In the case of high quality threat, the depth in the last pass (spring pass) is set to a very low value, say 0.038 mm as manufacturer recommends [55].

Due to a risk of overheating the cutting edge, the cutting speeds recommended for threading are lower than those recommended in turning. The appropriate cutting speeds for a particular workpiece / tool material combination can be obtained from manufacturer's catalogues [54].

4.4.5.1 Optimisation Procedure for Threading Operations

Optimum number of passes, infeed per pass and the speed are the only variables that need optimisation in a threading operation. The main steps of the optimisation procedure are as follows;

1- Considering the form of the thread (i.e., ISO metric, which is considered in this study) the total depth of the threat can be determined by using the well known equations given below.



$$d_t = \frac{d - d_m}{2} \tag{4.56}$$

$$d_m = d - 1.226869\,p$$

2- The infeed for the first pass is calculated as:

$$d_1 = 0.20899\,d_t + 0.16351 \text{ for straight infeed} \quad 4.57$$

$$d_1 = 0.20899\,d_t + 0.18881 \text{ for flank infeed} \quad 4.58$$

Where d_1 is depth for the first pass(mm), dt is total depth of the threat(mm), the constants in the equations are recommended by the manufacturer[37].

3- If a spring pass is considered and taken as 0.038mm, the total depth removed during the roughing passes, d, is:

$$d = d_t - 0.038 \quad 4.59$$

4- Since the value of d_1 is known , and by using constant area criterion, the infeeds for the other passes are calculated, until total depth d is removed.

5- The amount of overshoot is equally distributed over the roughing passes.

6- The cutting speed is calculated based on the recommended speed for workpiece/tool material combination and it is used for all passes.

4.4.6 Optimisation of Drilling Operations

Drilling operation must be done before a boring operation and this operation consumes considerable machining time, especially when HSS drills are used. But, in the case of carbide tipped drills, the speeds normally used with carbide turning tools become possible. The feeds used have the same magnitude for both types of drills.

4.4.6.1 Cutting Torque and Thrust in Drilling

The forces acting on a drill in a drilling operation can be shown schematically as in the Figure 4.17.

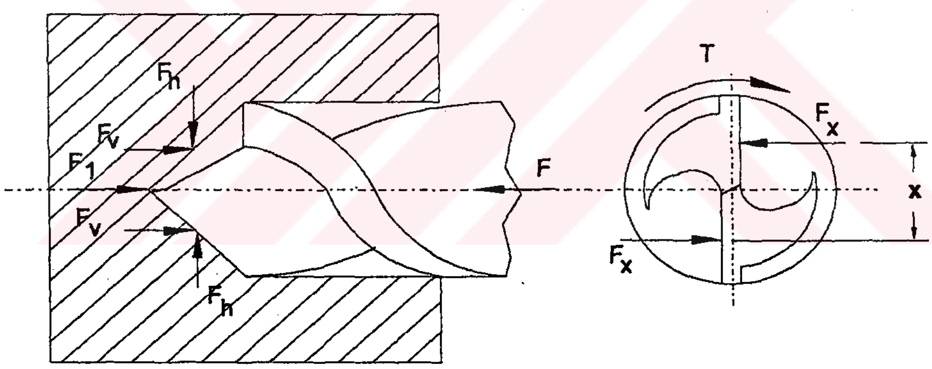


Figure 4.17 Cutting forces in drilling

Thrust load (Fy) in drilling is given by the empiric formula [10].

$$F_y = 9.81 C_p D^{x_p} f^{y_p} \quad \text{(N)} \qquad 4.60$$

where, D is the diameter of the drill (mm), f is the feed rate (mm/rev), C_p, x_p, y_p are constants for a given tool/workpiece pair.

The torque (M) in drilling is given by the formula[10].

$$M = 9.81 * 10^{-3} C_m D^{x_m} f^{y_m} \quad (Nm) \qquad 4.61$$

where, D is the diameter of the drill(mm), f is feed rate(mm/rev), C_m, x_m, y_m are constants for a given tool/workpiece pair.

4.4.6.2 Optimisation Procedure for Drilling Operations

Optimisation procedure for drilling determines the optimum feed first and then the cutting speed for the operation.

The restrictions which are considered for the determination of optimum feed rate are:

1) Maximum machine torque: Maximum torque which can be provided by a machine is:

$$M_1 = \frac{60 P_{max}}{\pi N_{break1}} \qquad 4.62$$

By using equation 4.61 and 4.62, the maximum allowable feed to satisfy the maximum machine torque restriction can be solved as:

$$f_{max1} = \left(\frac{60000 P_{max}}{9.81 \pi C^m D^{x_m} N_{break1}}\right)^{1/y_m} \qquad 4.63$$

2) Limiting torque for the drill: Limiting torque that the drill can withstand is calculated by the formula:

$$M_2 = \frac{\pi D_e^3 \tau}{16000 f_{s1}} \tag{4.64}$$

where, D_e is the equivalent diameter for the drill which is equal to 0.7D and τ is the maximum allowable shear strength of the drill material.

By the same method as explained above, the maximum value for the feed rate can be solved by using equations 4.61. and 4.64. as:

$$f_{max2} = \left(\frac{\pi D_e^3 \tau}{156.96 f_{s2} C_m D^{x_m}}\right)^{1/y_m} \tag{4.65}$$

3) Circumferential slip in the chuck: To avoid circumferential slip in the chuck , the torque developed in the cutting operation must be less than the frictional torque (M_3)in the chuck which can be calculated by using the formula:

$$M_3 = \mu_c r_g (F_{co} + \sum (m_j r_j) w_{min}^2) \tag{4.66}$$

Maximum allowable feed rate can be found by the same manner as explained above.

$$f_{max3} = \left(\frac{1000 \mu_c r_g (F_{co} + \sum (m_j r_j) w_{min}^2)}{9.81 C_m D^{x_m}}\right)^{1/y_m} \tag{4.67}$$

4) Axial slip in the chuck: The maximum allowable thrust to avoid axial slip in the chuck can be calculated by using the expression:

$$F_{a2} = \mu_a (F_{co} + \sum (m_j r_j) w_{min}^2) \tag{4.68}$$

By using equation 4.60. and 4.68. the maximum allowable feed to satisfy axial slip restriction can be solved as:

$$f_{max4} = \left(\frac{\mu_a (F_{co} + \sum (m_j r_j) w_{min}^2)}{9.81 C_p D^{xp}} \right)^{1/y_p} \qquad 4.69$$

5) Drill buckling: The maximum load to avoid drill buckling can be calculated by using the formula:

$$F_{al} = \frac{\pi^3 E D^4}{64 L^2 f_{s2}} \qquad 4.70$$

By using equation 4.60 and 4.70, the maximum allowable feed to satisfy drill buckling restriction can be solved as:

$$f_{max5} = \left(\frac{\pi^3 E D^4}{C_p D^{xp} L^2 f_{s2}} \right)^{1/y_p} \qquad 4.71$$

The optimum value of the feed rate is determined as:

$$f_{opt} = \min(f_{max1}, f_{max2}, f_{max3}, f_{max4}, f_{max5}) \qquad 4.72$$

Finally, optimum feed rate is modified if the drill length (L) is greater than (3*D). Feed rate is modified in the following manner;

$$f_{optn} = f_{opt} \qquad \text{if} \qquad L \leq 3D \qquad 4.73$$

$$f_{optn} = 0.85 f_{opt} \qquad \text{if} \qquad 3D \leq L \leq 5D \qquad 4.74$$

$$f_{optn} = 0.75 f_{opt} \qquad \text{if} \qquad 5D \le L \le 7D \qquad 4.75$$

$$f_{optn} = 0.5 f_{opt} \qquad \text{if} \qquad L > 7D \qquad 4.76$$

After the determination of optimum feed rate, optimum tool life is calculated by using the selected criteria (minimum cost) as explained in section 4.3. Optimum cutting speed is then calculated by using Taylor's expanded tool life equation for drills as;

$$V_{opt} = \frac{C_v D^{x_v}}{T_{opt}^{1/m} f_{opt}^{y_v}} \qquad 4.77$$

This speed is finally checked for the constraints as explained in section 4.3.3 and modified if it violates any one of them.

CHAPTER 5

EXECUTION OF THE PROGRAM

5.1 INTRODUCTION

This chapter introduces the computer programs which are prepared for the optimisation of cutting conditions. The flow of the program is illustrated with a specific example.

5.2 OPTURN: Optimised Turning

The program is written in Turbo C++ programming language. A user-friendly pop-up/pull down menu is prepared by using CLIPPER programming language. The program is mainly composed of four modules which are;

- The module for roughing operations
  - The sub module for external rough turning
  - The sub module for boring
  - The sub module for facing
- The module for drilling operations
- The module for grooving operations

- The sub module for external grooving
- The sub module for internal grooving
- The sub module for parting-off

♦ The module for threading operations

- The sub module for external threading
- The sub module for internal threading

The simplified flowcharts of the programs are given in the Appendix B and a simplified flowchart of the main program is given in Figure 5.1. The usage of the program is explained for the example part as shown in figure 5.2.

