Machinability Studies of High Strength Materials: steel (277 BHN)

By Abdalrahman Tawela B Sc Eng

A Thesis Submitted in Fulfilment
of the Requirements for the Degree of
Master of Engineering (M Eng)

Dublin City University

School of Mechanical and Manufacturing Engineering

Name of Supervisors Professor M A El-Baradie
Dr Garrett McGuinness

DECLARATION

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of Master of Engineering is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work

Signed ______________ ID No 99146142

Date 16-4-2003

ACKNOWLEDGEMENTS

I am very grateful to Professor M A El-Baradie and Dr Garrett McGuinness for their support and advice through my work I would also like to extend my gratitude to Professor M S J Hashmi, Head of the School for encouraging me and providing me with his help I would also like to thank all the academic staff of the school who have helped me over the past two years

I would like to thank Martin Johnson and James Barry for their knowledge, support and friendship during my two years at university

I would like to thank my parents for their continued support throughout my studies

ABSTRACT

Machinability assessment of a high strength steel was carried out using uncoated and coated inserts The material investigated was steel EN24T/817M40T 277 (BHN) The object of this assessment is to generate reliable machining data in terms of tool life, cutting force and surface finish in relation to cutting speed, feed rate and depth of cut During this research cutting tests were carried out by using both one variable-at-a-time and design of experiment approaches

For one-variable-at-a-time experiments, cutting forces, tool life and surface finish were measured In these tests, the cutting speed, feed rate and depth of cut were varied to study their effects on the tool life, cutting forces and surface finish With the design of experiment approach, the combined effects of the cutting variables on the machining responses were investigated

Using the mathematical models for different responses, a computerised machinability data base system was developed to facilitate the optimum selection of cutting parameters The selection of cutting parameters is applicable for EN24T/817M40T steel 817

TABLE OF CONTENTS

NOMENCLATURE

d	depth of cut (mm)
f	feed rate (mm/rev)
V	cutting speed(m/min)
F_x	axial (feed) force
F_y	radial force
F_z	tangential force
F	resultant cutting force
BHN	Brinell hardness number
N	Unit of force (newton)
ε	Experimental error
β	Parameter to be estimated
R_a	observed arithmetic average surface roughness (μm)
T	tool life (minutes)
VB_B	average width of flank wear (mm)
VB_N	width of notch wear (mm)
KT	crater depth (mm)
Q	metal removal rate (cm^3/min)
b	matrix of the parameter estimates
X	matrix of independent machining variables
X^T	transpose of x
$(X^T X)^{-1}$	inverse of the matrix $(X^T X)$
x_1	coded variable (speed)
x_2	coded variable (feed)
x_3	coded variable (depth of cut)
y	observed logarithmic response (tool life, cutting force and surface roughness)

CHAPTER ONE: INTRODUCTION

1. Introduction

Recommended parameters for machining steel using a lathe may be obtained from many sources, including the Machinability Data Handbook Data for the handbook has been obtained from the recommendations of metal producers, machine tool manufacturers, and cutting tool and cutting fluid manufactures, and from machinability reports and miscellaneous literature on machining Machinability data systems may also be used to ensure optimum production from the expensive equipment involved A machinability data system is considered essential for the selection of optimum cutting conditions during process planning It has become an important component in the implementation of computer integrated manufacturing (CIM) systems

Computerised machinability data systems have been classified into two general types, which are database systems and mathematical model systems The database systems are based on the collection and storage of large quantities of data from laboratory experiment and workshop experience and retrieval of recommended cutting speeds, feed rates and cost information for any specific cutting operation The mathematical model systems attempt to predict the optimum cutting conditions for a specific operation The machining response data such as tool life, surface roughness, cutting force and power are used to derive the optimum set of cutting conditions The major weakness of the mathematical model systems lies in the random errors contained in the machining response data and their effect on the validity of the predicted optimum set of cutting conditions It has usually been found that the metal cutting data is susceptible to an appreciable amount of scatter This is due to the non-homogeneity of the material being cut and its effect on the measurement of the machining response data, as well as due to errors associated with the measuring technique itself Therefore the predictions are only given in terms of mean values with confidence limits

The need for selection of appropriate machine tools, the determination of optimised cutting data and the selection of tools and cutting materials are the main problems in planning machining conditions Many researchers in this regard have suggested a machinability database system, which will provide information needed for the automatic selection of machining data The purpose of the data base system is to generate the recommended cutting speed, feed rate, and depth of cut using an optimisation algorithm

In this thesis a mathematical model utilizing the response surface methodology has been developed for predicting the surface roughness of machined components In this model a 2^3 factorial design is used to study the effect of cutting speed, feed rate, depth of cut, and nose radius on the surface roughness when turning steel EN24/817M40T when using tipped carbide tools under dry conditions The predicted surface roughness results are presented

The main aims of this study are

1- Generation and analysis of cutting test data for high strength steel EN24/817M40T of hardness 277 BHN
2- Development of optimum conditions for the process, in terms of cutting force, tool life, surface finish for steel EN24/817M40T by investigation of cutting conditions
3- Optimization of the machined surface roughness under different cutting conditions

In Chapter 2, a Literature survey related to the proposed work is presented Machining of high strength materials and definitions of machinability assessment are discussed and the factors which influence machinability have been reported

In Chapter 3 the theory of metal cutting is discussed, which includes cutting forces, tool life and surface finish Mechanisms of tool wear, which occur during machining, are presented Commonly occurring mechanisms, including diffusion, adhesion, abrasion and chemical wear, are described
The influence of the tool on surface finish has been reported, describing how the cutting edge leaves its own mark

The experiment facilities are described in Chapter 4, in which the experimental set-up used for the cutting test is outlined These include a description of the Kistler 3-

component dynamometer, surface roughness tester, and toolmaker's microscope The chemical and mechanical properties of the work material used for the tests are presented The cutting tool material and tool geometry are also described

Chapter 5 covers the experimental results based on a one-variable-at-time analysis for steel EN24/817M40T The cutting forces and tool life and surface finish results are presented and analysed The effects of speed, feed, and depth of cut on cutting forces, tool lives and surface finish are discussed Variation of the cutting forces with respect to speed feed and depth of cut are also shown The tool wear of coated and uncoated carbide for turning operations is investigated Wear of coated and uncoated tools is compared for the same machining conditions

In Chapter 6 the experimental results based on the design of experiments method are presented for steel EN24/817M40T Surface roughness has been measured/recorded when uncoated carbide inserts were used The influence of depth of cut and nose radius on surface roughness have been investigated and recorded Mathematical models of surface roughness based on the response surface methodology are presented Response contours of surface roughness are also shown in different plots Dual response contours of metal removal rate and the different responses are also shown

Finally, conclusions and recommendations for further work have been discussed in Chapter 7

CHAPTER TWO: LITERATURE SURVEY

2 Literature Survey

2.1 Introduction

A reasonable amount of work has been reported in the literature with regard to the machining of high strength materials The following review focuses on machinability of high strength materials during the turning operation

The use and advantages of high strength materials have been widely reported Machinability assessment as a definition, and the factors that influence machinability, have also been extensively reported

2 2 High strength materials

EN 24 / 817M40T steel is widely used in the manufacture of structural components used in corrosive environments Axle shafts and other machined parts may be manufactured using this material

In general these alloys are extremely difficult to machine because of the following [1]

(a) high shear strength,
(b) high work-hardening capacities,
(c) hard abrasive carbides in the microstructure,
(d) low thermal conductivity and specific heat, and thus high cutting temperature

As a result, both cutting forces and temperature in the cutting zone are extremely high Therefore machining rates and tool life values are very low It is felt that production rates and tool life values might be increased by optimising the cutting parameters

In this study, machinability experiments for EN24/817M40T steel using coated and uncoated carbide inserts under dry cutting condition were carried out The cutting experiments were under taken for the following reasons

(a) To measure cutting force and optimum cutting conditions,
(b) To obtain tool life values and relationships for the material and the inserts,
(c) To investigate the effect of cutting speed and feed rate on the surface roughness in turning operation for the material,

2 3 Machinability assessment

Machinability is a term used to describe the characteristics or behaviour of a metal when it is being cut Assessment of machinability is the most important problem when specifying the cutting conditions for an optimal economic utilisation of resources If tool life is the objective, then good machinability means long tool life If cutting force is the objective, then good machinability means low cutting forces If the surface finish is the objective, the good machinability means less roughness [2] In general, machinability can be defined as an optimal combination of the following factors

(a) Low cutting forces
(b) High metal removal rates
(c) Low tool wear rates
(d) Good surface finish
(e) Good surface finish integrity
(f) Accurate and consistent workpiece geometrical characteristics
(g) Good curl or breakdown of chip

In this study, the most important parameter for machinability is surface roughness This is assessed by investigating the following parameters

(a) Cutting forces
(b) Tool life
(d) Surface finish

2 3 1 Factors Influencing Machinablitiy

The factors which influence machinability are discussed in the following section

2 3 1 1 Machining Operation

The types of machining operations which are used in industry include such operations as turning, milling, drilling and planning

These operations can be broadly classified as

(a) Continuous cutting operations
(b) Intermittent cutting operations

Turning can be thought of as representative of continuous cutting operations, while milling is an intermittent cutting operation. The usual practice is to use the turning operation for machinability tests. However, it is recognized that the type of operation has a very significant effect on the machinability results.

2.3.1.2 Cutting Conditions.

El Baradie and Wilson have determined the following effects of cutting conditions on machinability [2].

Cutting speed: This is the most important variable in the cutting operation. Cutting speed directly affects the surface finish, tool life and cutting forces, so the cutting speed has significant effect on machinability. An increases in the cutting speed causes a decrease in tool life. A decreases in cutting forces causes a decrease in roughness.

Feed: The effect of increase in feed rate on tool life is similar to that of cutting speed, but the effect is much less pronounced. An increase in feed rate increases the cutting forces. Also the surface finish produced is a function of the feed rate.

Depth of cut: The variation in depth of cut has little effect on tool life while depth of cut has a significant effect on cutting forces.

Cutting fluid: The use of cutting fluids results in an increase in the life of the cutting tool.

2.3.1.3 Workpiece properties:

The workpiece properties have a profound effect on machinability [2]. The microstructure, chemical composition and physical properties are important.

Microstructure: Metals of similar microstructure generally have similar machining properties, but small changes in microstructure can greatly affect machinability.

Chemical Composition: The structure and mechanical properties of any alloy are determined basically by its chemical composition. Alloying elements have a strong influence on machinability

Physical Properties: the major physical properties affecting machinability are its hardness and work hardening properties.

Work Hardening Properties: Production operations such as drawing, rolling and forging – which sometimes call for pre- heating – have an important influence on the final structure of metal, and therefore on it's physical characteristics.

2 3 1 4 Tool Properties

Tool geometry and tool materials have the greatest effect on machinability [2]

Tool Geometry the normal rake angle has the largest influence on tool life and thus on machinability The tangential cutting forces is greatly influenced by the rake angle (Figure 2 1)

Tool Material the requirements of cutting tools are high hardness and thermal shock resistance and the ability to maintain these properties at the very high temperatures that occur in metal cutting

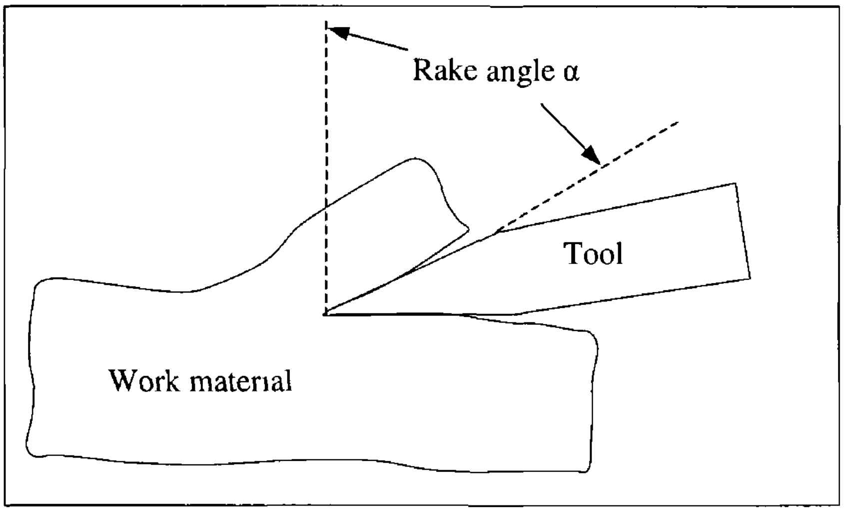


Figure 2 1 Rake angle

2 3 1 5 Machine Tool – Tool Workpiece Dynamics

An important practical problem in machining is vibration or chatter Chatter has three main adverse effects, (i) it may produce imperfection on the work surface, (ii) it may increase the rate of wear of the tool, and (iii) it may cause a high–frequency sound, which can be physically harmful to personnel [2]

2 3 1 6 Summary

The factors, which influence machinability, are presented in Figure (2 2)

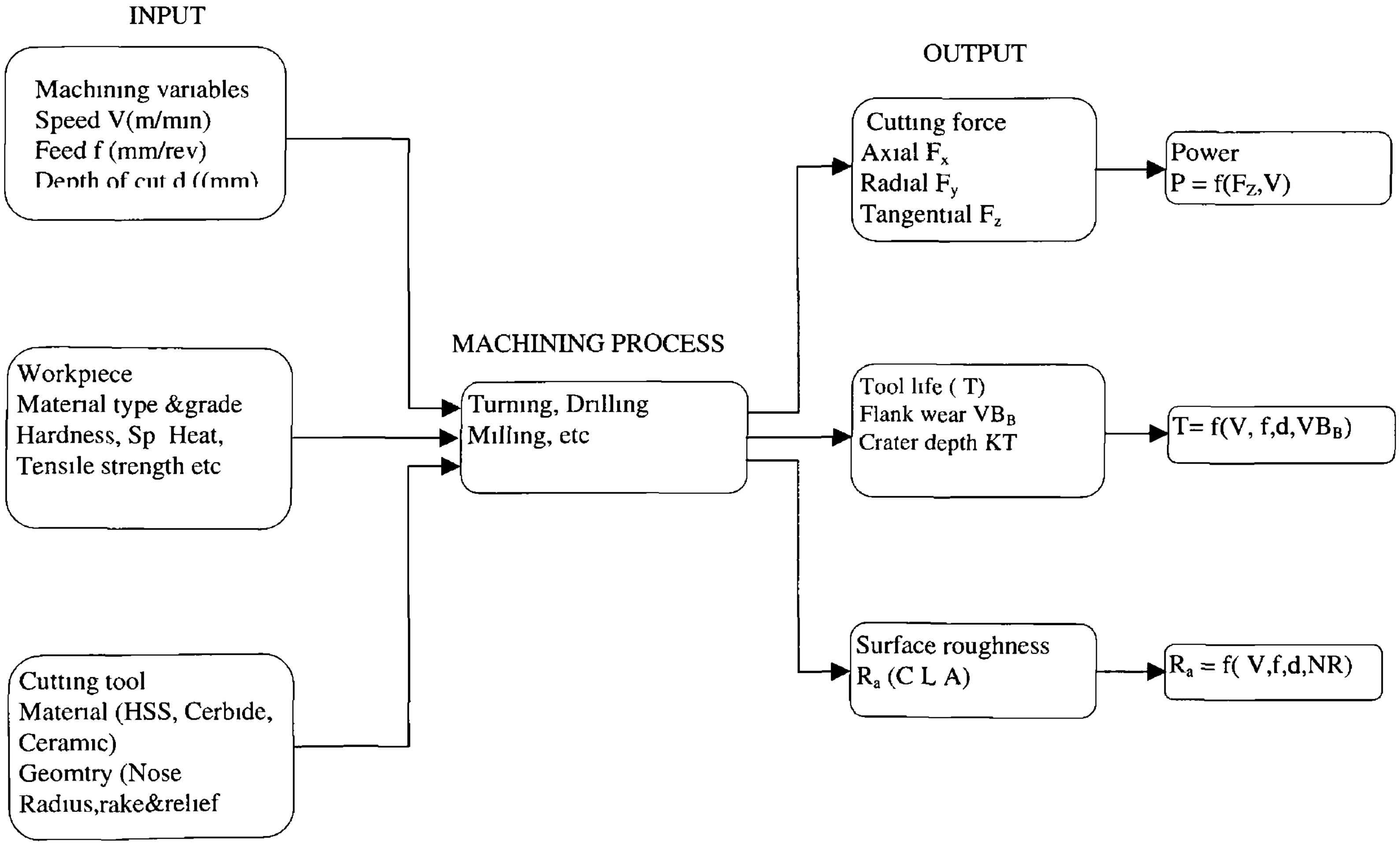


Figure 2 2 Various machinability parameters in a machining process

2.4 Cutting forces

Wuyi Chen [3] has discussed the cutting forces generated using tool materials such as cubic boron nitride (C B N) Tools with cutting steel hardened to 45-55 HRC have been evaluated The cutting tools used in the tests were high CBN concentration The workpiece material used in the tests was hardened GB699-88 55 steel hardened to 45-55 HRC