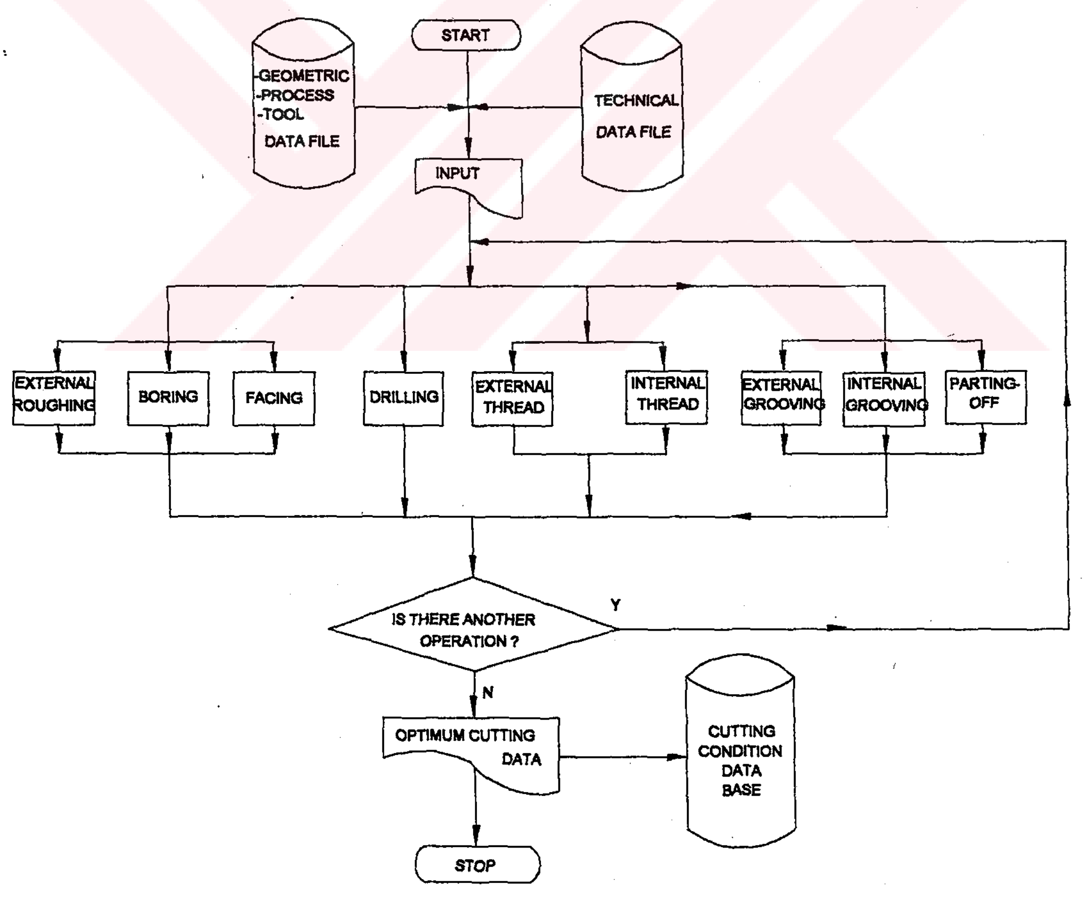
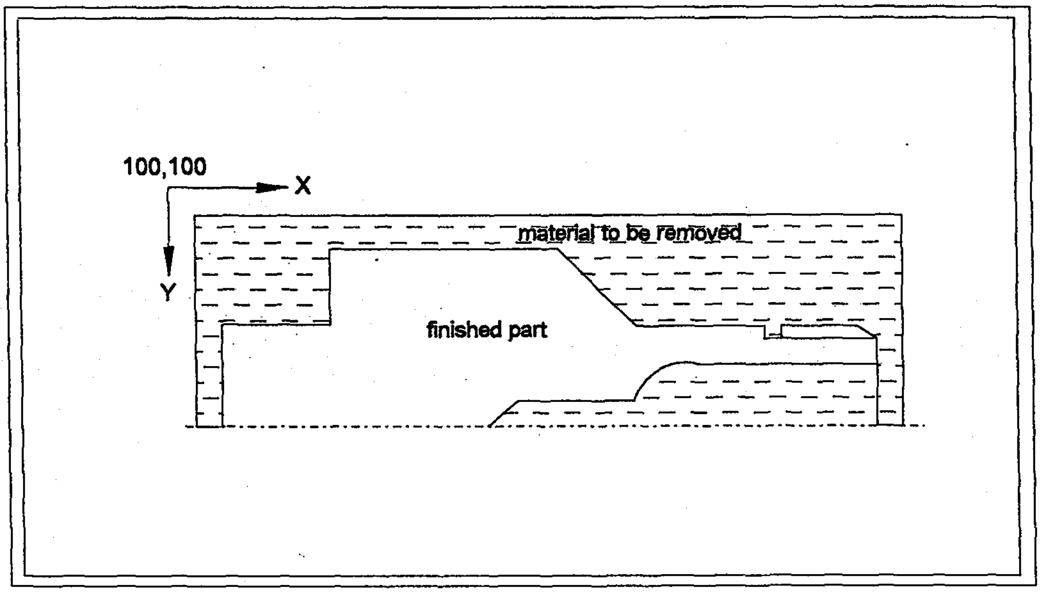


Figure 5.1 A simplified flow chart of the main program



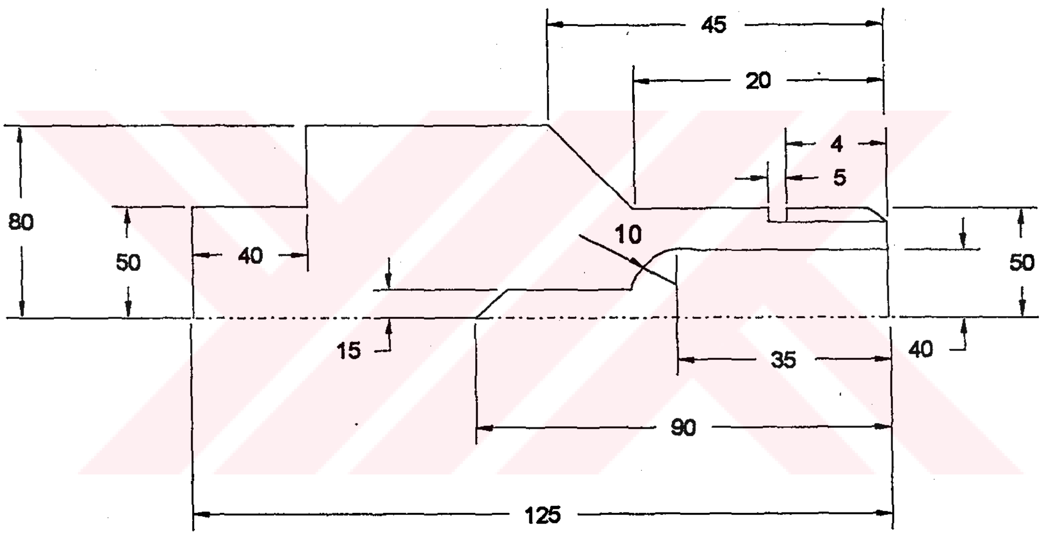


Figure 5.2 The example part

5.3 EXECUTION OF THE PROGRAM

When the program is executed, a user friendly pop-up/ pull-down menu is displayed on the screen (see Figure 5.3). The program can be used easily by using suitable keys from the menu.

The opening screen consists of mainly six menus, which are; INPUT, MANUAL, RUN, VIEW, HELP and EXIT.

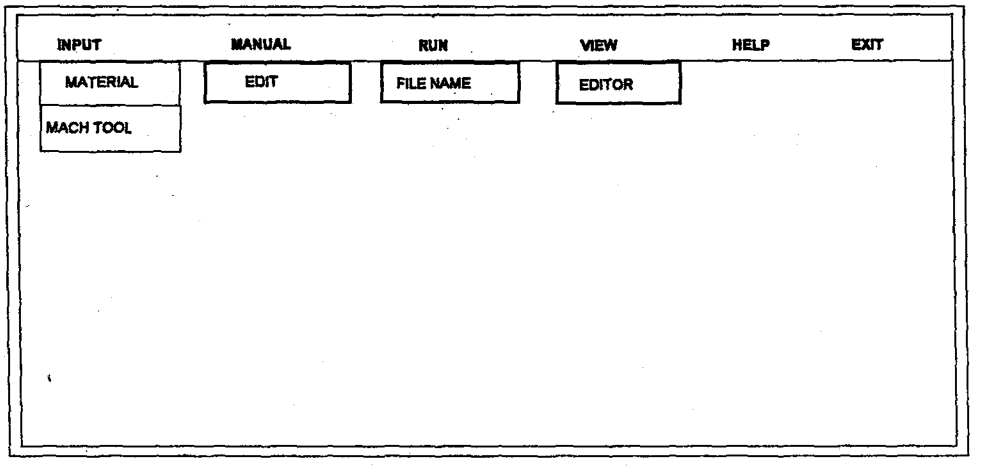


Figure 5.3 The menu of the program

The INPUT menu contains two sub menus, which are MATERIAL and MACHTOOL. By using these menus, machine tools, workpiece material, tool material and tool holder material can be selected. Once these are selected the other necessary data files(constants for the equations, cost data etc.) are opened automatically. Detailed explanations about inputs can be found in section 5.3.1.

RUN menu allows user to run the program.

MANUAL menu is used for taking the part geometry data with sequence of operations , ISO codes of cutting tools and corresponding holders from the user.

VIEW menu can be used for checking outputs of the program.

5.3.1 Input Data for the Optimisation

The input data for the optimisation program consists of six different groups which are;

a) Geometry of the blank and sequence of the operations: The co-ordinates of the blank and sequence of operations can be input manually (by using MANUAL menu) for every operation, or they can be taken from a file which contains the co-ordinates of the blank and sequence of operations (by using RUN menu). This data is the output of Process-Planning program which is prepared by M.C.Kayacan[36]. An example of these data for the example part is shown below.

Table 5.1 Geometry of the Blank and Sequence of Operations.

No	x1	y1	x2	y2	mx	my	θ_s	θ_e	RAD	Operation type
1	240	110	235	155	0	0	0	0	0	EFCN_LH
2	235	110	110	120	0	0	0	0	0	ECYL_LH
3	235	120	190	150	170	120	190	150	0	ECYL_LH
4	190	150	170	120	0	0	0	0	0	ECNC_LH
5	215	150	210	155	0	0	0	0	0	EGRV_LH
6	235	155	230	150	0	0	0	0	0	ECNC_LH
7	275	165	271	165	0	0	0	0	0	ETHR_LH
8	100	120	140	150	0	0	0	0	0	ECYL_RH
9	240	170	150	200	0	0	0	0	0	IDRIL
10	160	170	150	200	0	0	0	0	0	ICNC_LH
11	235	160	200	170	0	0	0	0	0	ICYL_RH
12	200	160	190	170	200	170	90	180	10	IPFR_LH

Table 5.1 includes the operation numbers (NO), and operation types (explanations about operation types can be found in Appendix D.), geometry definitions (x1, y1, x2, y2, mx, my, θ_s, θ_e, RAD.). In geometry definitions x1, y1, and x2, y2 define the left top and right bottom co-ordinates of the area to be machined for cylindrical, face, recess, and groove turning operations.

For all others, these indicate the starting and finishing co-ordinates of the cutting operation. The next five columns stand for the centre co-ordinates (mx, my), start and end angles (θ_S, θ_S), radius (RAD.) of an arc respectively. Geometric descriptions of some operations are shown in Figure 5.4 [34].

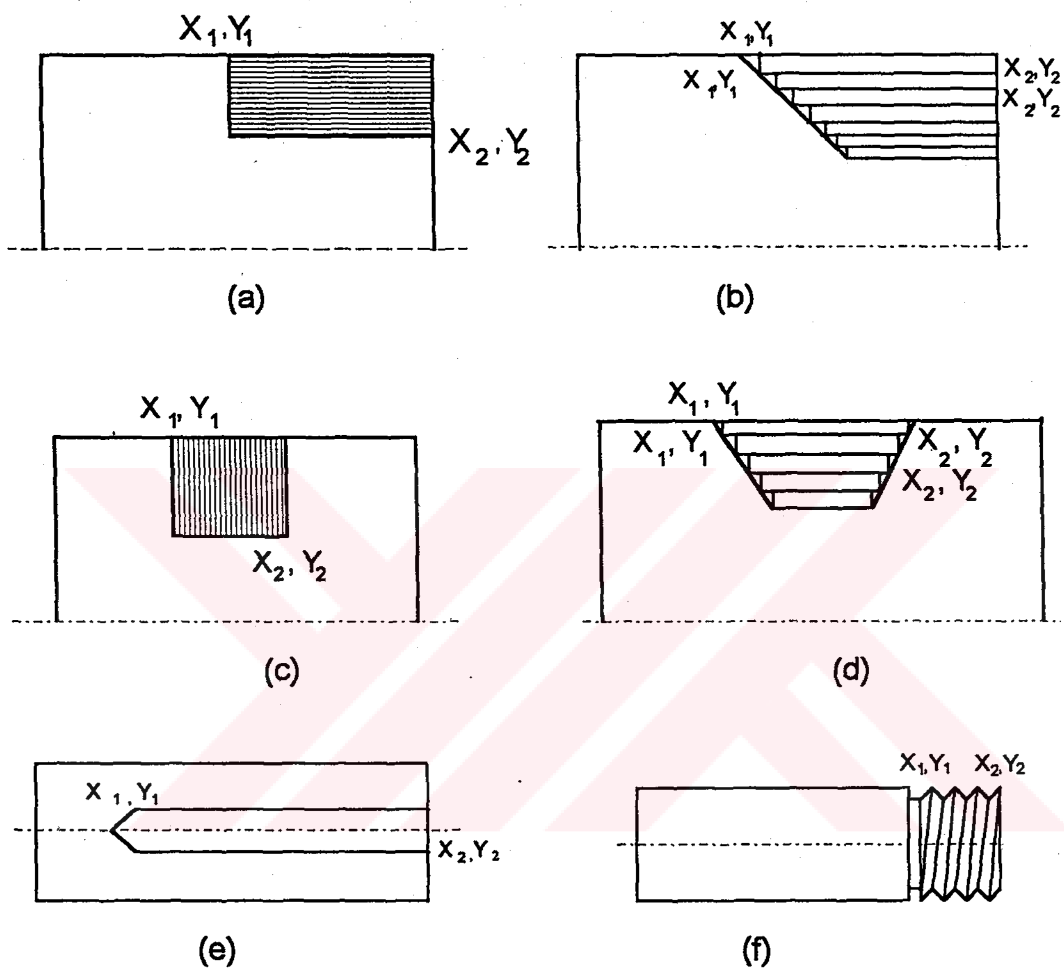


Figure 5.4 Geometric Descriptions of the operations. (a) Turning Operation, (b) Turning with Tapering, (c) Grooving or Parting, (d) Recess Operation, (e) Drilling Operation, (f) Threading Operation [34]

b) ISO codes or Manufacturer's codes of cutting tools and their holders: The cutting tools and holders can be determined manually by using TOOL and HOLDER menu or selected tools and holders for the operations can be taken from a file (by the help of RUN menu). The data in this file is the output of the Tool -Selection program[36]. An example of these data for the example part is shown below

Table 5.2 Selected Tools and Holders

	TOOL DESIGNATION.	HOLDER DESIGNATION
1	S N M M 19 06 12 F L	C S K P L 12 12 F 09
2	S N M M 19 06 12 F L	C S R P L 12 12 F 09
3	S N M M 19 06 12 F L	C S R P L 12 12 F 09
4	D N M G 15 04 08 F L	P D N N L 20 20 K 15
5	6.27211 L 006	2.18130 L 280 G
6	D N M G 15 04 08 F R	P D N N L 20 20 K 15
7	1.47002_220	1.37120 L 200 T
8	S N M M 19 06 12 F R	C S R P L 12 12 F 09
9	WOMX 030204 S	B 105 A 1500 D
10	D N M G 15 04 08 F L	S 25 M P S K N L 12
11	S N M M 19 06 12 F L	S 25 M P S K N L 12
12	D N M G 15 04 08 F L	S 25 M P S K N L 12

c) Machine data: The content of this data are; power-speed characteristics of spindle motor and feed-drive motors, bearing configurations, speed and feed limits for the machine, turning limits of the machine etc.. It is possible to choose a machine tool for the machining operation by using MACHINE TOOL menu. An example of these data is shown below.

MACHINE TOOL	TAKSAN		
SPINDLE DRIVE MOTOR(kW)	15		
FEED DRIVE MOTOR(kW)	4		
RAPID TRAVERSE SPEED(m/sec)	60		
MAX. TURNING DIAMETER(mm)	250		
MIN. TURNING DIAMETER(mm)	5		
SLIDE TRAVEL X/Z (mm)	50		
MAXIMUM SPEED(rpm)	4500	MINIMUM SPEED(rpm)	0
BREAK SPEED(rpm)	1500		
SPINDLE BEARING ARRANGEMENT	THRUST+RADIAL		

Figure 5.5 Specifications about machine tool

d) Chip breaking properties of cutting tools: Workpiece and cutting tool materials can be selected by using MATERIAL menu. Once these are selected and code of tool is choosen, chip breaking property of the corresponding cutting tool can be automatically found by making a search inside the files. The search is done by using IF-THEN structure.

e) Constants and exponents for force, torque, tool life, tool wear and cutting temperature equations: Once workpiece and cutting tool material are determined, the program automatically opens the corresponding file which includes these constants.

f) Cost data: After the selection of machine tools , cutting tools and holders, the cost data can be taken from a file which contains various cost terms, some of these are; cost of tools, cost of holders, machine cost, machining cost rate, labour cost rate etc.

5.3.2 Output of the Program

The output of the program for the example part is given in Table 4.3. The inputs of the program are as follow;

Machine tool :TAKSAN
Workpiece material : Medium carbon steel
Tool materials : Carbide
Holder materials : Tool steel

Table 5.3 The Optimised Cutting Conditions for the Example Part

Operation No	Type of operation	# of cut	Optimum Depth of cut (mm)	Optimum feed (mm/rev)	Optimum cutting speed (m/min)	Optimum spindle speed (rpm)	Cost (TL / mm^3)
1	EFCN_LH	1	3	0.198		337.6	50.12
		2	2	0.198		337.6	50.12
2	ECYL_LH	1	1.7	0.381	54.49	96.4	52.26
		2	1.7	0.381	54.49	98.3	52.26
		3	1.7	0.4	53.85	99	50.39
		4	1.7	0.4	53.85	101	50.39
		5	1.7	0.418	53.26	101.9	48.67
		6	1.5	0.418	53.26	104.1	50.87
3	ECYL_LH	1	1.7	0.437	52.69	104.9	47.08
		2	1.7	0.437	52.69	107.2	47.08
		3	1.7	0.456	52.15	108.4	45.6
		4	1.7	0.475	51.64	109.8	44.23
		5	1.7	0.475	51.64	112.4	44.23
		6	2.4	0.349	51.61	113.9	40.61
		7	2.4	0.366	50.69	116.8	39.13
		8	2.4	0.384	50.25	120	37.77
		9	2.4	0.402	49.82	123.4	36.52
		10	2.4	0.402	48.66	126.1	34.27
		11	2.4	0.437	47.955	130.2	33.27
		12	2.4	0.454	47.6	133.7	32.33
		13	2.4	0.472	47.29	138.6	29.5
		14	2.3	0.472	47.29	144	30.1
5	EGRV_RH	1		0.16		309.23	41.25
7	ETHR_LH	1	0.3024	1	120	383.2	414.96
		2	0.1167	1	120	382.2	420.96
		3	0.0861	1	120	382.2	427.76
		4	0.0703	1	120	382.2	429.84
		5	0.038	1	120	382.2	440.25
8	ECYL_LH	1	1.7	0.437	52.69	104.9	47.08
		2	1.7	0.437	52.69	107.2	47.08
		3	1.7	0.456	52.15	108.4	45.6
		4	1.7	0.475	51.64	109.8	44.23
		5	1.7	0.475	51.64	112.4	44.23
		6	2.4	0.349	51.61	113.9	40.61
		7	2.4	0.366	50.69	116.8	39.13
		8	2.4	0.384	50.25	120	37.77
		9	2.4	0.402	49.82	123.4	36.52
		10	2.4	0.402	48.66	126.1	34.27
		11	2.4	0.437	47.955	130.2	33.27
		12	2.4	0.454	47.6	133.7	32.33
		13	2.4	0.472	47.29	138.6	29.5
		14	2.4	0.402	48.66	126.1	34.27
		15	2.4	0.437	47.955	130.2	33.27
		16	2.4	0.454	47.6	133.7	32.33
		17	2.4	0.472	47.29	138.6	29.5
		18	2.3	0.472	47.29	144	30.1
9	IDRIL			0.066	69.283	1103.2	55.81
11	ICYL_LH	1	1.7	0.681	47.29	753.1	33.66
		2	3.8	0.534	47.29	643.7	19.27
		3	4.5	0.534	47.29	485.9	15.21

A comparasion between results obtained from optimisation program and selected from handbook for operations 2, 11 are given in table 4.4.