The operating parameter ranges were as follows, cutting speed v = 56 to 182 m/min, feed rates f = 0 08 to 0 31 mm/rev, depth of cut d =0 025 to 0 1 mm In addition, all tests were conducted under dry turning conditions It was observed that the cutting forces could be divided into three components feed force (F_x), radial thrust force (F_y) and tangential cutting force (F_z) Usually the tangential cutting force is the largest of the three components When cutting speed is increased, both the radial thrust force and the tangential cutting force decrease Depth of cut seemed to influence cutting forces more significantly than cutting speed and feed rate It was observed that as the nose radius increase from 0 3 to 1 mm, F_y increases by about 30%, whereas the changes in F_x and F_z are negligible It was also found that tool wear had a negligible influence on the feed force and the tangential cutting force Surface finish was improved by increasing cutting speed, though the improvement was very limited Producing a better surface finish at higher cutting speed is not unusual in metal cutting, The roughness increases as feed rate is increased, but the trend is less significant for the tools with large nose radius

Wang [4] has investigated the effects of multi-layer hard surface coating of cutting tools on the cutting forces in steel turning Results based on an experimental investigation with different commercially available carbide inserts and tool geometries over a range of cutting conditions are presented and discussed The hardness of the work material is 125 BHN Two types of SCMT and CNMM were selected All tools were supplied by Sandvik Australia Three levels of feed per revolution (0 13, 0 17 and 0 21 mm) and three levels of depth of cut (0 5, 1 0 and 2 0mm) were tested under two levels of cutting speed (108 and 206 m/min) The tangential, feed and radial force components were measured using a Kistler type 9257A three component piezo electric dynamometer However, when turning with surface coated carbide inserts the cutting forces were assessed and compared qualitatively and quantitatively with those for uncoated tools Comparing the cutting force components for surface coated and uncoated tools, he observed that for the same cutting conditions and tool geometry the feed forces F_x and radial forces F_y for coated tools were, for all of the 18 combinations of the cutting conditions, lower than those of the uncoated tools However, it was noticed that in general the percentage deviations for the three force components increased with an increase in the feed per revolution and the depth of cut and with a decrease in the cutting speed It was also noticed that with an increase in the feed, the rate of change for the tangential force F_z is greater than those of the other two force components

Hong, Ding and Jeong [5] have discussed the relationship between cutting forces and cutting speed when using an uncoated CNMA432-K68 insert (equivalent to C3 class or ISO K05-K20, M10-M20) in a turning operation The cutting conditions were, depth of cut 1 27 mm, feed 0 254 mm/rev, and cutting speeds ranging from 1 m/s to 2 5 m/s It was observed that as the cutting speed increases, the cutting forces decrease

Noordin and Venkatesh [6] have studied the performance of three cemented carbide cutting tools Finish turning of AISI 1010 steel with two coated tungsten based cemented carbide (one with Al_2O_3 (black) outer layer and the other with TiN (golden)), and an uncoated titanium based (silver Grey) cemented carbide tool has been discussed The tools were tested at cutting speeds (*V*) of 140, 200 and 280 m/min and high feed rates (*f*) of 0 23 and 0 28 mm/rev were used for high productivity A low depth of cut (*d*) of 1 mm was used However it was found that the tangential force was much higher than the other forces for any particular experiment Generally all three forces increased when the feed rate was increased from 0 23 to 0 28 mm/rev

Wang [7] has discussed the effect of using coated and uncoated carbide cutting tools on the cutting forces in steel turning Three levels of feed per revolution (0 13, 0 17 and 0 21 mm) and three levels of depth of cut (0 5, 1 0 and 2 0 mm) were tested under two levels of cutting speed (108 and 206 m/min) It was observed that the feed forces

F_x and radial forces F_y for coated tools are lower than those of uncoated tools It can be seen that in general the three force components increase with an increase in feed rate and depth of cut and with a decrease in cutting speed

Rahman and Ramakrishna [8] have developed feasible techniques for machining Carbon Fiber Reinforced Composites (CFRP) The machining parameters (cutting speed, feed rate and depth of cut) were varied Three types of cutting tool inserts (uncoated tungsten carbides, ceramic and cubic boron nitride (CBN)) were used to machine two types of specimens It was found out that, for the turning of these composites, a larger feed rate requires a larger cutting force

Hocheng, Yen and Ishihara [9] investigated the variation of cutting forces with cutting speed, feed rate and depth of cut The workpiece materials were bars of a graphite/aluminum composite (PG5), 55mm in diameter and 100 mm long The cutting tool material used for this experiment was tungsten carbide of grade K10 Four levels of depth of cut were used (0 25 mm, 0 50 mm, 0 75 mm and 1 mm) The feed rate was 0 3 mm/rev and the cutting speed was 300 m/min It was observed that there was no reduction in the cutting forces when cutting speed was increased It was found that the tangential force component increases with feed rate and depth of cut, as a result of the increased volume of material removed

Audy, Strafford and Subramanian [10] carried out a series of experiments in which cutting forces were measured with a Kistler three component piezoelectric dynamometer The tool materials used were coated and uncoated carbide at various speed and feed rates The work material was low carbide steel It was observed that increased cutting forces were influenced principally by the feed rate and depth of cut

Wang and Mathew [11] have presented results for a steel work material Cutting forces were measured by using a Kistler three component piezoelectric dynamometer The conditions used were feed rate f = 0 125 mm/rev and 0 250 mm/rev, cutting speed V = 150 m/min and 250 m/min, depth of cut ≈ 4 mm and nose radius r = 1 25 mm It was noticed that as the feed rate was increased, two of the cutting force components increased and one of them decreased

Masatoshi and Toru Fuse [12] found that the machinability is very low for Nitriding steel (SACM 645) in turning operations because the hardness of this steel is relatively high The hardness of the work material used in this work was 275 (Hv) However to improve the machinability of SACM 645, molybdenum and vanadium are added during making this steel All cutting tests were performed using a high speed lathe and P20 carbide tools Cutting conditions were carried out as follows cutting speeds, 150 m/min, 200 m/min, 260 m/min, depth of cut, 2 0mm and feed rate, 0 2 mm/rev It was noticed that the cutting force of steels decreased as cutting speed increase

Alauddin and El Baradie [13] have studied the influence of the machining conditions on the average cutting forces for half-immersion end milling in the up- and down-milling modes The cutting tests were carried out under dry conditions using carbide inserts It was observed that the cutting forces decrease as the cutting speed increases for down end milling The cutting forces decrease as the feed rate and depth of cut increases

Huang and Chow [14] carried out a series of turning tests using different cutting tools (P10, cemented carbide (with TiN coating), pure Al_2O_3 and AL_2O_3 (with TiC)) Cutting forces and surface finish were measured It was observed that the tangential cutting force component is the largest force, the axial cutting force is the second largest, whilst the radial cutting force is the smallest The cutting forces decrease with increasing cutting speed and the surface roughness is independent of the cutting speed

2.5 Tool life

Ozler and Inan [15] investigated the tool life by influence of cutting speed, feed rate, and depth of cut, in turning operations Expressions for the effects of cutting conditions on tool life were determined using a mathematical model developed by a factorial regression method A sintered carbide tool was used to machining austenitic manganese steel The hardness of the steel was 243 HB The experiment was carried out at cutting speeds of 22 m/min, 33 m/min, 46 m/min, 62 m/min and 75 m/min Feed rates of 0 05 mm/rev, 0 1 mm/rev, 0 2 mm/rev and 0 4 mm/rev and depths of cut of 0 5 mm, 1 5 mm, and 2 5 mm were used As cutting speed was increased, the tool life decreased The least influential of the cutting conditions on the tool life was the depth of cut As depth of cut was increased, a minimal decrease in the tool life was noticed These results showed that the effect of depth of the cut was less than the effects of cutting speed and of feed rate Thus, it could be deduced that the influence of cutting depth on tool life could be disregarded

Feed rate is another factor which influences the tool life The tool life decreased as the feed rate was increased The effect of feed rate was less than that of cutting speed The depth of cut seemed to have the least influence on the tool life

El Baradie [16] has developed tool life expression in terms of cutting speed and feed rate under dry cutting conditions The workpieces were cast in the form of cylindrical bars approximately 500-mm long and 200 mm diameter The bars were manufactured to BS 1452 1977 Grade 260 After centering the bars, 4mm thickness was removed from the outside surface to ensure total removal of any cast skin The hardness of the material was found to be between 145 and 154 BHN In all experiments the feed rate per revolution was maintained constant at 0 74(mm/rev), while the feed rate was varied by varying the spindle rotation (rpm) All tests were carried out with a fixed depth of cut (1 0 mm) under dry cutting conditions Three cutting speeds were used, 110 m/min, 195 m/min, and 350 m/min At each cutting speed, three feed rates were used 0 47 mm/rev, 0 63 mm/rev, and 0 84 mm/rev It was noticed that the 0 63mm/rev feed rate gives the highest tool life value, and that the tool life increases as feed rate increases up to 0 63mm/rev The largest increase in tool life occurs at a speed of 195 m/min The tool life increases from 2 16 min at 0 47 mm/rev to 4 66 min at 0 63 mm/rev, representing an increase of over 100% The tool life decreased to 4 08 min when the feed-rate was increased to 0 84 m min ^{1} while at the same cutting speed 195 m/min

Ghani and Choudhury and Husni [17] have presented a study of tool life while machining nodular cast iron using a ceramic tool The tests were done under various combinations of speed, feed and depth of cut The cutting tool used was CC650, a mixed alumina (Al_2O_3)-based ceramic with titanium carbide (TiC) It was observed that, based on the average flank wear of the ceramic inserts, tool life became shorter with an increase in speed, feed rate, or depth of cut

Che-Haron [18] has discussed the behavior of titanium alloys Uncoated cemented carbide tools were used for the turning of Ti-6Al-2Sn-4Zr-6Mo The experiments were carried out under dry cutting conditions The cutting speeds selected in the experiment were 100 m/min, 75 m/min, 60 m/min and 45-m/min The depth of cut was kept constant at 2 0 mm The feed rates used in the experiment were 0 35 mm/rev and 0 25 mm/rev Two types of insert were used in this experiment Tool wear was measured using an optical microscope It was noticed that at a lower feed rate of 0 25-mm/rev, both inserts gave better tool life under all cutting speeds, and tool lives were reduced significantly as the cutting speed was increased

Choudhury and El-Baradie [19] have investigated machining operations using both coated and uncoated carbide tools Tool life values were assessed at four levels of cutting speed while the feed rate was kept constant Similarly, the tool lives at three levels of feed rate and three levels of depth of cut were investigated while keeping the other two cutting parameters constant Flank wear was considered as the criterion for tool failure The cutting conditions selected were cutting speeds of 20 m/min, 26 m/min, 36 m/min, 48 m/min, feed rates from 0 12 m/rev to 0 30 mm/rev and depths of cut from 1 0 mm to 2 1 mm It was observed that as cutting conditions (cutting speed, feed rate, depth of cut) increased, the tool life decreased However the effect of cutting speed on tool life was more pronounced than the effect of feed rate and depth of cut for coated tools

Joshi and Ramakrishnan [20] designed and fabricated a tool holder The experiments were designed using Taguchi methods to analyses the influence of various factors and their interaction on the flank wear of rotary carbide tools during machining A tool life model was presented describing the effect of process and tool material dependent parameter on the magnitude of the flank wear to a rotary carbide tool It was observed that the feed rate has a significant effect on tool wear As the feed rate increased, the flank wear increased As the cutting speed increased, the tool wear was reduced

Lin and Bhattacharyya [21] have developed tool life studies for aluminium using PCD inserts The cutting condition were selected at cutting speeds of 300 m/min, 500 m/min and 700 m/min, feed rates of 0 1 mm/rev, 0 2 mm/rev and 0 4 mm/rev The depth of cut was kept constant at 0 5 mm The performance of the tools is based on the development of 0 25 mm maximum flank wear It was observed that the cutting time decreases with increasing cutting speeds and feed rates

Rahmana and Seaha [22] discussed the effect of cutting condition on the machinability of Inconel 718 The experiment was conducted on a lathe under wet conditions using TiN coated tools The three cutting forces (tangential, axial and radial forces) are measured Flank wear was measured by using an optical toolmaker's microscope, surface roughness was determined with a Taylor Hobson Surtronic 10 and cutting forces were observed with a 3-component dynamometer Two types of inserts supplied by Sumitomo Electric were used They were (1) K type substrate, TiN physical vapour deposition (PVD) coated cemented carbide grade EH20Z-UP and (2) Multi AI_2O_3 chemical vapour deposition (CVD)coated cemented carbide grade AC25 The cutting speeds and feed rate were varied as the depth of cut was held constant The cutting speeds were 30 m/min, 40 m/min, 50 m/min and the feed rates were 0 2 mm/rev, 0 3 mm/rev and 0 4 mm/rev and depth of cut was 2 mm It was noticed that the tool life decreases at high cutting speed, and cutting forces increase as feed rate and cutting time increase, as cutting time and feed rate increase axial force also increases

Ferreira and Coppini [23] have studied some aspects of the machining of carbon fibre reinforced composites (CFRC) using tool materials like cemented carbide and cubic boron nitride (CBN) The experiments were carried out at different cutting speeds and feed rates to investigate the influence of the cutting condition on tool wear It was observed that the tool flank wear decreased when the cutting speed increased from 150 to 500 m/min

Zone-Ching and Din-Yan Chen, [24] have discussed the effect on cutting forces and tool wear when using cubic boron nitride (CBN) for cutting hardened steel at different cutting conditions It was observed that the flank wear rate is usually greater at the low cutting speeds and the cutting force is greatest when the depth of cut is larger

Che Haron and Ginting [25] have studied the performance of cutting speed on tool life for steel bars by using coated and uncoated carbide tools In this study, tool steel with ISO designation 95MnCrW1 was selected as the workpiece material Machining tests were performed under wet and dry cutting conditions at various cutting speeds, while the feed rate and depth of cut were kept constant It was observed that the tool life of coated and uncoated carbide tools decreases quickly at higher speeds