Table 5.4 Machining Cost Comparison for Optimised and Selected Data

		Optimised cutting data				Selected cutting data			
Opr. No	# of passes	Depth of cut(mm)	Feed (mm/rev)	Cutting speed (m/min)	Cost (TL/mm^3)	Depth of cut (mm)	Feed (mm/rev)	Cutting speed (m/min)	Cost (TL/mm^3)
1	1	3	0.198		50.12	2.5	0.1		54.58
	2	2	0.198		50.12	2.5	0.1		54.58
2	1	1.7	0.381	54.49	52.26	1.66	0.2	72	60.24
	2	1.7	0.381	54.49	52.26	1.66	0.2	72	60.24
	3	1.7	0.4	53.85	50.39	1.66	0.2	72	60.24
	4	1.7	0.4	53.85	50.39	1.66	0.2	72	60.24
	5	1.7	0.418	53.26	48.67	1.66	0.2	72	60.24
	6	1.5	0.418	53.26	50.87	1.7	0.15	72	58.72
3	1	1.7	0.437	52.69	47.08	2	0.2	70	50.1
	2	1.7	0.437	52.69	47.08	2	0.2	70	50.1
	3	1.7	0.456	52.15	45.6	2	0.2	70	50.1
	4	1.7	0.475	51.64	44.23	2	0.2	70	50.1
	5	1.7	0.475	51.64	44.23	2	0.2	70	50.1
	6	2.4	0.349	51.61	40.61	2	0.2	70	50.1
	7	2.4	0.366	50.69	39.13	2	0.2	70	50.1
	8	2.4	0.384	50.25	37.77	2	0.2	70	50.1
	9	2.4	0.402	49.82	36.52	2	0.2	70	50.1
	10	2.4	0.402	48.66	34.27	2	0.2	70	50.1
	11	2.4	0.437	47.955	33.27	2	0.2	70	50.1
	12	2.4	0.454	47.6	32.33	2	0.2	70	50.1
	13	2.4	0.472	47.29	29.5	2	0.2	70	50.1
	14	2.3	0.472	47.29	30.1	2	0.2	70	50.1
5	1		0.16		41.25		0.1		50.8
8	1	1.7	0.437	52.69	47.08	2.2	0.2	70	48.8
	2	1.7	0.437	52.69	47.08	2.2	0.2	70	48.8
	3	1.7	0.456	52.15	45.6	2.2	0.2	70	48.8
	4	1.7	0.475	51.64	44.23	2.2	0.2	70	48.8
	5	1.7	0.475	51.64	44.23	2.2	0.2	70	48.8
	6	2.4	0.349	51.61	40.61	2.2	0.2	70	48.8
	7	2.4	0.366	50.69	39.13	2.2	0.2	70	48.8
	8	2.4	0.384	50.25	37.77	2.2	0.2	70	48.8
	9	2.4	0.402	49.82	36.52	2.2	0.2	70	48.8
	10	2.4	0.402	48.66	34.27	2.2	0.2	70	48.8
	11	2.4	0.437	47.955	33.27	2.2	0.2	70	48.8
	12	2.4	0.454	47.6	32.33	2.2	0.2	70	48.8
	13	2.4	0.472	47.29	29.5	2.2	0.2	70	48.8
	14	2.4	0.402	48.66	34.27	2.2	0.2	70	48.8
	15	2.4	0.437	47.955	33.27	2.2	0.2	70	48.8
	16	2.4	0.454	47.6	32.33	2.2	0.2	70	48.8
	17	2.4	0.472	47.29	29.5	2.2	0.2	70	48.8
	18	2.3	0.472	47.29	30.1	2.2	0.2	70	48.8

9			0.066	69.283	55.81		0.021	50	67.7
11	1	1.7	0.681	47.29	33.66	3.3	0.2	70	28.24
	2	3.8	0.534	47.29	19.27	3.3	0.2	70	28.24
	3	4.5	0.534	47.29	15.21	3.4	0.2	70	28.24
				Total COST	1783.09			Total COST	2252.1

As seen from the results, it is possible to obtain about 30 percent cost saving by using optimisation program.

CHAPTER 6

DISCUSSION AND CONCLUSIONS

6.1 DISCUSSION AND CONCLUSIONS

The research work discussed in this thesis is concerned with the development of procedures and programs to determine the optimum cutting conditions for operations that can be performed on a CNC turning centre. This work is also a part of CAD/CAM studies which is continuing at the University of Gaziantep in Mechanical Engineering Department by the CAD/CAM research group.

Although there are many studies in the literature related on the optimisation of cutting conditions, only, in a small part of these studies, optimisation of cutting conditions for all turning operations are considered. Generally, optimisation of single-pass operations are studied. In this work, optimisation of cutting parameters for main turning operations (roughing, facing, boring, drilling, threading, grooving and parting-off) that can be performed on a CNC lathe is considered.

The number of restrictions considered in the previous optimisation of cutting conditions studies are limited. This situation effects the safety of the machining operation. In this study, a number of constraints are considered additionally, which are; holder strength and rigidity, torque-speed characteristics of feed-drive motors, deflection of the workpiece, bearing design loads in feed-drive mechanisms.

The main conclusions from the work can be summarised as follows; The program can be used to determine the cutting conditions automatically for rough turning (roughing, facing, boring), drilling, threading, grooving and parting-off operations. Finishing operations after boring, roughing and facing operations are also considered as the last pass for these operations. It was shown that the optimum depth-feed combination for roughing, boring and facing operations, is determined by making a search on the chip breaking diagram. The optimum values for the feed and depth of cut are found by considering the grid points on the boundary separating the feasible and non-feasible regions of the chip breaking diagram. For the other operations, feasibility check methods are used.

In determining the cutting conditions; OPTURN takes into consideration many constraints that will apply on the process such as:

- Maximum and minimum depth of cuts and feeds for the tool and workpiece material
- Maximum allowable tool force
- Holder strength and rigidity
- Spindle motor torque-speed characteristic

- Work holding limitations (axial slip, circumferential slip, component throw-out)
- Torque-speed characteristics of feed-drive motors
- Deflection of the workpiece
- Geometrical accuracy of the workpiece
- Bearing design loads
- Cutting tool velocities
- Cutting temperatures
- Tool wear
- Surface roughness

The program can run automatically by using outputs of OPPS-ROT (An optimised process planning system for rotational parts)[34] which is developed by CAD/CAM research group, or it can be run manually by preparing three data files which include: part data (that contains types of operations, sequence of operations, and blank geometry of each operation.), ISO codes of selected tools and corresponding holders. While inputting these data files, an editor which is prepared for this purpose can be used. Type of machine used and its characteristics (which includes spindle and feed-drive motor characteristics, type of bearings, machine capacity etc.), tool and workpiece materials can be selected by using related menus of the program. The other required data for the optimisation such as constants for tool life, cutting force, cutting temperature, tool wear, cost equations are selected automatically by the program by comparing type of tool and workpiece material combination.

It was shown that cost savings of 25-55% is possible with this program compared with the results obtained using the data from handbooks.

Running of this program is extremely simple and little skill is required. The program is written in Turbo C++ programming language. A menu program is developed by using CLIPPER programming language for enabling interaction with the user.

6.2 RECOMMENDATIONS FOR FURTHER STUDY

Future works that can be made for the modification of the program developed in this study, can be summarised as:

1) The constants of the cutting force, extended Taylor's tool life, tool wear and cutting temperature equations, which depend on a particular combination of tool and workpiece material, are not readily available. So the work is restricted for a number of tool-workpiece material combination. This data can be determined experimentally.

2) Dynamic instability check can be added to the constraints. Radial deflection of the workpiece in the external operations is taken as the measure of instability in this study as Rahman advised[45], but further investigations are necessary.

3) If long boring bars are used in the boring operations, stability of these boring bars may be investigated and should be added to the constraints.

4) In the deflection analysis, only the external operation was considered, since it is very complicated to calculate the geometry of the workpiece when

internal operations are considered. A finite element approach may be used for the deflection analysis.

5) In the optimisation of threading operations only metric 60° thread profiles are considered. The programme may be extented for the other thread profiles.

6) Profiling and reaming operations were not considered in this work. The optimisation of these operations can also be included.

LIST OF REFERENCES

1. Filiz İ.H., Dereli, T., and Kayacan, M.C.,1994. "Automatic Generation of CNC Part Programs for Rotational Parts", 6th International Machine Design and Production Conference, pp. 281-288, September 21-23, METU, Ankara.

2. Filiz, İ.H., Kayacan, M.C., and Dereli, T., 1994. "ROMOD: A Product Modelling System for Rotational Parts",, 6th International Machine Design and Production Conference, pp. 271-279, September 21-23, METU, Ankara.

3. Juneja, B. L., Sekhon, G.S., Fundamentals of Metal Cutting and Machine Tools, John Wiley & Sons, New Delhi, 1987.

4. Armarego, E.J.A., Brown, R.H., The Machining of Metals, Prentice-Hall, Inc., New Jersey, 1969.

5. Fenton, R.G., Gagnon, M.F.J., 1993, "Computer Aided Tool Material Selection for Metal-Cutting Operations", Annals of the CIRP, Vol. 42, pp. 565-568

6. Hinduja, S. and Barrow, G., 1986. "TECHTURN - A Technically Oriented System for Turned Components", Proceedings of International Conference on Computer Aided Production Engineering, pp 255-260, Edinburgh, April.

7. Arseculeratne, J.A., Hinduja, S., Barrow, G., 1992. "Optimum Cutting Conditions for Turned Components", Proc. Ins. Mach. Engrs. Vol. 206, pp 15-30.

8. Ermer, D.S., 1970,"A Bayesian Model of Machining Economics for Optimization by Adaptive Control ",Transaction of the ASME, Vol. 92, pp. 628-632.

9. Davis, R.P., et. al., 1980,"Optimizing Machining Parameters in a Frame-Work for Adaptive Control",Comput. & Indus. Engng, Vol. 4, pp. 143-151.

10. Bhattacharyya, A., Ham, I., Design of Cutting Tools, A.S.T.M., Dearborn, Michigan, 1969.

11. Boothroyd, G., Fundamentals of Metal machining and Machine Tools, McGraw-Hill, Washington, 1975.

12. Curry, G.L., Deuermeyer, B.L., 1990,"An Algebraic Modelling Language and Microcomputer Environment for Linear Programming and Related Optimisation Methods", Comput. & Indus. Engng, Vol. 18, pp. 29-36.

13. Kimbler, D.L., et. al., 1978,"Alternative Approaches to the Machining Parameter Optimisation Problem",Comput. & Indus. Engng, Vol. 2, pp. 195-202.

14. Agapiou, J.S., 1992. "The Optimisation of Machining Operations Based on a Combined Criterion Part 2: Multipass Operations", Transaction of the ASME, Vol. 114, pp. 508-513.

15. Somlo, J., Nagy, J.,"A New Approach to Cutting Data Optimization",Advances in Computer Aided Manufacture, North-Holland Pub. Co., 1977.

16. Sertaç, M.N., 1984, Optimization of Single-Pass Turning Operations by Geometric Programming Method, M.Sc. Thesis, METU, Ankara

17. Groover, M.P., 1975,"Monte Carlo Simulation of the Machining Economics Problem ",Transaction of the ASME, Vol. 97, pp. 931-938.