Ezugwu and Wang [26] have developed cutting tool materials which have significantly improved the machinability of a large number of metallic materials, including cast irons, steel and some high temperature alloys (such as nickel-based developments for cutting titanium alloys (Ti-6AI-4V)) It was noticed that tool life is extremely short at high cutting speeds but improves dramatically as the speed is reduced Another important variable affecting the tool life is the feed rate It was observed that the tool life was not changed dramatically with a change in feed rate The effect of depth of cut must be considered also Increasing the depth of cut from 0 75 mm to 3 mm decreases the tool life from 46 minutes to 14 minues at a cutting speed of 60 m/min

Astakhov and Osman [27] have investigated the variation in tool life over a range of cutting speeds for a turning process with a workpiece material of stainless steel (0 12% C, 18%Cr, 10% Ni) The cutting tool used was carbide BK8 It was noticed that the curve for the tool life increases with an increase in cutting speed

2.6 Surface finish

Rahman and Ramakrishna [28] investigated surface finish and cutting force for machining Carbon Fibre Reinforced Composites (CFRP), where the machining parameters namely cutting speed, feed rate and depth of cut, were varied The cutting tools used in this work were ceramic (TNGA 160408-CERAMIC), Cubic Boron Nitride (TNGA 160408-QBN), and Tungsten Carbide (TNGA 160408-CERMET) It was observed that the surface roughness is higher at a feed-rate of 0 3 mm/rev than at a feed-rate of 0 1 mm/rev for both tungsten carbide and ceramic inserts

Che-haron [29] described the behavior of titanium alloys and the mechanism involved at the tool Uncoated cemented carbide tools were used for the turning of Ti-6AI-2Sn-4Zr-6Mo The experiments were carried out under dry cutting conditions The cutting speeds selected in the experiment were 100 m/min, 75 m/min, 60 m/min and 45-m/min The depth of cut was kept constant at 2 0 mm The feed rates used in the experiment were 0 35 and 0 25 mm/rev Two types of carbide inserts of ISO designation CNMG 120408 were used It was observed that as the cutting speed increased, the roughness value decreased Highest surface roughness value recorded for 883-MR4 insert 5 28μm and it was recorded at cutting speed of 60-m min ^{1}

Thomas [30] has discussed optimization of cutting parameters to control the required surface quality The study was carried out for dry turning of mild carbon steel samples at different values of cutting speed, feed rate and depth of cut The best surface roughness conditions were achieved at a low feed rate (less than 0 35mm/rev), a large tool nose radius (1 59mm) and a high cutting speed (265 m/min and above) The results show that the depth of cut does not have a significant effect on surface roughness It was observed that the increase in dynamic forces became more significant with increasing depth of cut

Yves Marc and Thomas [31] investigated the effects of cutting parameters on surface roughness during a lathe dry boring operation Carbon steel tube samples were used as the work material A full factorial design was used to evaluate the effect of six independent variables (cutting speed, feed rate, depth of cut, tool length and type of boring bar) The improvement on surface roughness was achieved by controlling cutting speed, feed rate, and tool nose radius

Jeong-Youn [32] carried out the machining of an aluminium alloy using endmaillin operation This generally results in a short tool life and poor surface quality It was observed that a high cutting speed, a low depth of cut and low feed speed are required for a high quality surface when machining aluminium

Gillibrand D and Pierce C T [33] investigated surface finish (roughness) and tool life, using uncoated carbide inserts corresponding to ISO P25 grade and coated inserts of titanium nitride on a P35 substrate The cutting tests were carried out on a medium carbon steel (080M40) It was observed that the coated tools gave an improvement in tool life of more than 300% over the uncoated tools for each cutting speed used in the test program Coated carbide tools also gave a lower surface roughness

Paul [34] studied the influence of cutting conditions on surface finish for a turning operation The workpiece material was steel (9SMnPb28k DIN) The objective was to establish a correlation between cutting velocity, feed and depth of cut and the roughness evaluating parameters R_a and R_t following the international norms The cutting conditions selected were cutting speeds of 250 m/min, 150 m/min and 100 m/min, feed rates of 0 10 mm/rev, 0 16 mm/rev and 0 25 mm/rev and depths of cut of 0 5 mm, 0 75 mm and 1 00 mm It was observed that cutting velocity has the greatest influence on the roughness As the cutting speed increases, the roughness decreases, and the depth of cut has no significant influence on the roughness

Mashal and El-Axir [35] have investigated the tribological characteristics of rapidly solidified Al-8Fe-4Ce Designs of experiment techniques were used to improve the experimentation design without a loss of accuracy in the results The interaction of cutting parameters (cutting speed, feed rate and depth of cut) was examined and their effect on the average surface roughness was reported The cutting speed used ranged from 8 8m/min to70 m/min, and the depth of cut ranged from 0 03 mm to 0 32 mm It was found that at high cutting speed and small depth of cut with small feed rate causes a significant reduction in R_a

2.7 Experiment design

Choudhury and El - Baradie [36] carried out a series of turning tests on nickel base super alloy (Inconel 718) using coated and uncoated carbide inserts under dry conditions The investigation involved the development of response models (tool life, surface roughness, and cutting force) for turning Inconel 718 utilising factorial design of experiments and response surface methodology First-order predictive models covering the speed range of 10 m/min - 33 m/min and second-order models within the speed range of 7 m/min - 45 m/min have been developed at a 95% confidence interval The three main parameters of machinability assessment were (i) tool life, (ii) surface finish, and (iii) cutting force

A machinability model may be defined as a functional relationship between the input of independent cutting variables (speed, feed, depth of cut) and the output, known as response (tool life, surface finish, cutting force), of a machining process In order to develop this model, it is necessary to design and carry out an experiment involving the work material and the cutting tool The experimental work provides the response data as a function of the cutting speed, feed rate, and depth of cut The tool material used for the turning test were Sandvik cemented tungsten carbide (both uncoated and coated) inserts Sandvik manufactures these inserts The uncoated carbide inserts were CNMA 12 04 04 grade H13A, whilst the coated carbide grade was GC3015 The tool life model can be described using the following equation

$$T_{\text{uncoated carbide}}=383\ 5V^{-2\ 0985}f^{1\ 6952}d^{1\ 003} \quad (2\ 1)$$

It was noticed that the tool life decreases with increasing cutting speed, feed rate and the depth of cut The cutting speed has the most dominant effect on tool life, followed by the feed rate and than the depth of cut The first-order tool life equation using a coated carbide insert is given by

$$T_{\text{coated carbide}}=85\ 2V^{1\ 801}f^{1\ 885}d^{0\ 647} \quad (2\ 2)$$

Surface roughness can be described by following form

$$R_{a\text{uncoated carbide}}=47\ 8V^{0\ 193}f^{1\ 3596}d^{0\ 0704} \quad (2\ 3)$$

Surface finish improves with an increase in the cutting speed at a constant feed rate and constant depth of cut However, it was found out that the surface roughness increases with an increase in the feed rate The surface finish was observed to improve with increase in cutting speed or depth of cut, and it was observed that the influence of depth of cut on the improvement of surface finish was greater than the effect of the speed

Cutting forces decrease with an increase in speed, whilst they increase with an increase in feed or depth of cut The depth of cut was found to have the maximum influence on the cutting forces

Suresh and Venkateswara [37] have developed a surface roughness prediction model for machining mild steel, using Response Surface Methodology (R S M) The experiments were carried out using TiN-coated tungsten carbide (C N M G) cutting tools when machining mild steel work-pieces using a wide range of machining conditions A second order mathematical model was used The relationship between surface roughness and the other independent variables was modeled as follows

$$R_a = C\, v^{k1} f^{k2} d^{\,k3} r^{k4} \qquad (2\ 4)$$

where C is a constant and k_1, k_2, k_3, k_4 are parameters

The proposed first-order model developed from the above functional relationship using the R S M method is as follows

$$Y=1\ 029483-0\ 11222x_1+0\ 564299x_2-0\ 08131x_3+0\ 022143x_4 \qquad (2\ 5)$$

The transformed equation of surface roughness prediction is as shown below

$$R_a=28\ 14185v^{0\ 192844} f^{0\ 814111} d^{-0\ 117306} r^{0\ 031946} \qquad (2\ 6)$$

This approach provides optimum machining conditions for corresponding given maximum and minimum values of surface roughness This approach is quite advantageous in order to have the range of surface roughness values, and their corresponding optimum machining conditions, for a certain range of input machining parameters It was noted that the developed surface roughness prediction model takes into account cutting speed, feed rate, depth of cut, cutting tool, nose radius and their interactions

Choudhury and El-Baradie [38] have developed first- and second-order equations for turning high strength steel The tool-life models were developed in terms of cutting speed, feed rate, and depth of cut, using experimental design The effects of the main cutting variables (cutting speed, feed, and depth of cut) on tool life were investigated using the factorial design method All of the cutting tests were performed using uncoated carbide tools under dry conditions The cutting conditions were selected at cutting speeds of 28 m/min, 36 m/min, 65 m/min, 117 m/min and 150 m /min and feed rate of 0 12 mm/rev, 0 15 mm/rev, 0 25 mm/rev, 0 40 mm/rev and 0 50 mm/rev and depths of cut of 0 42 mm, 0 50 mm, 0 75 mm, 1 125mm, and 1 33 mm The proposed relationship between the tool life and the independent machining variables can be represented by the following equation

$$T = 4564 V^{-1\ 7903} f^{-0\ 4883} d^{-0\ 1924} \quad (2\ 7)$$

It was observed that the tool life decreases with an increase in cutting speed, feed rate, and depth of cut It was found that the cutting speed has the most dominant effect on tool life followed by the feed rate and the depth of cut

Alauddin and El Baradie [39] have described a study of the influence on surface-roughness of factors which affect the surface finish produced in an end milling process These factors are the cutting speed, feed rate and depth of cut A work material of 190 BHN steel was used The model for the mathematical prediction of the surface roughness was developed in terms of cutting speed, feed rate and axial depth of cut The effect of changes in these cutting parameters on the surface roughness was investigated using response surface methodology

The response surface was determined at three selected levels of axial depth cut These selected levels were low (a_a=0 72mm), center (a_a=1 00mm) and high (a_a = 1 40 mm) The proposed relationship between the tool surface finish and the independent machining variables can be represented by the following equation

$$R_a = 39\ 48 V_c^{-0\ 3977} f_r^{0\ 7431} a_a^{0\ 4779} \quad (2\ 8)$$

However it was observed as feed rate and depth of cut increase the surface roughness increases, and as the cutting speed increases the surface roughness decreases

Alauddin and El Baradie [40] developed tool life model for end milling of steel (190BHN) using high-speeds The variables were investigated using design of experiments and response surface methodology A first-order equation covering the speed range 26 m/min to 35 m/min and a second-order equation covering the speed range 24 to 38 m/min were presented The proposed relationship between the tool life and the independent machining variables can be represented by the following equation

$$T = 2210\ 55 v^{-1\ 20} f_z^{-0\ 25} a_a^{-0\ 15} \quad (2\ 9)$$

where T is the predicted tool life (min) This equation is valid for slot milling steel (190BHN) using a HSS under dry conditions and the following ranges of cutting speed (v) and feed per tooth (f_z)

$26 \leq v \leq 35$ m/min

$0\ 06 \leq f_z \leq 0\ 20$ mm/tooth

$0\ 44 \leq a_a \leq 0\ 82$ mm (2 10)

However it was observed that an increase in the machining variables (cutting speed, feed and depth of cut) decreases tool life

Munoz- Escalona and Cassiesier Z [41] discussed the effect of feed rate, nose radius of a tool and cutting speed on the quality and surface finish when machining different types of steel (AISI1020, AISI 1045 AISI 4140 and AISID2) The hardness of the steels were 90 HBN, 197 HBN, 344 HBN, and 230 HBN The cutting speeds were selected at 2 m/min, 4 m/min, 6 m/min, 8 m/min, 20 m/min, 30 m/min, 49 m/min, 50 m/min, 60 m/min and 70 m/min The feed rates were selected at 0 1 mm/rev,0 2 mm/rev and 0 3 mm/rev The cutting speeds were selected at 0 3 mm, 0 4 mm and the tool's nose radius were 0 4 mm, 0 8 mm and 1 2 mm By using multiple linear regression, a mathematical model for roughness of the different steel types tested was produced

General roughness mathematical model

$$Ra = 124\ 83(r^{-0\ 297} d^{0\ 056} f^{0\ 607} v^{-0\ 138} BHN^{-0\ 445}) \qquad (2\ 11)$$

where BHN is the Brinell hardness number

It was observed that greater roughness values were obtained at lower cutting speeds The surface finish was improved by increasing cutting speed and by decreasing the feed rate The depth of cut does not seem to have a significant influence on surface finish The surface finish is more directly affected by the feed rate, than the cutting speed

CHAPTER THREE: THEORY OF METAL CUTTING

3 Theory of Metal Cutting

3 1 Introduction

In this chapter the theory of metal cutting is discussed, including cutting forces, tool life and surface finish In a following section a study of the mechanics of chip formation, and cutting forces during the turning operation is presented

Several mechanisms of tool wear, which occur during machining, are presented Common mechanisms include diffusion, adhesion, abrasion and chemical wear

The influence of tool design on surface finish has been reported, including how the cutting edge leaves its own mark Finally the influence of tool geometry on surface finish is discussed

3 2 Cutting forces

A cutting tool should be designed to take maximum advantage of the forces that the machine applies through either the tool or the workpiece The cutting action in machine tools is not the same as that of a knife This is apparent from their shape The cutting tool is relatively blunt and is able to cut because of the large force applied The ideal surface roughness represents the best possible finish that can be obtained for a given tool shape, feed rate and depth of cut The ideal surface finish for a turning operation where a sharp-cornered tool is used is illustrated in Figure (3 4)

The metal cutting process is a result of relative movement between the cutting tool and the work material which is to be machined The relative movements between the cutting edge and the workpiece material results in an amount of metal corresponding to the depth of cut being separated from the workpiece material in the form of chips, whilst the feed movement brings new material in front of the cutting edge after a particular cut has been finished [42]

The machining processes can be classified into (i) orthogonal cutting processes and (ii) oblique cutting processes In orthogonal cutting, the cutting edge is perpendicular to the relative velocity between tool and workpiece and involves two forces The oblique cutting, on the other hand, involves a three – forces situation where the cutting edge is inclined to the cutting velocity Cutting forces involved in a single-point turning operation can be divided into three components, feed force (F_x) radial thrust force (F_y), and tangential cutting force (F_z), as shown in Figure 3 1 The tangential component F_z is in the direction of cutting velocity [43] The radial component, F_y as the name denotes, is in the direction of the radius of the workpiece The third component F_x is parallel to the axis of workpiece, i e in the direction of longitudinal feed (Figure 3 1) The resultant force F becomes

$$F = \sqrt{F^2{}_x + F^2{}_y + F^2{}_z}$$

During the orthogonal cutting turning operation only two cutting forces can be considered, the force between the tool face and the chips (R) and the force between the workpiece and the chip along the shear plane (R') These must be as follows

$$R = R'$$

The forces R and R' are conveniently resolved into three sets of components as indicated in Figure 3 2

a) In the horizontal and vertical direction, F_P and F_Q

b) Along and perpendicular to the shear plane F_S and N_S

c) Along and perpendicular to the tool face, F_C and N_C [44]

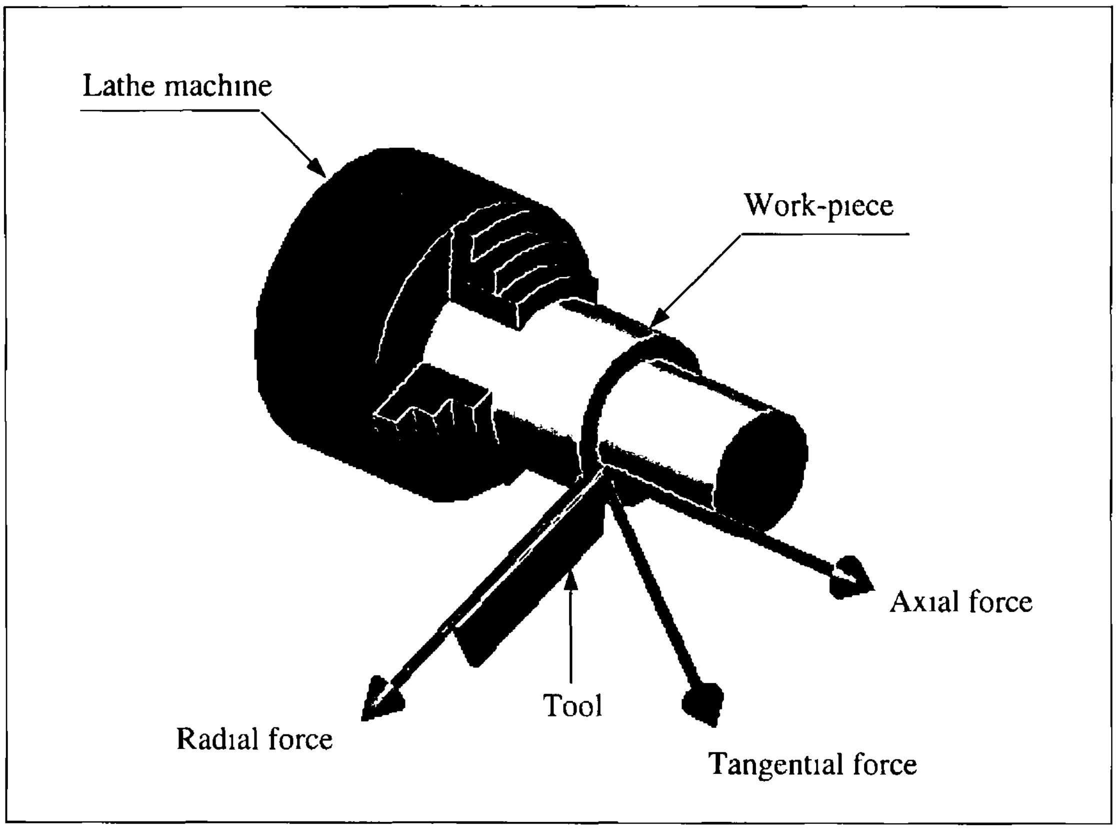


Figure 3 1 Three components of measurable cutting forces acting on single- point turning tool

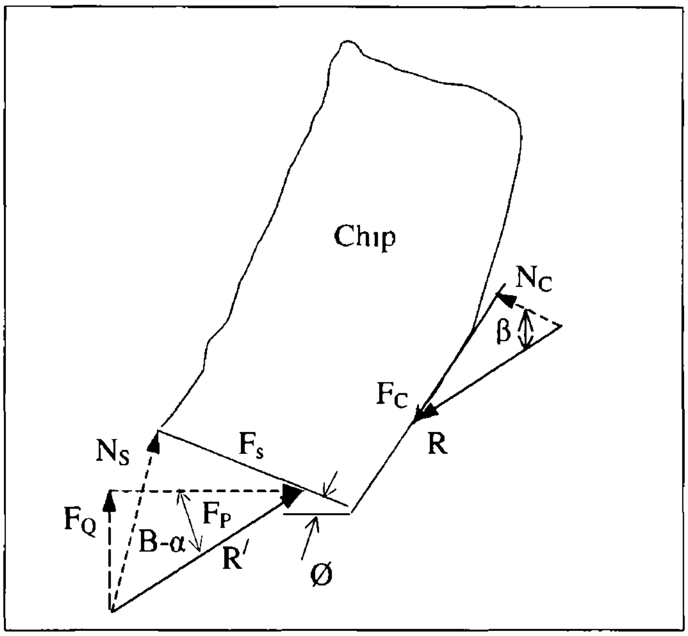


Figure 3 2 Free body diagram of chip and two cutting forces R, R′

If the forces R and R$'$ (which are equal and parallel) are coincident, the diameter of the reference circle is as shown in Figure3 3

An analytical relationship may be obtained for the shear and friction components of force in term of the horizontal and vertical components (F_P and F_Q) which are the components normally determined experimentally by means of a dynamometer It is evident that

$$F_S = F_P \cos\phi - F_Q \sin\phi$$
$$N_S = F_Q \cos\phi + F_P \sin\phi$$
$$F_C = F_P \sin\alpha + F_Q \cos\alpha$$
$$N_C = F_P \cos\alpha - F_Q \sin\alpha$$

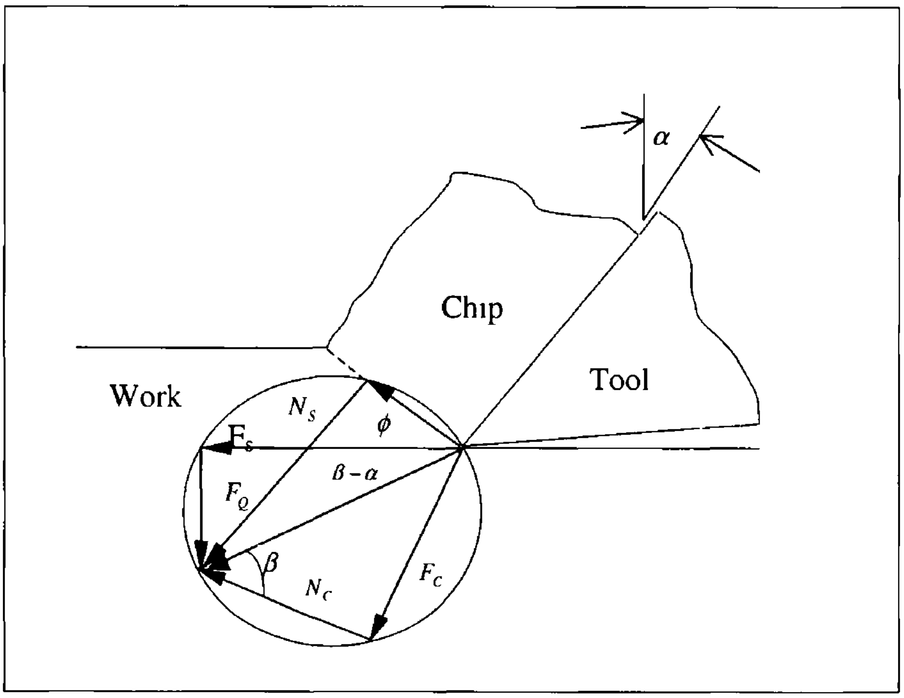


Figure 3 3 Composite cutting force circle

3.3 Tool life

Durıng metal cuttıng operatıons, tool lıfe ıs one of the most ımportant economıc consıderatıons Any tool or work materıal ımprovement that ıncreases tool lıfe ıs desırable The tool ıs ın contact wıth both the workpıece and chıp under condıtıons of hıgh temperatures and stress Cuttıng condıtıons resultıng ın a very short lıfe can be uneconomıcal ıf tool changıng and replacement costs are hıgh Alternatıvely condıtıons yıeldıng a long tool lıfe can be unprofıtable ıf productıon rates are low Therefore, an accurate assessment of tool lıfe, and an understandıng of tool degradıng mechanısms, ıs very ımportant ın determınıng the machınabılıty of a materıal

A new or newly- ground tool has sharp cuttıng edges and smooth flanks When put ınto operatıon, ıt ıs subjected to cuttıng forces that are concentrated over a relatıvely small contact area on the rake face and the flank Also, the chıp slıdes over the rake face and the machıned surface rubs past ıts flank, and as a result temperatures over the contact surface are quıte hıgh Each tıme the tool enters or exıts from the cut, ıt ıs subjected to mechanıcal as well as thermal shock Under such adverse condıtıons, the hard tool materıals lıke HSS and carbıdes gradually wear out and even fracture, necessıtatıng a tool change The machıne has to be stopped durıng the tıme the tool ıs beıng changed and then returned to the cuttıng posıtıon Precıous machınıng tıme ıs lost ın the process Tool wear and the tıme between two successıve tool changes (tool lıfe) are therefore subjects of very great ımportance ın the theory and practıce of metal cuttıng [42]

3.3.1 Tool wear mechanısms

Some of the most ımportant tool wear mechanısms for a hard metal (tool) ın contact wıth a softer but deformıng metal, slıdıng past the former at a faırly hıgh speed, are descrıbed as follows

3 3 1 1 Dıffusıon wear

Dıffusıon wear occurs when a metal ıs ın slıdıng contact wıth another metal and the temperature at theır ınterface ıs hıgh Condıtıons may become rıght for atoms ın a metallıc crystal lattıce to move from an area of hıgh to low atomıc concentratıon (Fıgure 3 4) The dıffusıon mechanısm ıs dependent on the ambıent temperature and thus any increase in temperature causes an exponential increase in the rate of diffusion [45]

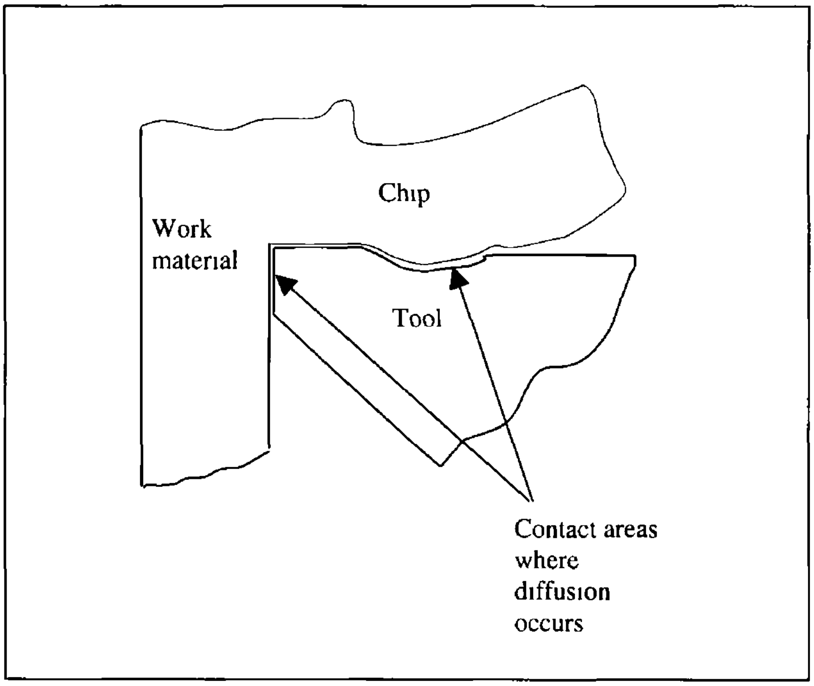


Figure 3 4 Wear by diffusion

3 3 1 2 Adhesive wear

This form of wear occurs when two surfaces are brought into intimate contact under normal loads and form welded junctions which are subsequently destroyed when subjected to shearing loads The junction formed could fracture at the weld line More particles join up with those already adhering and a so-called built-up edge is formed Later some of these fragments which may have grown up to microscopic size are torn from the surface of the hard metal [42] When this process continues for some time, it appears as if the surface of the hard metal has been nibbled away and made uneven as shown Figure 3 5

3 3 1 3 Abrasive wear

This form of wear occurs when hard constituents of one surface plough through the material of the other surface This is basically a cutting process Consequently, the amount of wear depends on the relative hardness of the contacting surfaces as well as their elastic and plastic properties and mating geometries In metal cutting, the underside of the chip passes over the tool rake or face surface The particles may be hard constituents present in the work material or fragments of the highly strain-hardened and unstable built-up edge as shows Figure 3 6

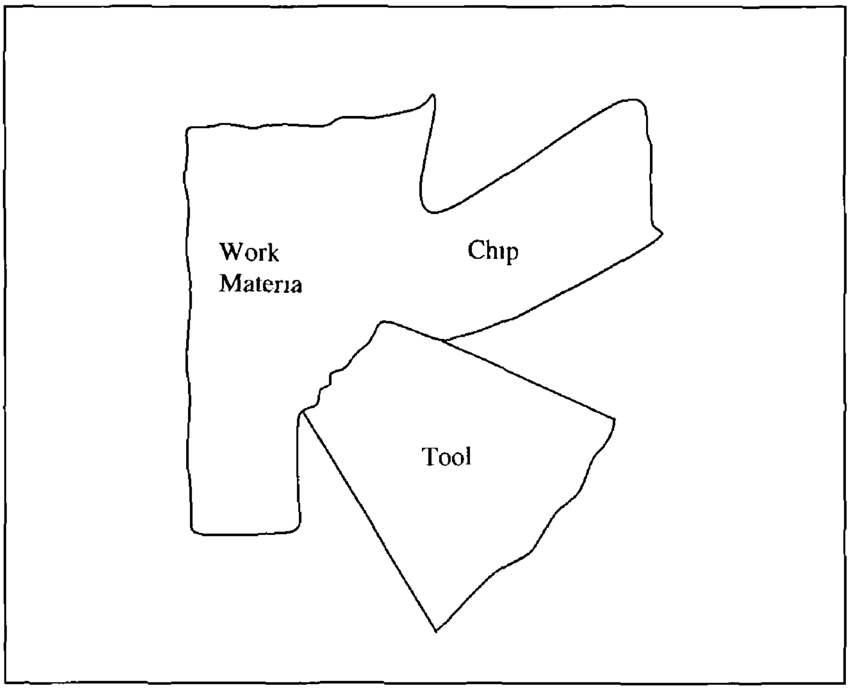


Figure 3 5 Adhesive wear

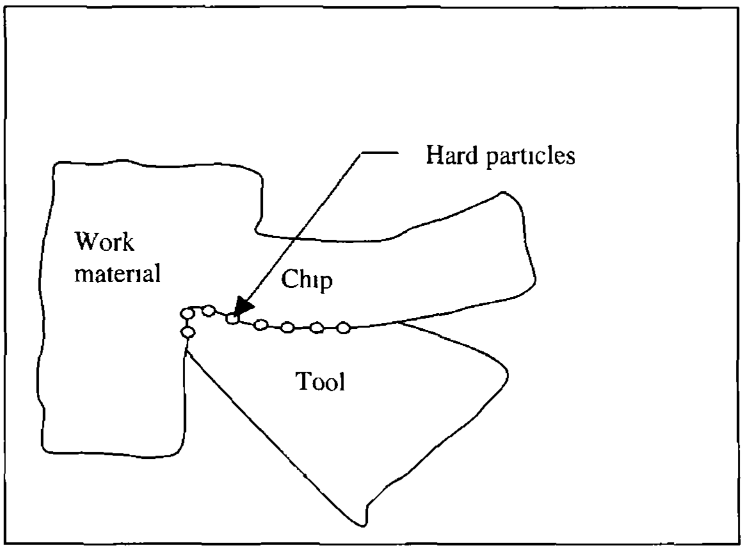


Figure 3 6 Abrasive Wear

3 3 1 4 Chemical wear

Chemical wear occurs through the interaction between tool and workpiece material in an active environment This could be cutting fluid or air at high temperature