18. El Hakim, M.A., et. al., 1983,"A Computer Program for the Optimization of the Machining Variables",Comput. & Indus. Engng, Vol. 7, pp. 317-336.

19. Wang, H. Wysk, R.A., 1986,"An Expert System for Machining Data Selection",Comput. & Indus. Engng, Vol. 10, pp. 99-107.

20. Ravignani, G.L., 1978,"A Computational Algorithm for Direct Application of Tool Life Values in Machining Economics", Annals of the CIRP, Vol. 27, pp. 459-464.

21. Rao, S.S., Hati, S.K., 1978,"Computerized Selection of Optimum Machining Conditions for a Job Requiring Multiple Operations", Transaction of the ASME, Vol. 100, pp. 356-362.

22. Brewer, R.C., 1958,"On the Economics of Basic Turning Operations",Transaction of the ASME, Vol. 80, pp. 1498-1958.

23. Kals, H.J.J., et. al., 1978, "A Computer Aid in the Optimisation of Turning Conditions in Multi-Cut Operations", Annals of the CIRP, Vol. 27, pp. 465-469.

24. Jha, N.K., 1986,"Optimizing the Number of Tools and Cutting Parameters in Multi-Tool Turning for Multiple Objectives through Geometric programming", Appl. Math. Modelling, Vol. 10, pp. 162-169.

25. Van Houten, F.J.A.M., et. al. 1981, "The Development of a Technological Processor as a Workpiece Programming System", Annals of the CIRP, Vol. 30, pp. 363-368.

26. Iwata, K., et. al., 1972,"A Probabilistic Approach to the Determination of the Optimum Cutting Conditions",Transaction of the ASME, Vol. 72, pp. 1099-1107.

27. Tipnis, V.A., Friedman, M.Y., 1976,"Cutting Rate-Tool Life Characteristic Functions for Metarial Removal Processes, Part 1:Theory ",Transaction of the ASME, Vol. 75, pp. 481-486.

28. Tipnis, V.A., Friedman, M.Y., 1976,"Cutting Rate-Tool Life Characteristic Functions for Metarial Removal Processes, Part 2: Verification and Applications",Transaction of the ASME, Vol. 75, pp. 487-495.

29. Ermer, D.S., Shah, B.V., 1973,"Analytical Sensitivity Studies of the Optimum Machining Conditions for Milling, Drilling, Reaming, and Tapping",Transaction of the ASME, Vol. 72, pp. 312-316.

30. Hinduja, S., Petty, D.J., Tester, M. and Barrow, G., 1985. "Calculation of Optimum Cutting Conditions for Turning Operations", Proc. Ins. Mach. Engrs., Vol. 199, No.B2.

31. Danai, K., Ulsoy, A.G., 1987,"A Dynamic State Model for On-Line Tool Wear Estimation in Turning",Transaction of the ASME, Vol. 109, pp. 396-399.

32. Kılıç, S.E., 1983. "Optimisation of Cutting Conditions for Multi-Pass Turning Operations", Metu Journal of Pure and Applied Sciences, Vol. 16, No. 1, pp.21-39.

33. Ermer, D.S., Kromodihardjo, S., 1983. "Optimization of Multipass Turning with Constraints", Transaction of the ASME, Vol. 103, pp. 462-468.

34. Kayacan, M. C., Filiz, İ.H., Sönmez, A. İ., Baykasoğlu, A., Dereli, T., "OPPS-ROT: An Optimised Process Planning System for Rotational Parts", Paper to be published.

35. Dereli, T., 1994, Computer Aided Part Program Generation and Simulation of Turning Processes, M.Sc. Thesis, University of Gaziantep.

36. Kayacan, M.C., 1995 ,Computer Aided Process Planning System For Rotational Parts, Ph. D. Thesis, University of Gaziantep

37. 1980, Machining Data Handbook 3rd Edition, Met-Cut Research Association Inc., Machinability Data Centre, USA.

38. Chen s., Hinduja S. and Barrow G., 1988, "Automatic Tool Selection for Rough Turning Operation.", Int. J. Mach. Tools and Manufacturing, 22, pp 534-553.

39. Jawahir, I.S.,Van Luttervelt, C.A., 1993,"Recent Developments in Chip Control Research and Applications", Annals of the CIRP, Vol. 42, pp. 659-693.

40. Jawahir, I.S., 1990, "On the Controllability of Chip Breaking Cycles and Modes of Chip Breaking in Metal Cutting", Annals of the CIRP, Vol. 39, pp. 47-51.

41. Weill, R., Wertheim, R., 1980,"New Parting Tool System with Self-Gripping, Replaceable Carbide Inserts", Annals of the CIRP, Vol. 29, pp. 29-33.

42. Kuljanic, E., 1991,"Face Turning on CNC Lathe",Annals of the CIRP, Vol. 40, pp. 53-56.

43. Andreasen, J.L., De Chiffre, L., 1993,"Automatic Chip-Breaking Detection in Turning by Frequency Analysis of Cutting Force", Annals of the CIRP, Vol. 42, pp. 45-48.

44. Kalajdzic, M.J., Solaja, V.B., 1979,"Rotational Speed Limits for Basic Types of Chucks" ,Annals of the CIRP, Vol. 28, pp. 297-301.

45. Rahman, M., 1988,"In-Process Detection of Chatter Threshold", Transaction of the ASME, Vol. 103, pp. 462-468.

46. Jang, D.Y., Serieg, A., 1992,"Machining Parameter Optimisation for Specified Surface Conditions",Transaction of the ASME, Vol. 114, pp. 254-257.

47. Kaldor, S., Ber, A., Lenz, E., 1979,"On the Mechanism of Chip Breaking",Transaction of the ASME, Vol. 101, pp. 241-249.

48. Yellowley, I., Adey, D., 1991,"A New Approach to the Real Time Optimisation of Turning Operations", Int. J. Mach. Tools Manufact., Vol. 32, pp. 453-466.

49. Filiz, İ.H., Bell, R., 1991,"Axial Preload on Bearings", Machine Design, Vol. 146, pp. 78-82.

50. Arshinov, V., Aleksiev, G., Metal Cutting Theory and Cutting Tool Design, Mir Publishers, Moscow, 1976.

51. Tobias, S. A., Machine-Tool Vibration, John Wiley & Sons, New York, 1965.

52. Budyans, G.R., Advanced Strength and Applied Stress Analysis, McGraw- Hill, Tokyo, 1977.

53. HERTEL - Cutting Tool Systems for Turning

54. SANDVIK COROMANT- Turning Tools 93/94

55. SANDVIK COROMANT- Modern Metal Cutting, A Practical Handbook

56. SUPERTURN Turning Center machine Catalogue.

57. Görür, G., 1995 ,Computer Aided Design of the Main Drives of Machine Tools, Ph. D. Thesis, University of Gaziantep

APPENDIX A

Table A.1 Cutting Force Constants for Turning [7,38]

Workpiece material	Tool material	R_1	R_2	R_3	x_1	x_2	x_3	y_1	y_2	y_3
Free Machining carbon steels (low carbon)	carbide	1918	718	612	0.901	1	0.325	0.902	0.784	1.003
Free Machining carbon steels (medium carbon)	carbide	1473	362	360	0.902	0.569	0.286	0.861	0.290	1.041

Table A.2 Cutting Force and Torque Constants for Drilling [10]

Workpiece material	Tool material	C_m	C_p	x_m	x_p	y_m	y_p
Free Machining carbon steels (low carbon)	carbide	8	32	2	1.1	0.7	0.7
	HSS	34	85	1.9	1	0.8	0.7
Free Machining carbon steels (medium carbon)	HSS	42	92	2	1.05	0.8	0.72
Free Machining carbon steels (high carbon)	HSS	75	270	2.1	1.15	0.76	0.77
Cast Iron BHN=190	carbide	12	42	2.2	1.2	0.8	0.75
	HSS	23	60	1.9	1	0.8	0.8
Bronze	HSS	12	31	1.9	1	0.8	0.8

Table A.3 Expanded Tool Life Equation Constants for Turning

Workpice material	Tool material	A	n	n_1	n_2
Free Machining carbon steels (low carbon)	HSS	1819714.666	3.1166	0.9382	0.262
	Carbide	4712794402	3.4213	0.8669	0.2598
	Carbide	1928809929	3.4654	0.74324	0.2613
	Carbide	117630874.4	3.1586	0.6555	0.2509
Free Machining carbon steels (medium carbon)	HSS	22385555.56	4.168	1.4678	0.3126
	Carbide	3217733416	3.5953	0.9573	0.2706
	Carbide	1272537514	3.5984	1.0743	0.2719
	Carbide	328677928.4	3.4737	0.8459	0.268
Free Machining carbon steels (high carbon)	HSS	2104024999	6.7548	2.618	0.5349
	Carbide	673836942.7	3.5	1.1316	0.2694
	Carbide	318950916.9	3.5754	1.0516	0.2696
	Carbide	162819320.3	3.8046	1.1945	0.3013
Manganees alloys	HSS	145562.2468	3.2682	1.9592	0.2446
	Carbide	519899782.9	3.3305	0.9171	0.2530
	Carbide	5944924337	3.3678	0.5699	0.2536
	Carbide	185438879.6	3.3457	0.8147	0.2575
Chromium alloys	HSS	36663.77	3.4	2.2337	0.2949
	Carbide	269928505.7	3.2682	0.9838	0.246
	Carbide	309806420.4	3.414	1.0581	0.2639
	Carbide	64724439.05	3.2063	0.8794	0.2454
Aluminum alloys	HSS	7279493.98	3.2163	1.721	0.2469
	Carbide	108586884100	3.6434	0.9946	0.2732

Table A.4 Exponents for Tool Life equation in Drilling[10]

Workpiece material	Tool material	C_v	x_v	y_v	1/m
Free Machining carbon steels (low carbon)	carbide	30	0.35	0.28	0.2
	HSS	5	0.4	0.7	0.2
Free Machining carbon steels (medium carbon)	HSS	7	0.4	0.7	0.125
Cast Iron BHN=190	carbide	34.2	0.45	0.3	0.2
	HSS	10.5	0.25	0.55	0.125
Bronze	HSS	23.4	0.25	0.55	0.125

Table A.5 Constants used in Tool Wear and Tool Temparature equations[31].