Oxidation occurs at several points on the cutting tool but is most dangerous at the cutting edge

3 3.2 Tool life criteria

The type of wear that is believed to contribute most to the end of useful tool life in a specific series of tests shall be used as a guide to the selection of one of the tool-life criteria specified below The type and value of the criterion used shall be reported Figure 3 7 shows wear of a single point tool The crater depth KT is measured at the deepest point of the crater and it varies along the main cutting edge Flank wear is generally greatest at the extremities of the main cutting edge Because of the complicated flow of chips at the tool corners region of the cutting edge, the conditions are more severe at the corners

3 3 2 1 Common criteria for high speed steel tools

The criteria most commonly used for high-speed tools are as follows

a) Catastrophic failure
b) The average width of the flank wear land is VB_B = 0 3 mm if the flank wear land is considered to be regularly worn in zone B
c) The maximum widths of the flank wear land VB_B max = 0 6mm if the flank wear is irregularly worn, scratched, chipped or badly grooved in zone B [46]

3 3 2 2 Common criteria for sintered carbide tools

The failure criteria most commonly used for sintered carbide tools are as follows [46]

a) The average width of the flank wear land is VB_B = 0 3 mm if the flank wear land is considered to be regularly worn in zone B
b) The maximum widths of the flank wear land VB_B max = 0 6 mm if the flank wear is irregularly worn in zone B
c) The depth of the crater KT given, in millimetres, by the formula

$$KT = 0\ 06 + 0\ 3f$$

where f is the feed in millimetres per revolution This leads to the feed following values of KT for the feeds specified in the recommendation where KT applies as a criterion [46]

3 3 2 3 Common criteria for ceramic tools

The failure criteria most commonly used for ceramic tools are as follows[46]

a) Catastrophic failure

b) The average width of the flank wear land is VB_B = 0 3 mm if the flank wear land is considered to be regularly worn in zone B

c) The maximum width of the flank wears land VB_B = 0 6 mm if the flank wear land is not regularly worn in zone B

3 3 2 4 Common criterion for finish turning

Surface roughness is a common criterion for finish turning and the following R_a values, according to ISO/R 468, are preferred 0 4 - 0 8 - 1 6 - 3 2 - 6 3 - 12 5 µm

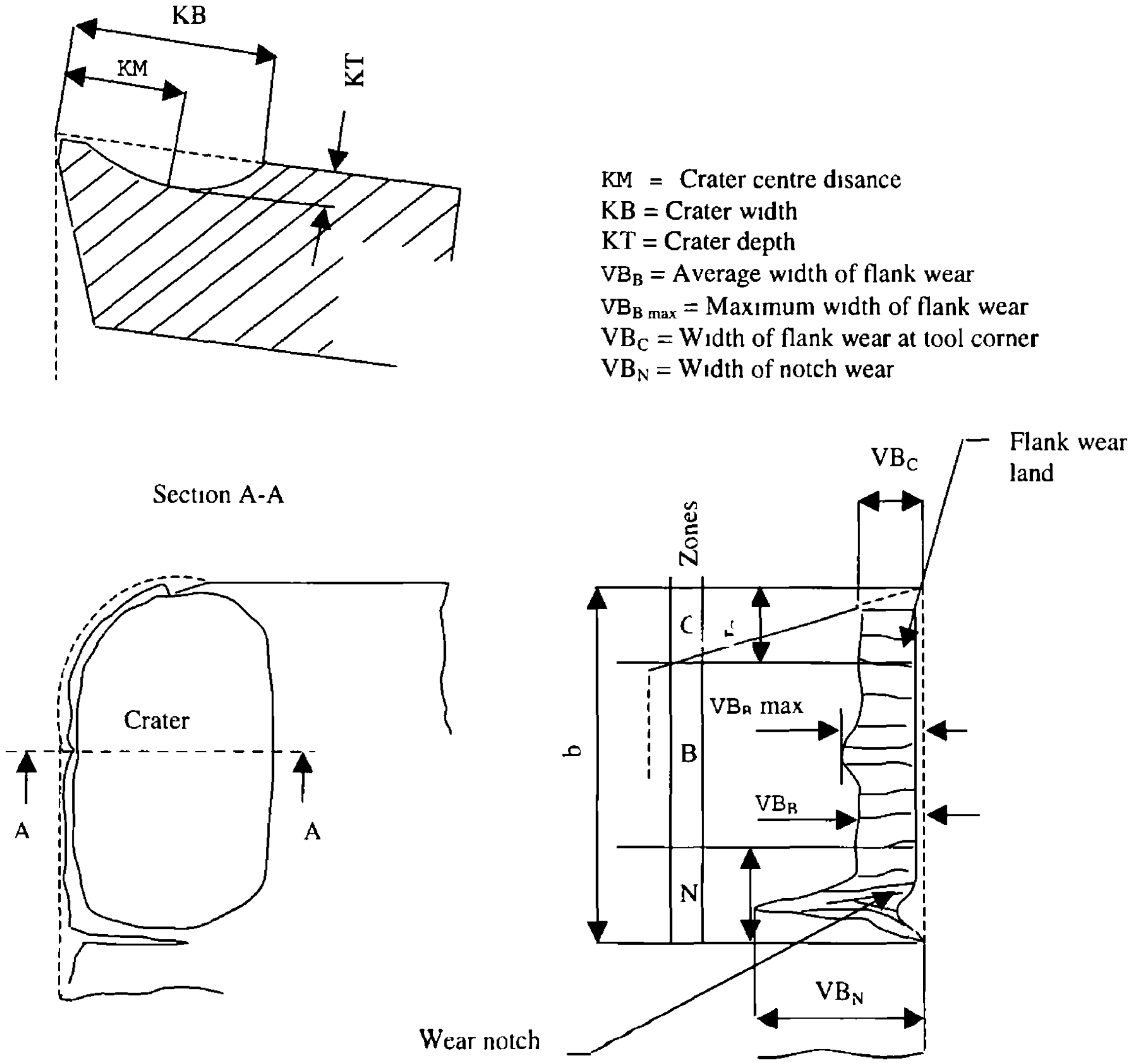


Figure 3 7 Some types of wear on turning operations

3.4 Surface finish

Machining operations are used to produce a desired shape and size by removing excess stock from a blank in the form of chips New surfaces are generated through a process of plastic deformation and crack propagation The workpiece is subjected to intense mechanical stress and localized heating by tools having one or more shaped cutting edges Each cutting edge leaves its own mark on the machined surface Also the workpiece and tool, together with the machine on which they are mounted, form a vibratory system liable to random, forced or induced vibration For these reasons, the surface of the machined component is more or less damaged Surface finish and surface integrity are the terms used to denote the degree of such damage In other words, the above terms describe the geometrical and micro structural quality of machined surface

Surface finish (or surface texture) refers to the following properties of a machined surface

Waviness it consists of all surface irregularities whose spacing is greater than the roughness sampling length (about 1 mm)

Surface flaws· these are randomly spaced irregularities, (i e those, which occur at some particular location on the surface or at widely, varying, intervals)

Roughness this consists of relatively closely spaced or fine surface irregularities mainly in the form of feed marks left by the cutting tool on the machined surface [47]

The primary texture can be measured by various constants as shown in Figure 3 8 Indices used include average arithmetic roughness height R_a, smoothening depth R_p, maximum roughness R_t, and root-mean-square RMS height Individually, these constants are of very limited value in assessing primary texture, but collectively they help to build up an accurate picture of it

3 4 1 Definitions

- R_p Smoothing depth (distance between the highest point and the mean line) R_p generally results from the condition of the production tool (such as a lathe tool or grinding wheel)

- R_t Maximum roughness within the tracing stroke (highest point to lowest point) An example of the cause of R_t and its magnitude would be the grit used in a grinding wheel and its size

- R_a Average arithmetic roughness This is also known as centerline Average (British) and Arithmetic Average (American) R_a tends to be quoted in microns R_a is a mean value of the roughness (Figure 3 8) It may be seen that the centerline is divided the areas such as A_1+A_2+ A_8

-RMS Root- Mean – Square This is an average geometric roughness and was an American Standard In 1955, it become obsolete, but naturally enough will still be encountered occasionally It is sufficient to say that its numerical value is some 11% higher than that of R_a

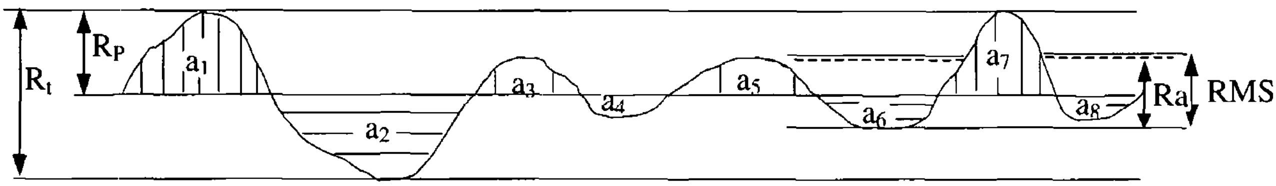


Figure 3 8 The various parameters R_a, R_p, R_t and RMS are illustrated

For turning, when chip formation occurs without built-up edges, the tool profile is etched or reproduced on the machined surface (Figure 3 9) The geometry of feedmarks depends on feedrate, side-cutting edge angle, nose radius and end-cutting edge angle

In Figure 3 9 the tool has a sharp corner (i e nose radius is nearly zero)

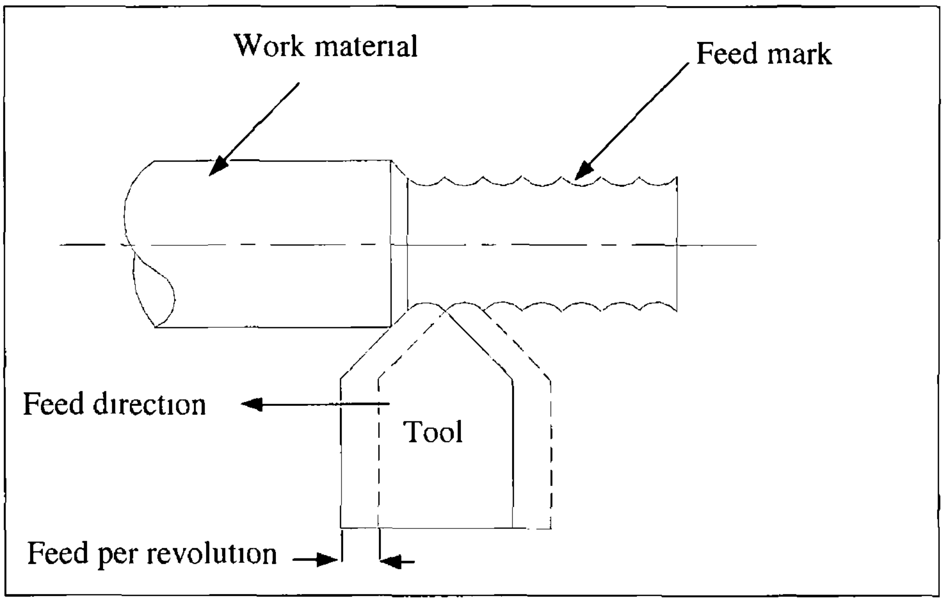


Figure 3 9 Feedmarks observed during Turning

In (Figure 3 10 a) the geometrical relations for this condition can be as follows

$$f = AD + DC = BD\tan\theta_s + BD\cot\theta_e$$

$$f = h(\tan\theta_s + \cot\theta_e)$$

$$h = \frac{f}{\tan\theta_s + \cot\theta_e} \tag{3 1}$$

$$h_{CLA} = \frac{f}{4(\tan\theta_s + \cot\theta_e)} \tag{3 2}$$

The centreline average roughness is defined as the mean height of peaks or mean depth of valleys with respect to the mean surface The centreline roughness is $h_{CLA}=h/4$

In the case of tool radii, it can be shown that the peak-to-valley roughness is given by the following expression [44]

$$h = (1-\cos\theta_e)r_n + f\sin\theta_e\cos\theta_e - \sqrt{2fr_n\sin^3\theta_e - f^2\sin^4\theta_e} \tag{3 3}$$

When the feed is so small that cutting take place entirely on the radius nose (Figure 3 10,c) it was found that

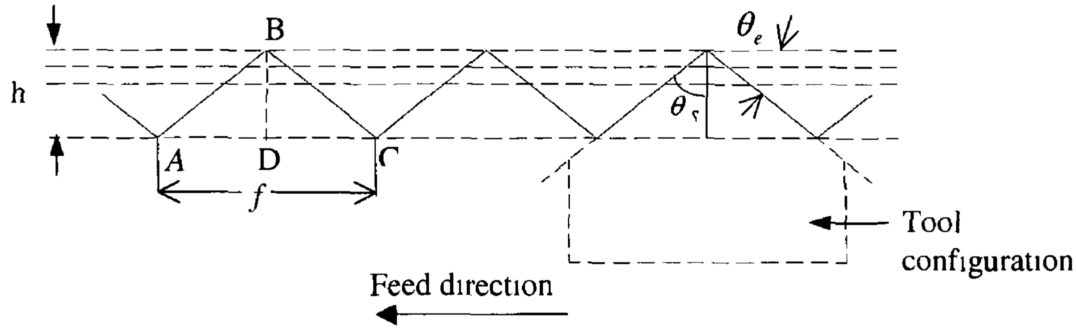
$$h = r_n - r_n\cos\phi$$

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

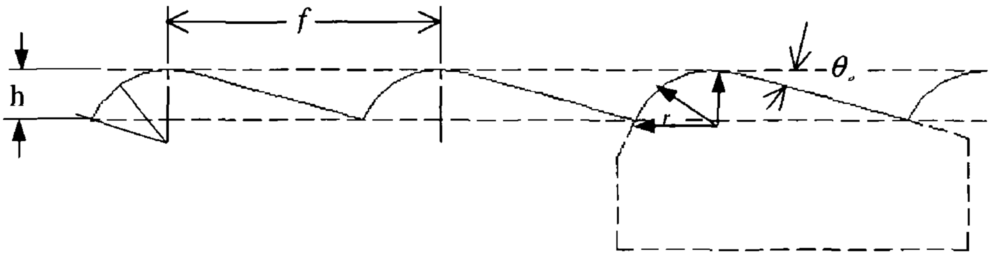
$$\sin\phi = \frac{f}{2r_n}$$

$$h = \frac{f^2}{8r_n} \qquad (3\ 4)$$

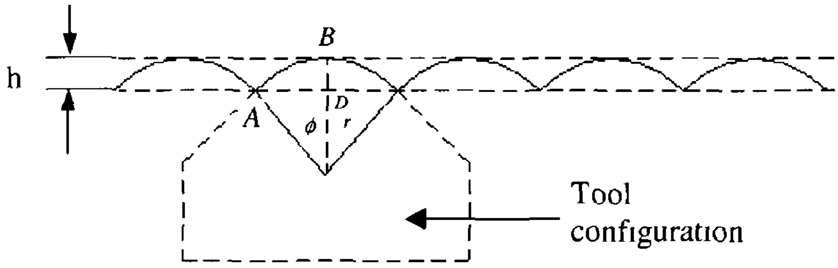
where f is feed rate, r_n is nose radius and h is higher roughness From equation (3 4) it can seen that the surface roughness depends on the feed rate and nose radius



(a) Tool without a nose radius



(b) Tool with a nose radius- larger feed rate



(c) Tool with a nose radius-small feed rate Figure,

Figure 3 10 Different types of feedmark

CHAPTER FOUR: EXPERIMENTAL WORK PROGRAMME

1. Experimental Work Programme

4.1 Introduction

In this chapter the experimental facilities which were used are discussed The details of the machines, equipment, work material, and cutting tool inserts used are described, and the experimental set-up is presented Experiment hardness tests are also reported

4.2 Experimental set-up

A three- component dynamometer Kistler type 9265A1 with charge amplifiers was used along with computer to measure and record cutting forces Surface finish was measured by using the Surftest instrument and the tool wear was measured using a Toolmakers microscope A diagram of the experimental-set up is presented in Figure 4 1

4.2.1 Machine and Equipment

(a) Lathe machine Colchester / Mascot 1600, maximum spindle speed 1600 rpm, feed range of 0 06 – 1 0 mm/rev

(b) Kistler three component dynamometer Type 9265A1 (calibrated range F_x = 0 – 15000 N, F_y = 0 – 15000 N, and F_z = 0 – 30000 N) with three Kistler charge amplifiers are employed

(c) Surface roughness tester (Mitutoyo Surftest 402 series 178)

(d) Tool wear was measured under a toolmakers microscope

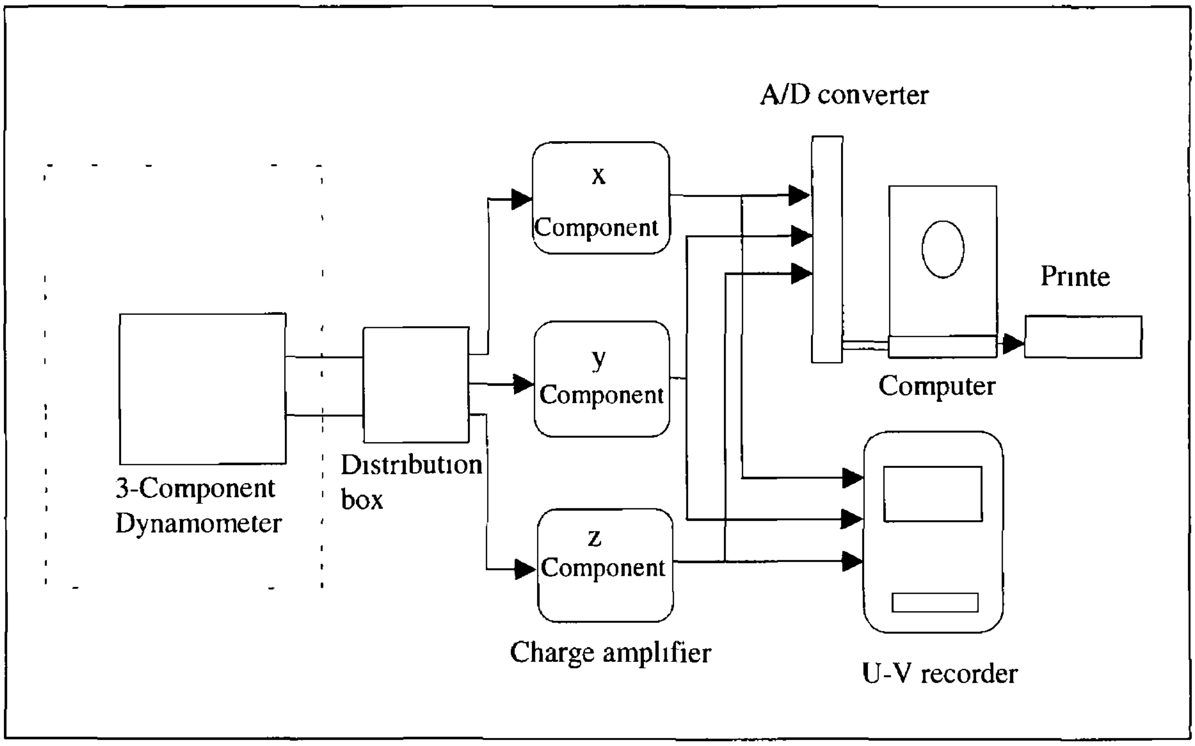


Figure 4 1 diagram of force measuring set-up

The dynamometer consists of three components, distribution box, three charge amplifiers, an analog to digital (A/D) converter and a computer

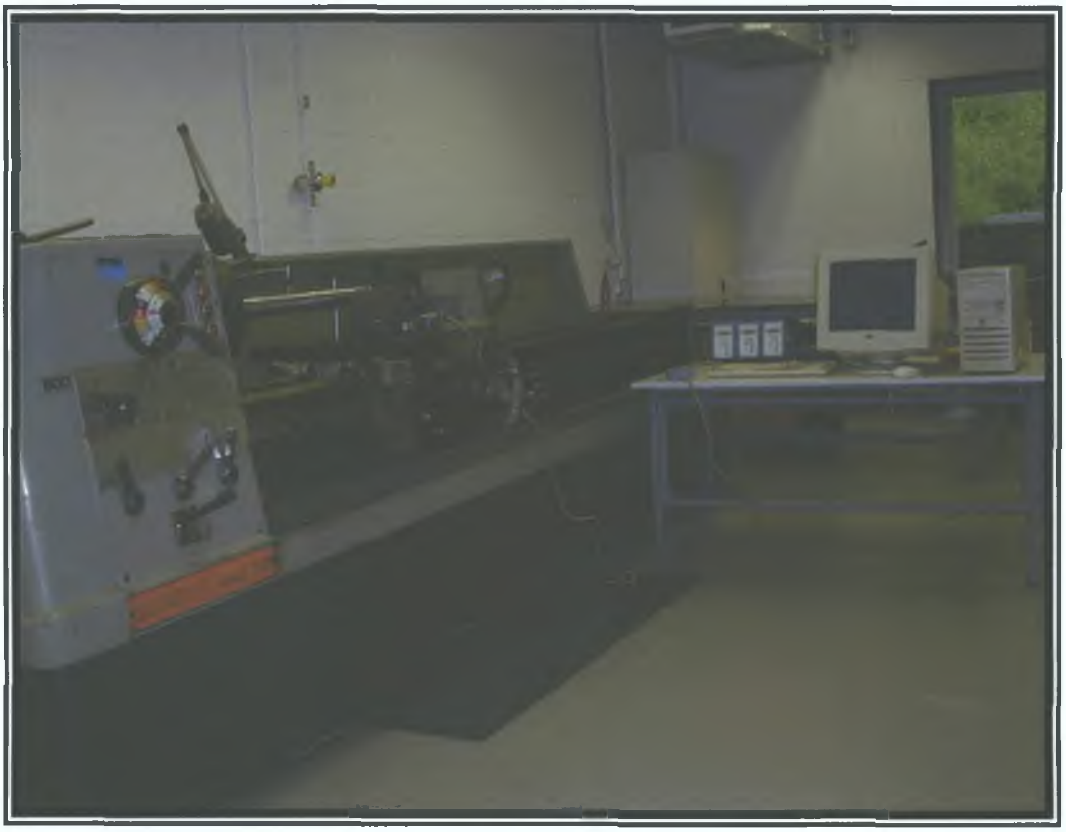


Figure 4.2 shows the experimental set-up

4.2.1.1 Three- component dynamometer

The dynamometer type 9265A1 consists of a basic unit type 9265A with a toolholder type 9441 screwed on. This is used for turning operations. The dynamometer accepts lathe tools up to 32 ×32mm or 32mm in diameter and it measures three component of cutting force; axial force, radial force and tangential force, as shown Figure (4.3).

The dynamometer type 9265A2 consists of a basic unit type 9265A with clamping plate type 9443. This type of dynamometer is used for milling, grinding etc.

The dynamometer type 9265A3 consists of a basic unit type 92265 with toolholder type 9441 screwed on and a separate clamping plate type 9443 (Figure 4.4). The type 9265A3 dynamometer can perform the duties of types 9265A1 and 9265A2. The calibrated range data of F_x and F_y are from 0 to 15 kN and F_z is from 0 to 30kN [48].

A proportional electric charge corresponding to each of the three-force component is generated in the dynamometer and converted by the charge amplifiers into proportional voltage. The technical details are given in [48].

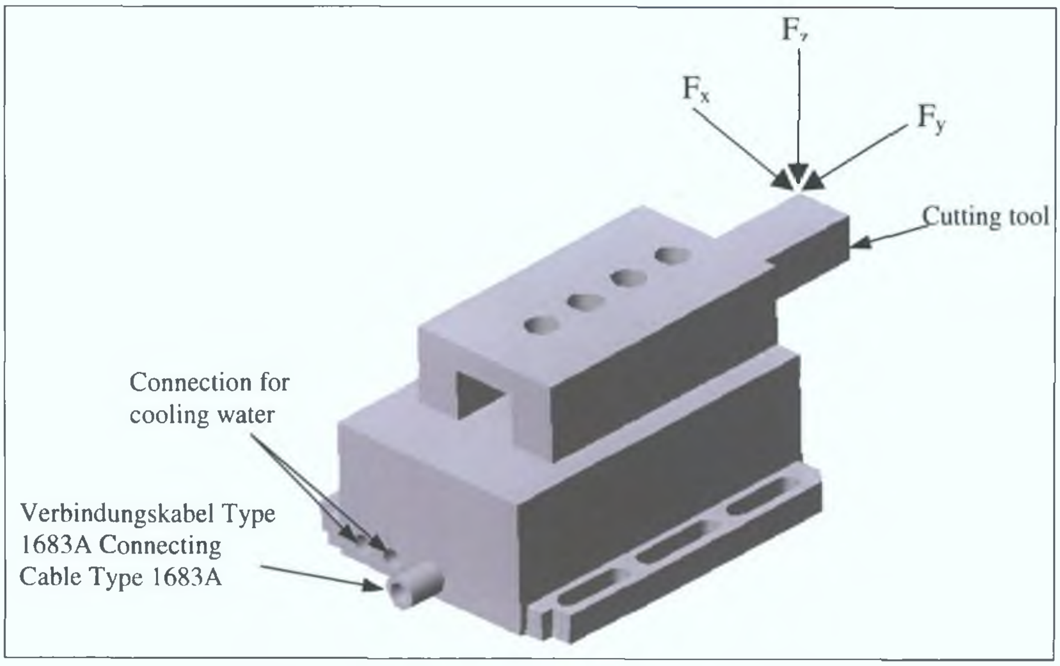


Figure 4.3 Three-component dynamometer

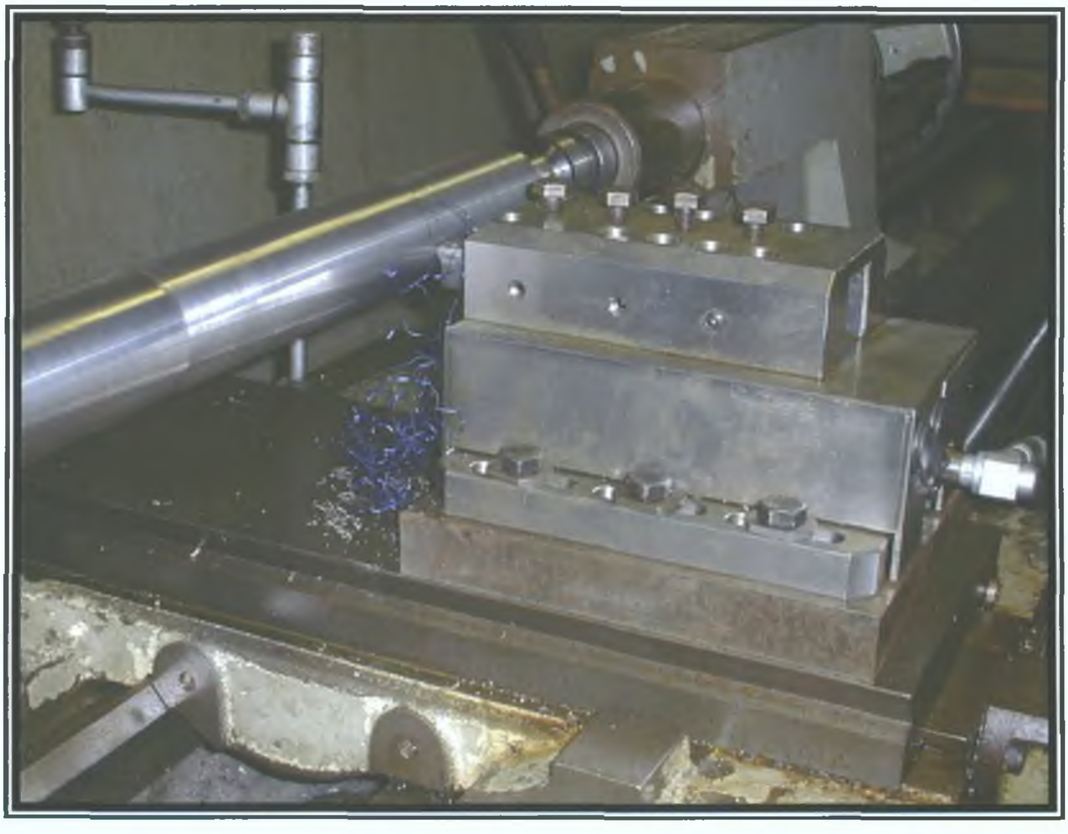


Figure 4.4 Dynamometer connected to the lathe machine

4.2.1.2 Charge amplifier

The instrument is controlled and monitored by an 8-bit microprocessor. The communication between the charge amplifier stage and processor is done serially, through the corresponding converters with electrical isolation by opto-couplers. According to the transducer sensitivity, the measuring range in mechanical units used in practice can be inferred. The technical details are given in [49].

When several transducers are paralleled, the charge amplifier measures the sum of all charge. A typical application is paralleling four force transducers and measuring the total force. Three charge amplifiers for three cutting forces are presented in Figure 4.5.