Parameter	Value	Work Material	Tool Material
Z	5.2E-5	Steel	Carbide
X	10 - 20	Steel	Carbide
G	10000	Steel	Carbide
J	8	Steel	Carbide
U	22000	Steel	Carbide
K1	72	Steel	Carbide
K2	2500	Steel	Carbide
C	0.056	Steel	Carbide
q1	0.4	Steel	Carbide
q2	0.6	Steel	Carbide
q3	1.45	Steel	Carbide
m1	0.4 - 0.5	Steel	Carbide
m2	-0.78	Steel	Carbide
m3	-0.95	Steel	Carbide
I	450	Steel	Carbide

APPENDIX B

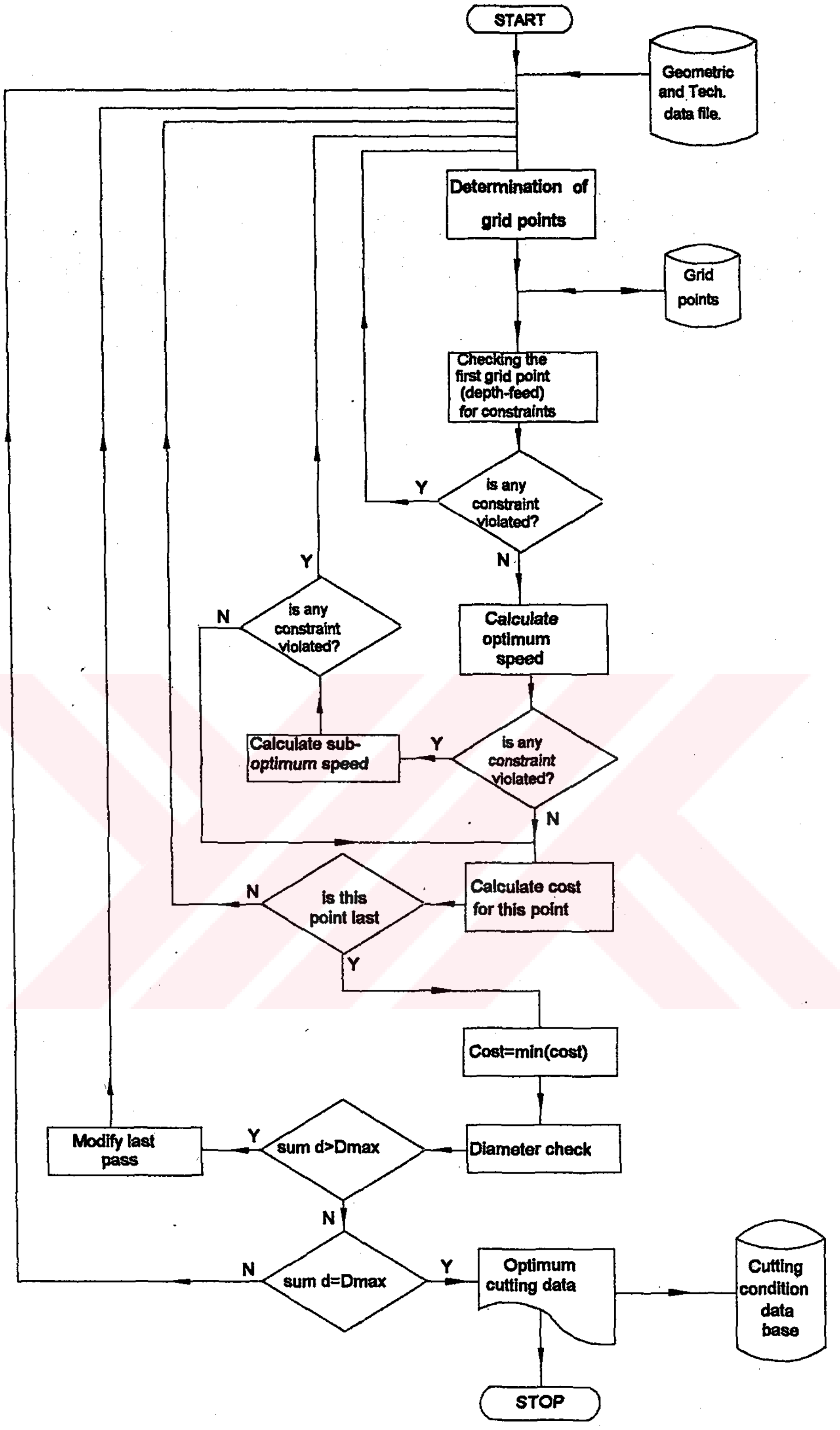


Figure B.1 A simplified flow chart for the optimisation of roughing operations(External Rough Turning, Boring, Facing)