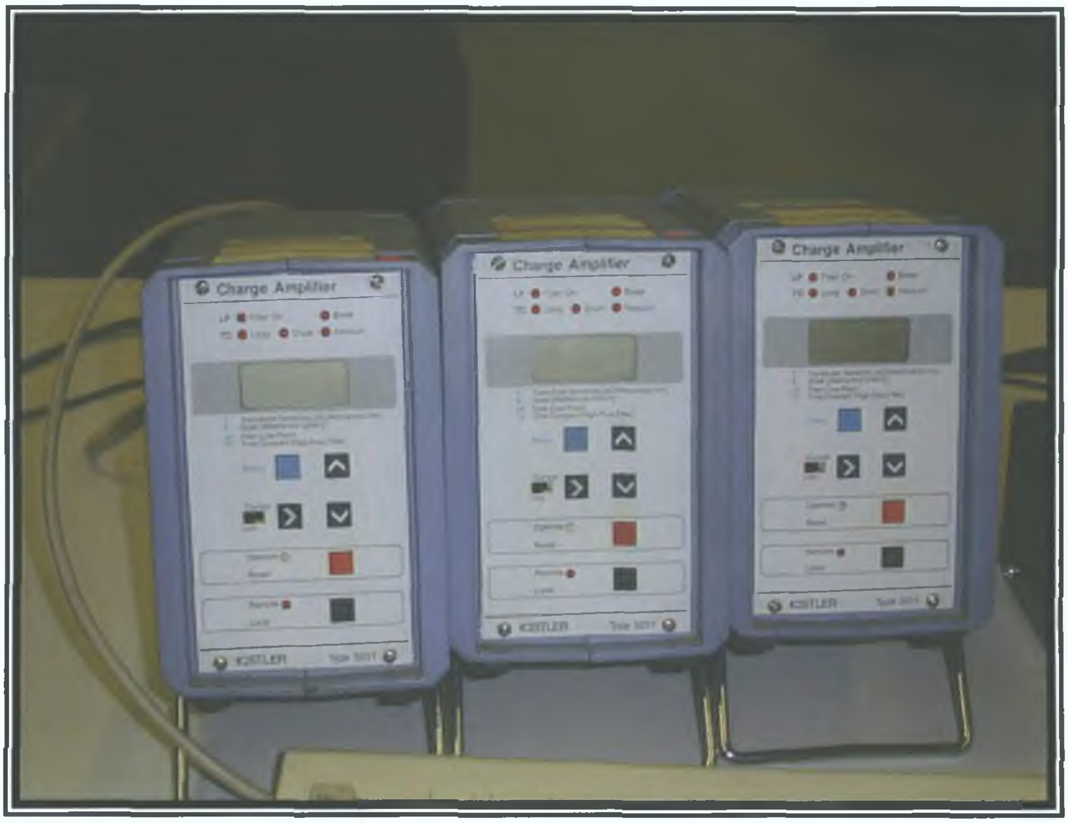


Figure 4.5 Three charges amplifiers for F_x, F_y, F_z

4.2.1 3 Computer

A Pentium MNX 128 M HZ 8 GB hard disk computer was used to capture the cutting force data Data acquisition was achieved using Labview software The DAQcard-6062E, PCI-MIO-16E-4 777383-01 was used

4.2.1.4 Toolmakers microscope

A toolmaker microscope was used for flank wear measurement The microscope is shown in Figure 4 4 The details of the microscope are as follows

Type Mitutoyo Corporation

COD No 176-941

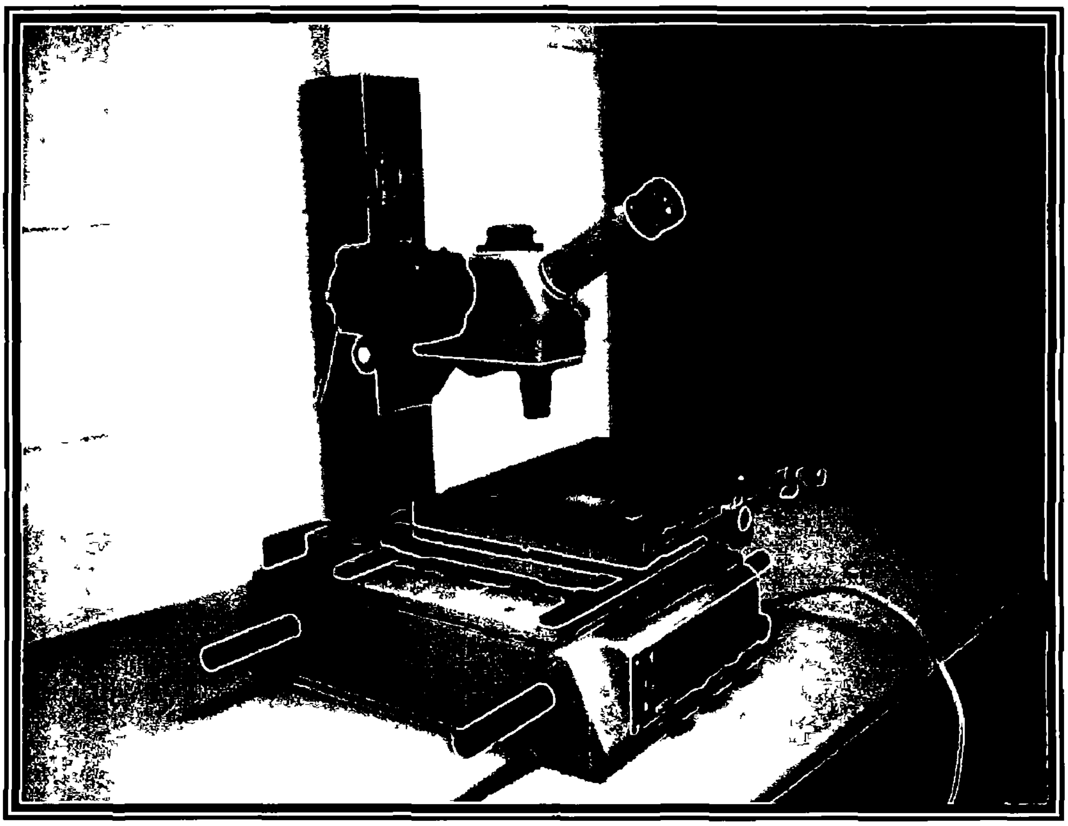


Figure 4 6 Mitutoyo toolmakers microscope

4.2.1.5 Surface roughness tester

The surface finish was measured using a Surftest instrument (Figure 4.7). Usually, the different parameters used to express surface roughness are R_a, R_z, R_p, and RMS [47]. However in this thesis the R_a value has been used to describe surface roughness. The ranges of R_a values were selected at 10 and 50 μm (depending on the values of roughness being measured). If values of roughness are small, the range of 10 μm is selected. If values of roughness are high, 50 μm is selected. Four sample measurements over the diameter of work material were taken. These were taken at different positions to ensure that the values obtained are representative of the whole surface area.

The specification details and technical information on the Mitutoyo Surftest - 402 are given in the operation manual [50].

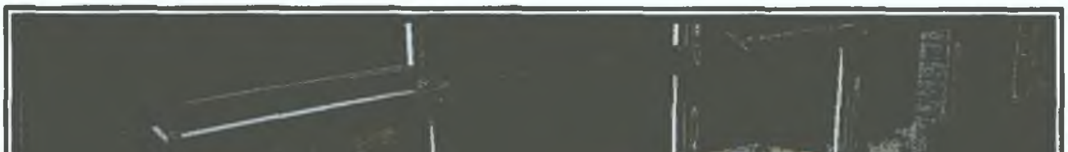


Figure 4.7 shown Mitutoyo Surftest is measuring workpiece

The capabilities of the Surftest 402 are as follows

<u>Driving/ Display unit</u>

Displayable range

R_a, R_q (0 01-2 00), (0 1-10 0), (0 2-50 0)

R_z, R_{max} (0 1-10 0), (0 2-50 0), (1-250)

Cut-off value 0 25, 0 8 and 2 5 mm

Driving speed 0 5 mm/s during measurement and 1 mm/s during return (Approx)

Elevation range for the detector coarse range, 40 mm, fine range, 10 mm

Display liquid crystal display

Power supply Nickel cadmium storage batteries 6pcs/set NO 995433

Detector No 178-350

Detecting method Differential inductance type

Stroke	0 3mm
Linearity	0 2mm
Stylus tip	Diamond
Tip shape	conical of 90°
Tip radius	0 5μm
Force variance ratio	8 μN/1μm
Curvature of radius of skid	30mm

4.2.2 Workpiece material

The work material which was used as the test specimen was high strength steel, specified as EN24T/817M40T (2meters long 70 mm diameter)

Tables 4 1 Chemical composition of steel EN24T/817M40T

C	Si	Mn	P	S	Cr	Ni	Mo	Cu	AI	Sn	Ca
0 400	0 270	0 610	0 014	0 034	1 110	1 390	0 220	0 210	0 010	0 010	0 043

Table 4 2 Mechanical properties of steel EN24T/817M40T

Ultimate tensile strength (N/MM^2)	Yield strength (N/MM^2)	Hardness BHN
936	795	277

4.2.3 Experiment of material hardness

A hardness test experiment was carried out to ensure that the material meets the specified material hardness of 277 BHN at different depths 2 types of tests were conducted, as follows

a. Rockwell 'B' scale

1/16, ball with a load of 100kg

b Rockwell 'C' scale

120, diamond cone with a load of 150kg

The hardness experiments were carried out at different points on a straight line from the outer edge to the centre point of the, work material (see Figure 4 8) It was found that the hardness of the material was lower at a greater depth of cut until the middle of the area between center point and outer diameter, and then increased again The experiment was carried out twice Results are shown in Table 4 3

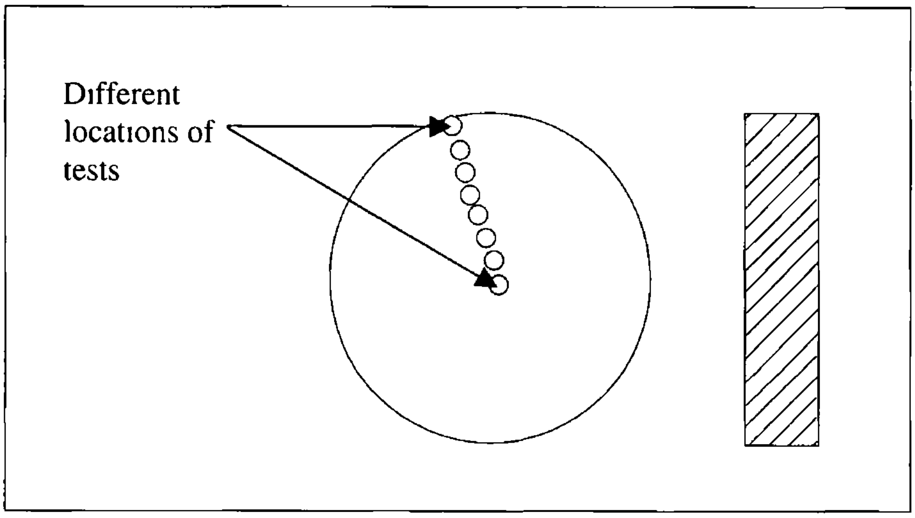


Figure 4 8 shows experiment hardness test on the section of the work material

Experiment No 1	150kg Diamond	Hardness of material	Experiment No 2	150kg Diamond	Hardness of material
1(outer)	29 8	285	1	29 2	280
2	29 8	285	2	29 2	280
3	29 8	285	3	29 2	280
4	29 2	280	4	28	276
5	29 2	280	5	28	276
6	27 1	266	6	27 2	266
7	26 4	261	7	26 4	261
8	27 2	266	8	27 2	266
9	27 8	271	9	29 2	280
10	29 2	285	10	29 8	285
11	29 8	285	11	29 8	285
12(centre)	29 8	280	12	29 8	285

Table 4 3 Material Hardness Experiments

The average for those points is

$$\text{Experiment 1 } Bhn = \frac{285 + 285 + \qquad + 280}{12} = 277\ 41\ \text{BHN}$$

$$\text{Experiment 2 } Bhn = \frac{280 + 280 + \qquad + 285}{12} = 276\ 66\ \text{BHN}$$

4 2 3 1 Discussion

The results obtained were taken from the outer edge of the section to the centre point However it was noticed that the hardness of the workpiece decreased until the small area before centre point, then the hardness increases until the centre point

The average result of the hardness tests that were carried out was around 277 BHN

4.2.4 Tool Material

Coated and uncoated cutting tool inserts were used for turning operation Cutting tools were manufactured by the Sandvik Company

4 2 4 1 Coated

In this experiment the coated tool (specification TNMG 16 04 04-PF 4015) was used However this tool has a thick CVD coating of TiCN, Al_2O_3 and TiN The coating has an extremely good wear resistance Under the coating there is a hard substrate, with a cobalt enriched zone close to the surface Due to this the grade can withstand high cutting temperatures and still have a good edge line security This makes GC4015 ideal for high cutting speeds and dry machining in the P15 area A top performing grade, and tool of TNMG 16 04 04-PM, TNMG 331-PM, CVD coated cemented carbide The thick wear resistant coating and the tough substrate with good edge security make it a high performing all-round grade for medium to light roughing applications in steel [51]

4 2 4 2 Uncoated

Uncoated specification TNMG 16 04 04 – QM, TNMG 331 – QM was used This uncoated grade that can withstand high temperatures without being deformed The combination of good abrasive wear resistance and toughness make it a good choice for machining of heat resistant steel and titanium alloys

CHAPTER FIVE: EXPERIMENTAL RESULTS AND DISCUSSION: ONE-VARIABLE-AT-A-TIME

5. Experimental Results and Discussion: One Variable at a time

5.1 Introduction

In this chapter the results of experiments conducted changing one variable at a time are presented to determine the effect of cutting speed, feed rate and depth of cut
The following output parameters were measured

- Cutting forces
- Tool life
- Surface finish

5 2 Cutting Forces

In a turning operation, the primary cutting motion is rotational with the tool feed parallel to the axis of rotation The principal cutting force F which acts upon the cutting tool is resolved into three components, feed forces (F_x), radial thrust force (F_y) and tangential cutting force (F_z) Usually, the tangential cutting force is the largest of the three components The tangential force F_z acts along the direction of the cutting speed

A series of cutting tests were carried out on a Colchester lathe to investigate the effect of speed, feed, and depth of cut on the cutting forces The experiment was carried out under dry cutting conditions The specification of the cutting tool and workpiece used has been described in Chapter 4

The different cutting forces components were measured using a Kistler dynamometer connected to a PC based data system through the charge amplifiers A UV chart recorder was also incorporated in the data acquisition system to measure the force components More details and technical information and description of the system were presented in Chapter 4

The first experiment was carried out to determine the variation in tangential forces F_z, axial (feed) forces F_x and radial forces F_y with changes in cutting speed at constant feed rate of 0 10 mm/rev and for depth of cuts of 0 50,1 00,1 50 mm as shown in Figures 5 1, 5 2,and 5 3 Similar plots of force versus cutting speed at feed rates of

0 20 and 0 30 mm/rev were carried out as shown in Figure 5 4, 5 5, 5 6, 5 7, 5 8, and 5 9 Every experiment has been conducted three times to confirm the results The variability of the results is presented in Figure 5 1 All further results presented in this chapter represent the average of three experimental values The raw experimental data is contained in Appendix A Values measured were within ±1% to ±5% for each result

It was noticed in all the experiments that the tangential component of the cutting force is the highest, followed by the axial and radial components Generally as the cutting speed increases, the forces decrease and become almost constant As the depth of cut and the feed rate increase, the cutting forces increases The greatest effect on cutting forces is caused by depth of cut at given feed rate

The axial force is less than the radial force at higher depth of cuts (1 0 and 1 5 mm) When the depth of cut is low (0 5 mm) and feed is high (0 30 mm/rev), the radial component is higher than the axial force component as shown in Figure 5 7 This suggests that the chip flow direction is radial instead of axial at a lower depth of cut With increase in depth of cut, the direction of chip flow changes from radial to axial with an increase in the axial force

Figure 5 1 shows that in all experiments the tangential cutting force decreases as the cutting speed increases The reason for this is that the temperature of the workpiece increases with higher cutting speed, and the strength of the material is therefore reduced

The increase in axial and radial forces with cutting speed is due to the increase in friction as the workpiece material temperature rises