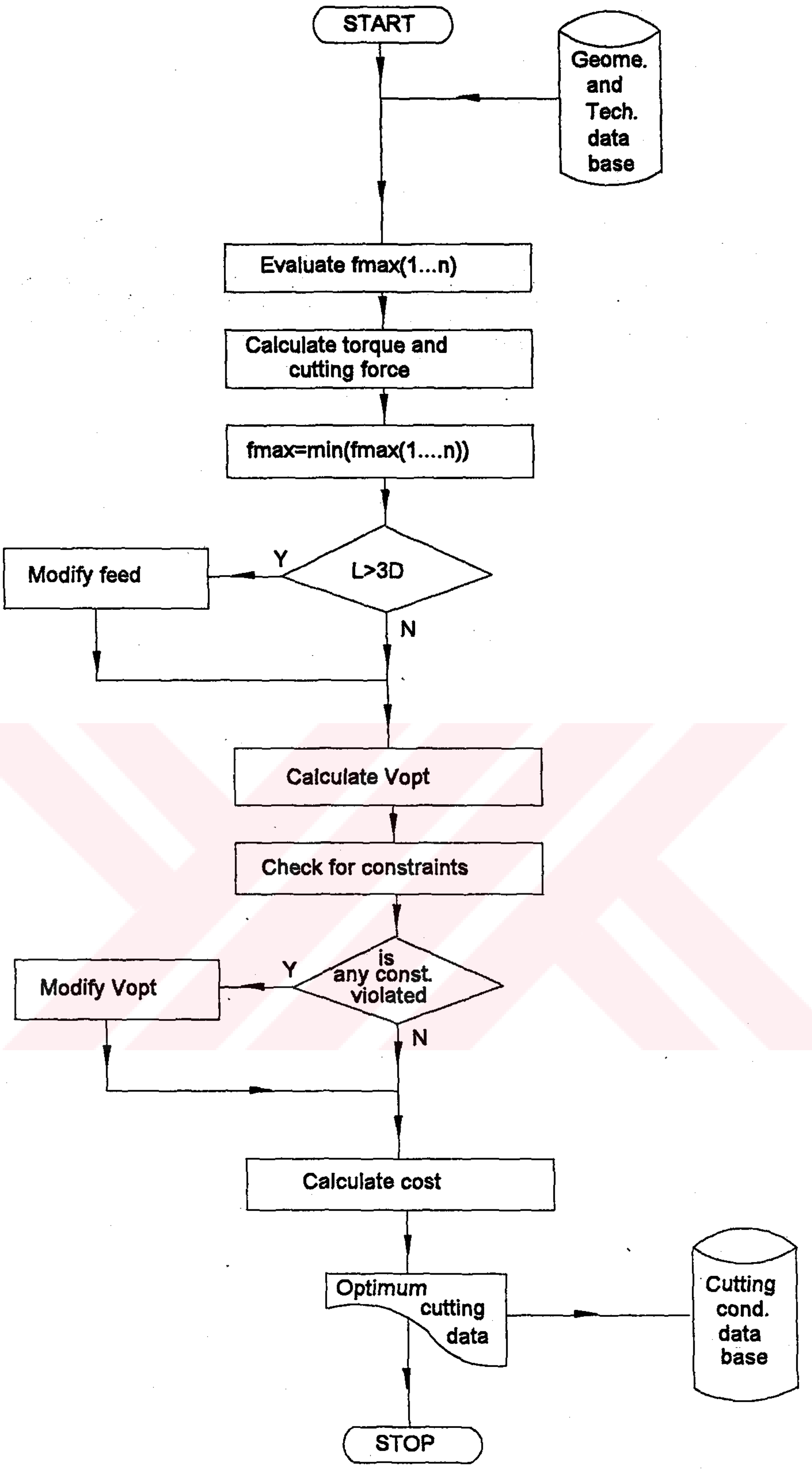


Figure B.2 A simplified flow chart for the optimisation of drilling operations

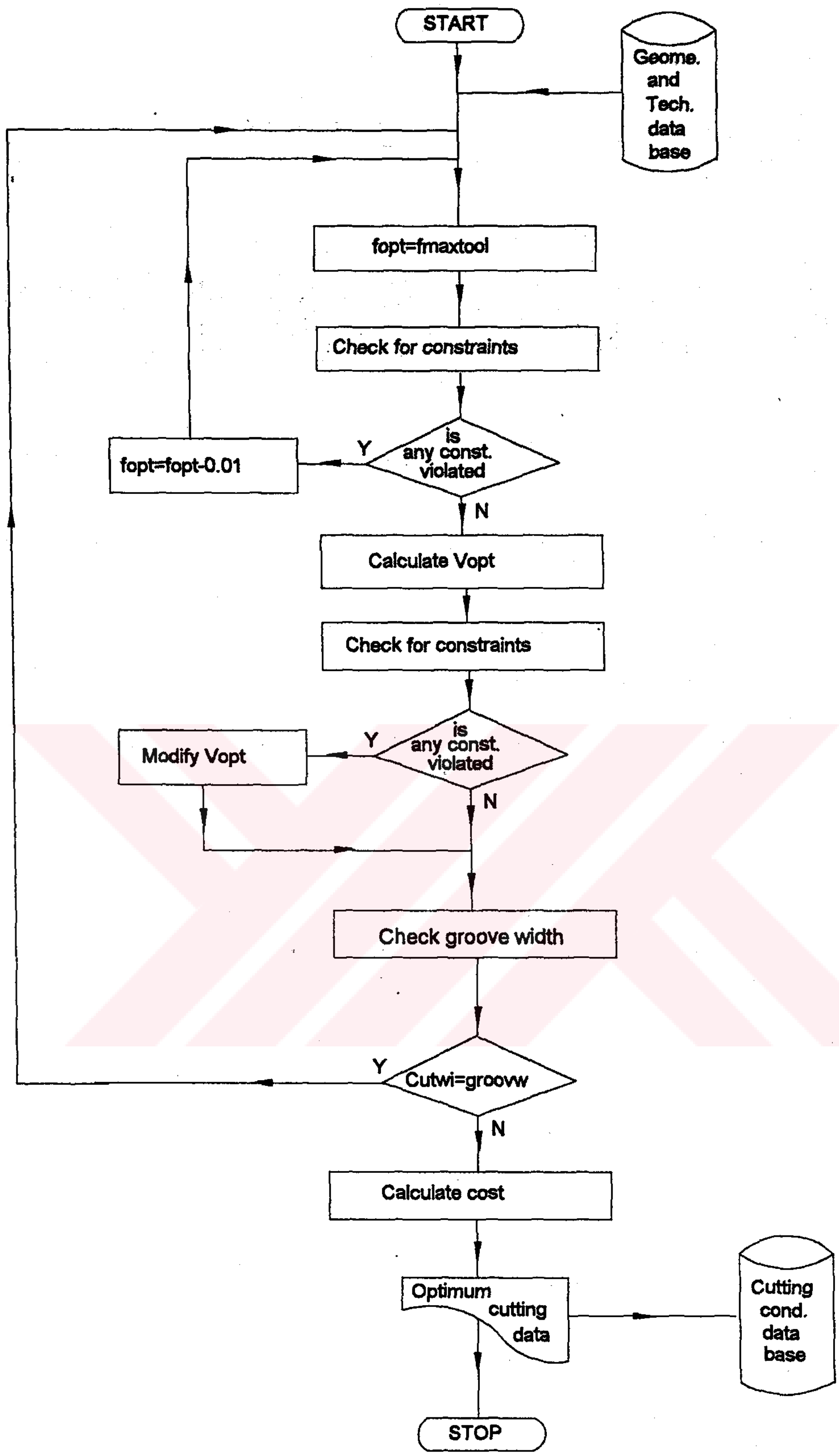


Figure B.3 A simplified flow chart for the optimisation of grooving and parting-off operations

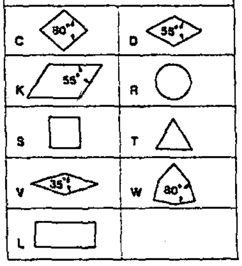
APPENDIX C

INDEXABLE INSERTS - TURNING

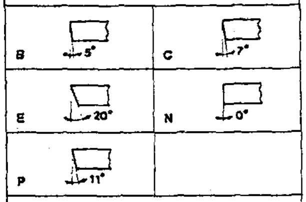
C	N	M	G	12	04	12			QM
1	2	3	4	5	6	7	8	9	10

Extract from ISO 1832-1985

1 Insert shape and included angle ε_r



2 Clearance angle on major cutting edge

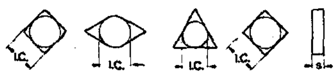


O Specific description

3 Tolerances ± on s and I.C.

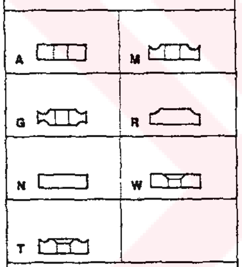
Class	s	I.C.
G		±0.025
M	±0.13	±0.05 - ±0.15[1]
U		±0.08 - ±0.25[1]

[1] Varies depending on the size of I.C. See below



Inscribed circle I.C. mm	Tolerance class M	Tolerance class U
3.97 5.0 5.56 6.0 6.35 8.0 9.525 10.0	±0.05	±0.08
12.0 12.7	±0.08	±0.13
15.875 16.0 19.05 20.0	±0.10	±0.18
25.0 25.4	±0.13	±0.25
31.75 32.0	±0.15	±0.25

4 Insert type



X Special design

5 Insert size = cutting edge length, l mm

I.C. mm	C	D	R	S	T	V	W
3.97					06		
5.0			05				
5.56					09		
6.0			06				
6.35	06	07			11		
8.0			08				
9.525	09	11	09	09	16	16	
10.0			10				
12.0			12				
12.7	12	15	12	12	22		08
15.875	16		15	15	27		
16.0			16				
19.05	19		19	19	33		
20.0			20				
25.0			25				
25.4	25		25	25			
32			32				

For inserts shape K (KNMX, KNUX) only the *theoretical cutting edge length is indicated.*

6 Insert thickness, s mm

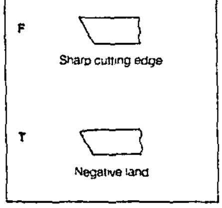
01 s = 1.59
T1 s = 1.98
02 s = 2.38
03 s = 3.18
T3 s = 3.97
04 s = 4.76
05 s = 5.56
06 s = 6.35
07 s = 7.94
09 s = 9.52

7 Nose radius, r_ε mm

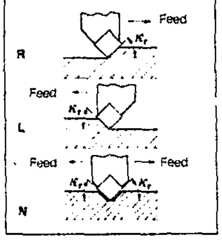
00 $r_\varepsilon = 0$
02 $r_\varepsilon = 0.2$
04 $r_\varepsilon = 0.4$
08 $r_\varepsilon = 0.8$
12 $r_\varepsilon = 1.2$
16 $r_\varepsilon = 1.6$
24 $r_\varepsilon = 2.4$
32 $r_\varepsilon = 3.2$

Round insert:
00 if I.C. is converted from an inch value
M0 if I.C. is a metric value.

8 Cutting edge condition



9 Tool style *feed direction*



10 Manufacturer's option

The ISO code consists of nine symbols including 8 and 9 which are used only when required. In addition the manufacturer may add further two symbols e.g. -QF = finishing operations, -QM = semi-finishing *and light roughing operations*, -QR = roughing operations

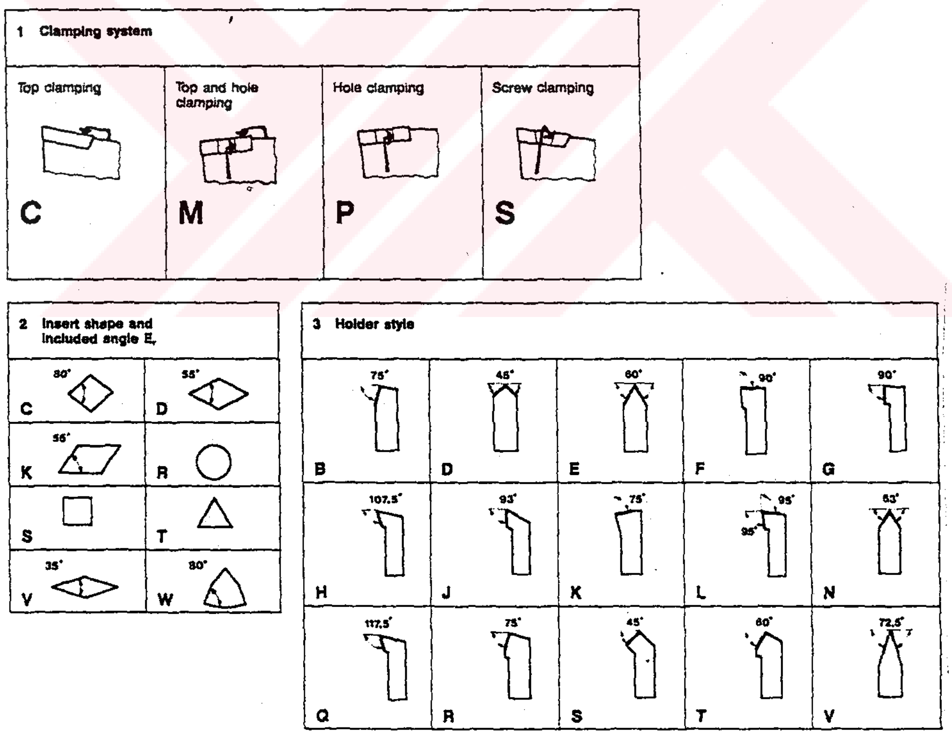
Figure C.1 Indexable Inserts for Turning

CODE KEY - TURNING TOOLS

P	S	K	N	R	20	20	K	12	-	
1	2	3	4	5	6	7	8	9		10

BT32	P	S	D	N	N	-	32	40	-	15
11	1	2	3	4	5		6	8		9

Extract from ISO 5608-1989



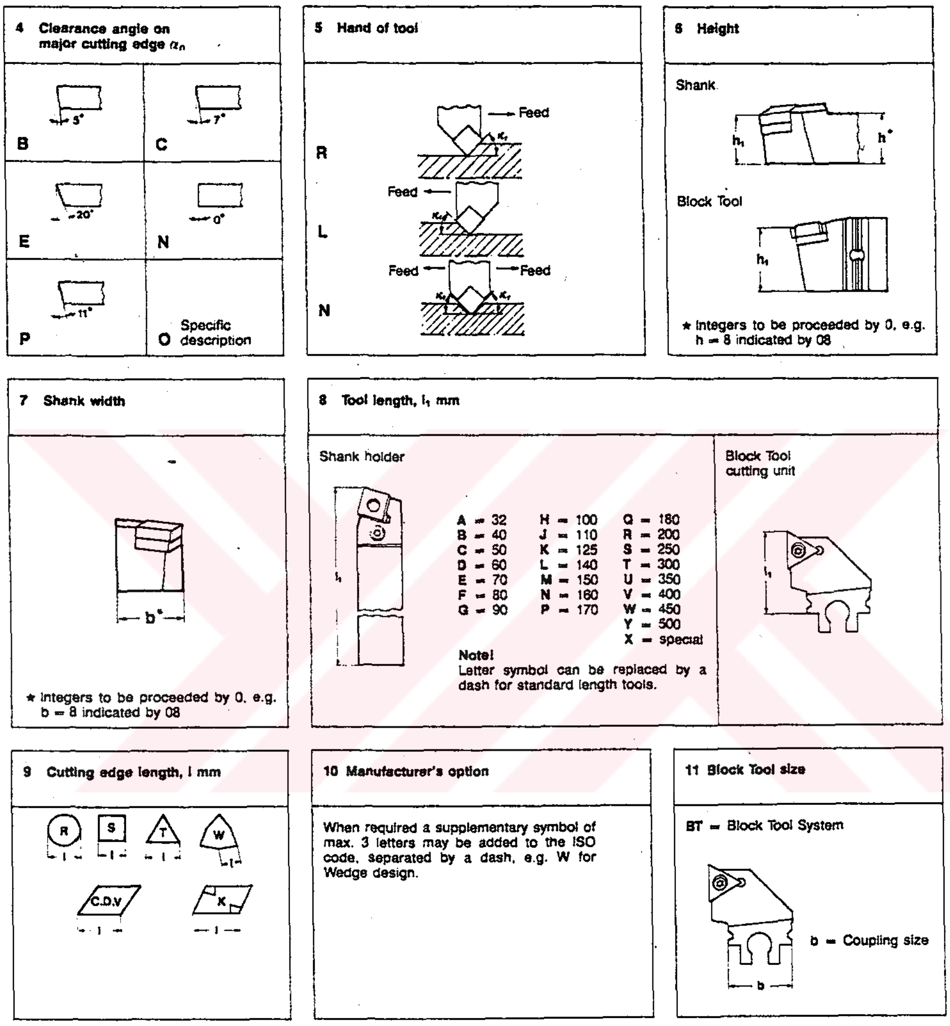


Figure C.2 Tool Holders for External Turning Operations

BORING BARS

S	40	V	-	S	C	L	C	R		12	-	
1	2	3		4	5	6	7	8		9		10

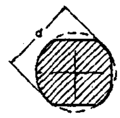
BT25	-	S	S	K	C	R	-	D2060	-	09	-	
11		4	5	6	7	8		12		9		10

Extract from ISO 6261-1984

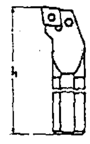
1 Type of bar

A	Steel bar with internal coolant supply
E	Carbide shank bar
F	Anti-vibration bar
S	Solid steel bar

2 Bar diameter

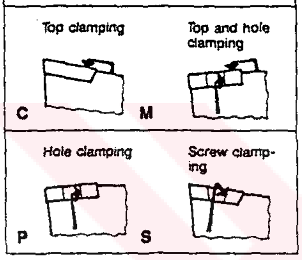


3 Tool length, l_1 mm

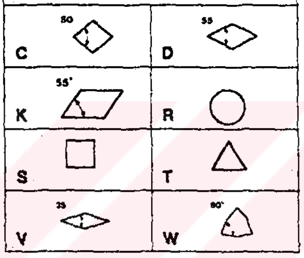


F = 80, H = 100, K = 125, M = 150, P = 170, Q = 180, R = 200, S = 250, T = 300, U = 350, V = 400, W = 450, Y = 500, X = special

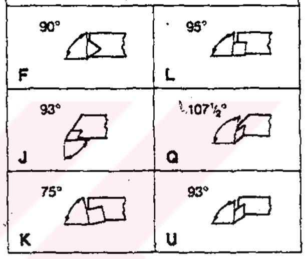
4 Clamping system



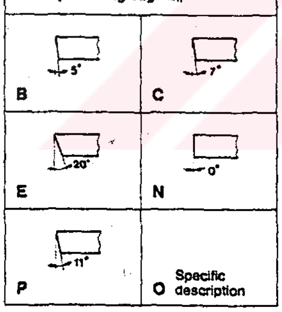
5 Insert shape and included angle ε_r



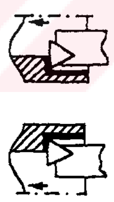
6 Bar style



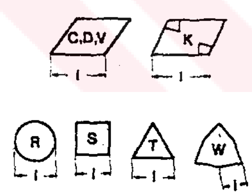
7 Clearance angle on major cutting edge α_n



8 Hand of tool



9 Cutting edge length, l mm



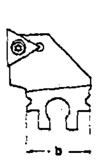
10 Manufacturer's option

When required a supplementary symbol of max. 3 letters may be added to the ISO code, separated by a dash, e.g.

D = extended f-dimension, +1,0 mm
E = extended f-dimension, +2,0 mm
R = round shank
W = wedge design
X = back boring

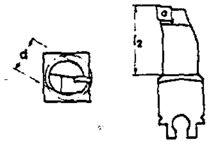
11 Block Tool size

BT = Block Tool System



b = Coupling size

12 Block Tool cutting unit size



d × l_2 proceeded by a D (indicating internal cutting units)

Figure C.3 Boring Bars for Internal Turning Operations

THREADING INSERTS

R	166.0	G	–	16	MM0	1	F -	150	
1	2	3		4	5	6	7	8	9

1 Hand of insert

R = right hand style insert
L = left hand style insert

2 Main code

166.0 = T-MAX U-Lock[1])

3 Type of machining

G = inserts for external threading
L = inserts for internal threading

4 Insert dimension

T-MAX U-Lock
Cutting edge length
11 = IC 1/4" = 6.35 mm
16 = IC 3/8" = 9.52 mm
22 = IC 1/2" = 12.70 mm

5 Thread profile

VM0 = V-profile 60°
VW0 = V-profile 55°
MM0 = Metric 60°
UN0 = UN 60°
WH0 = Whitworth 55°
NT0 = NPT
RN0 = Round 30°
PT0 = BSPT
TR0 = Trapezoidal
AC0 = ACME
SA0 = STUB-ACME
NJ0 = UNJ
MJ0 = MJ
NF0 = NPTF
BU0 = Buttress
VA0 = VAM
NV0 = New VAM
RD0 = API Rd
V381 = V-0.038R
V401 = V-0.040
V501 = V-0.050

6 Number of teeth per cutting edge

Varies from 1 to 3 teeth.

7 Cutting edge condition

– = ER-treated
F = sharp cutting edge without ER-treatment

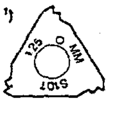
8 Pitch

mm: pitch × 100
Inch: number of threads per inch × 10

9 Supplementary code

Taper on diameter/inch per foot
1 = 1 i.p.f
2 = 2 i.p.f
3 = 3 i.p.f

[1])



Marking:
All inserts are marked with the profile, grade and pitch: internal inserts being identified with a circle. To prevent erasure, the marking is either sintered-in or laser cut on the face of the inserts.

Figure C.4 Threading Inserts

THREADING TOOLS (THREE-EIGHTS AND HALF-INCH INSERTS)

BT25	–	R	166.0	KF	Z	–	20 D2040	–	16
1		2	3	4	5		6		7

1 Block Tool size

BT = Block Tool System

b = Coupling size

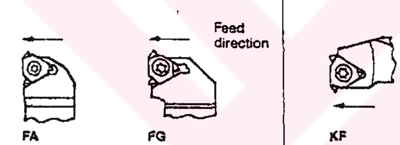
2 Hand of tool

R = right hand style
L = left hand style

3 Main code

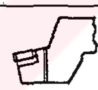
166.0 = T-MAX U-Lock

4 Type of tool and holder style



5 Design

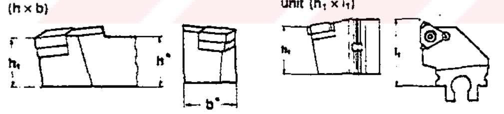
Z = Drop head design (For upside down mounting)



6 Shank dimension—External and internal machining

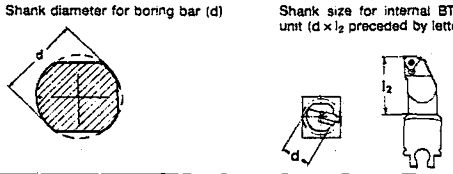
Shank size for external toolholder (h × b)

Shank size for external BT cutting unit ($h_1 \times l_1$)



Shank diameter for boring bar (d)

Shank size for internal BT cutting unit ($d \times l_2$ preceded by letter D)



7 Insert dimension

Insert size in mm
16 = IC 3/8" = 9,52 mm
22 = IC 1/2" = 12,70 mm

Figure C.5 Tool Holders for External Threading Operations

THREADING BORING BARS (QUARTER INCH INSERTS)

R	166.0	KF	-	16	-	12	20	-	11	B
1	2	3		4		5	6		7	8

1 Hand of tool

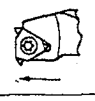
R = right hand style
L = left hand style

2 Main code

166.0 = T-MAX U-Lock

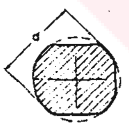
3 Type of tool and holder style

KF = Internal

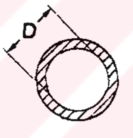


4 Bar diameter

Shank diameter for boring bar (d)

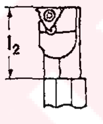


5 Hole diameter



D = min. hole diameter

6 Programming length

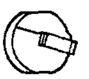


l_2 = max. depth of thread

7 Insert dimension

T-MAX U-Lock
Insert size in mm
11 = IC 1/4" = 6.35 mm

8 Bar design



B = Round cross-section, eccentric in relation to the larger diameter.

Figure C.2 Boring Bars for Internal Threading Operations

Table C.1 Designation Code of Grooving and Drilling Inserts[36,53]

Grooving code	Code of Grooving	"3.90022L006"
	Manufacturer Code	"3.90"
	Cutting Width (2.2 mm)	"022"
	Cutting direction	"L"
	Manufacturer's Code	"006"
Drilling code	Code of the drilling	"B 201 A 03000"
	Manufacturer's Code	"B 105"
	Version	"A"
	Diameter of the drill (3 mm)	"03000"

Table C.2 Designation Code for Grooving and Drilling Tool Holders[36,53]

Grooving code	Code of Grooving	"3.8610 R 022"
	Manufacturer's Code	"3.861"
	Width of the holder	"10"
	Cutting direction	"R"
	Cutting Width (2.2 mm)	"022"
Drilling code	Code of the drilling	"B 105 A 0300"
	Manufacturer's Code	"B 105"
	Version	"A"
	Diameter of the drill (3 mm)	"0300"

APPENDIX D

Table D.1 The Turning Operations and Their Acronyms Used in This Thesis[35,36]

NO	ACRONYM	THE TURNING OPERATION
1	ECNC_LH	External conical turning left-hand
2	ECNC_RH	External conical turning right-hand
3	ECYL_LH	External cylindrical turning left-hand
4	ECYL_RH	External cylindrical turning right-hand
5	EFCN_LH	External facing left-hand
6	EGRV_LH	External grooving left-hand
7	EPRF_LH	External profile turning left-hand
8	EPRF_RH	External profile turning right-hand
9	ERCS_LH	External recess turning left-hand
10	ERCS_RH	External recess turning right-hand
11	ETHR_LH	External threading left-hand
12	ETHR_RH	External threading right-hand
13	ICNC_LH	Internal conical turning left-hand
14	ICNC_RH	Internal conical turning right-hand
15	ICYL_LH	Internal cylindrical turning left-hand
16	IGRV_LH	Internal grooving left-hand
17	IPRF_LH	Internal profile turning left-hand
18	IPRF_RH	Internal profile turning right-hand
19	IRCS_LH	Internal recess turning left-hand
20	IRCS_RH	Internal recess turning right-hand
21	ITHR_LH	Internal threading left-hand
22	ITHR_RH	Internal threading right-hand
23	IDRL	(Internal) drilling
24	IRMN	(Internal) reaming