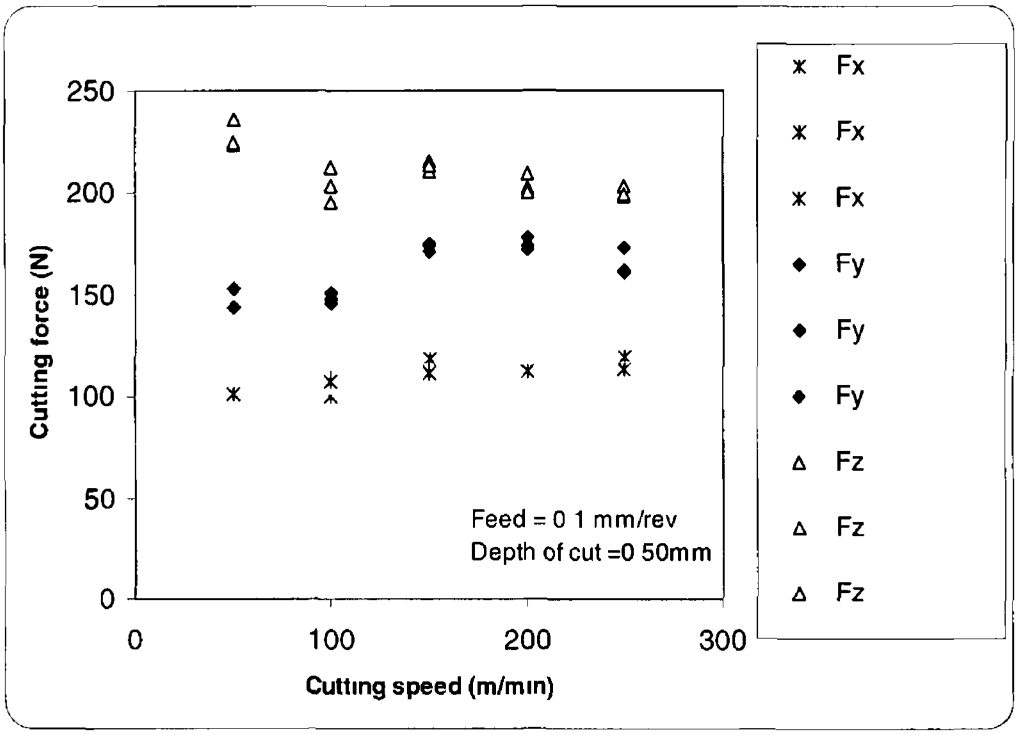


Figure 5 1 Variation of cutting forces with cutting speed at feed = 0 10 mm/rev and depth of cut = 0 50 mm three results presented for each case

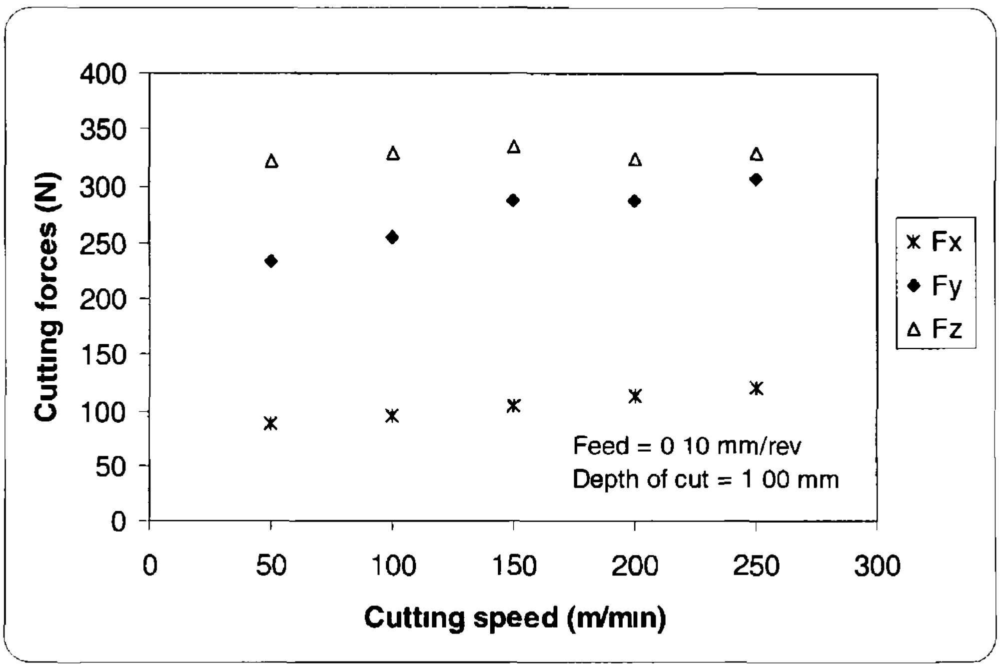


Figure 5 2 Variation of cutting forces with cutting speed at feed = 0 10 mm/rev and depth of cut =1 00 mm

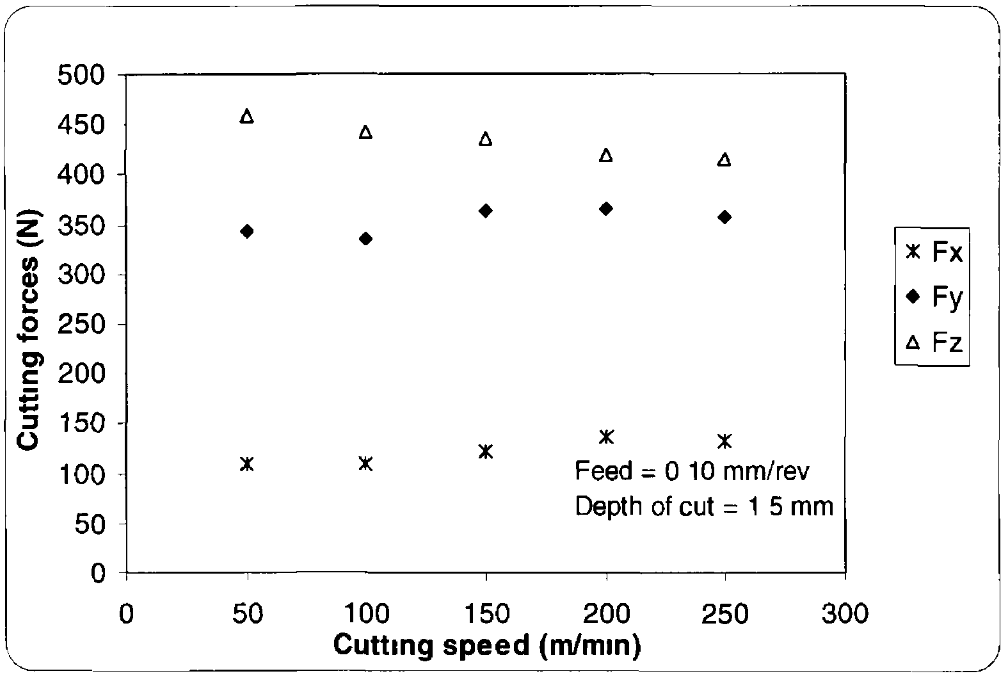


Figure 5 3 Variation of cutting forces with cutting speed at feed = 0 10 mm/rev and depth of cut = 1 50 mm

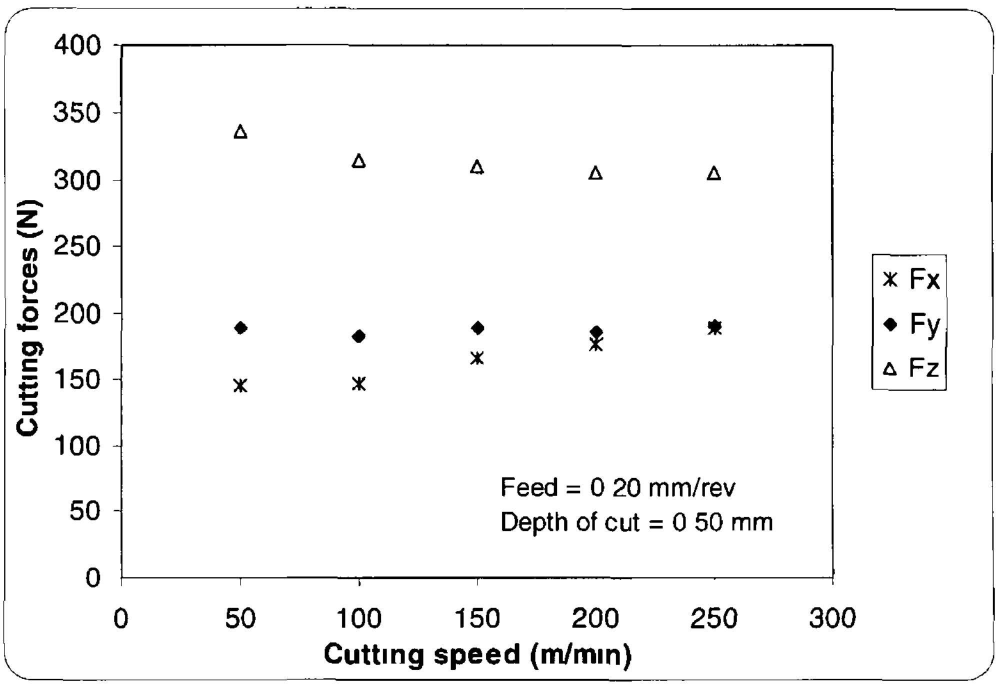


Figure 5 4 Variation of cutting forces with cutting speed at feed = 0 20 mm/rev and depth of cut = 0 50 mm

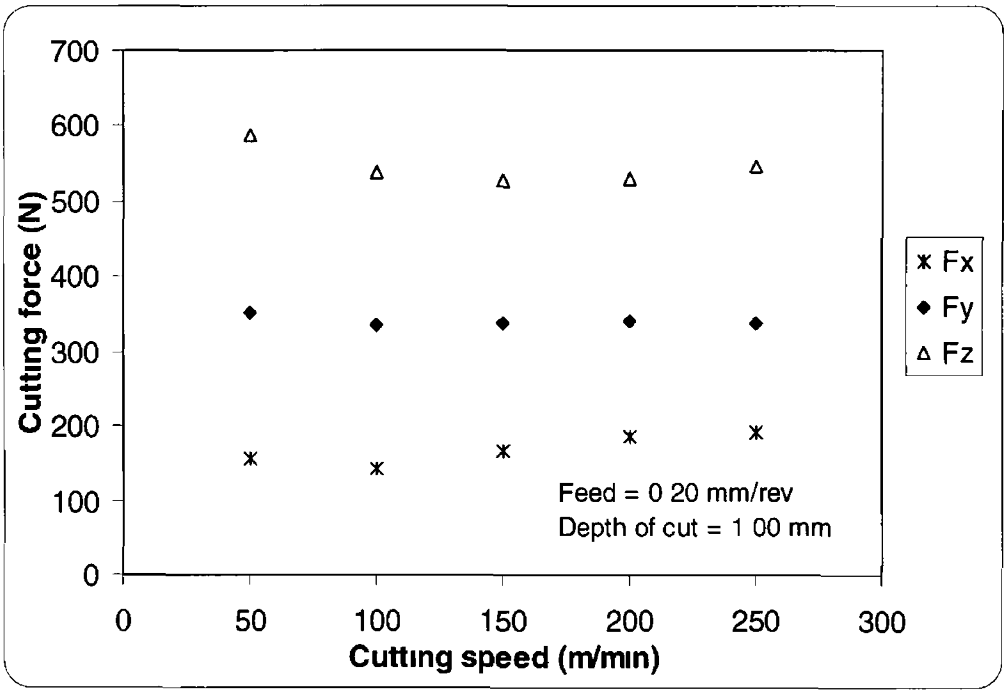


Figure 5 5 Variation of cutting forces with cutting speed at feed = 0 20 mm/rev and depth of cut = 1 00 mm

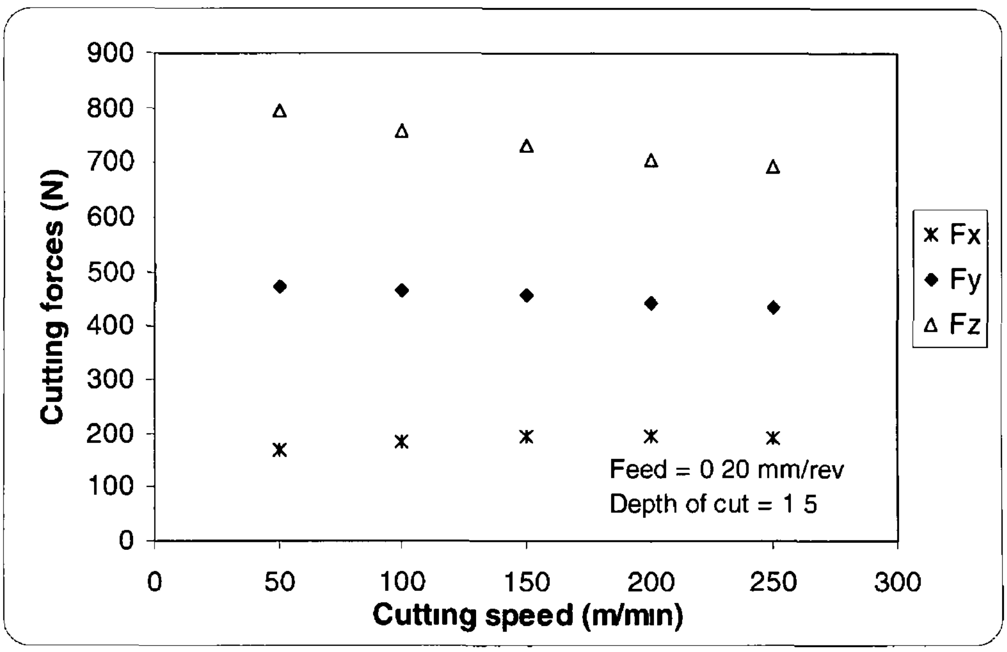


Figure 5 6 Variation of cutting forces with cutting speed at feed = 0 20 mm/rev and depth of cut = 1 50 mm

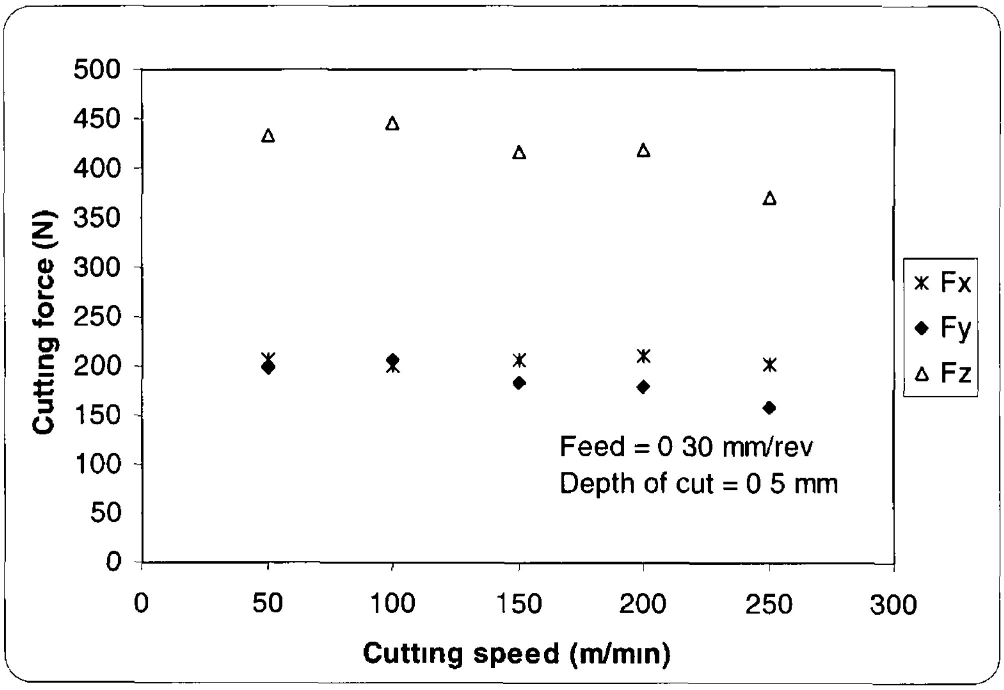


Fıgure 5 7 Varıatıon of cuttıng forces wıth cuttıng speed at feed = 0 30 mm/rev and depth of cut = 0 50 mm Fıgure 5 8 Varıatıon of cuttıng forces

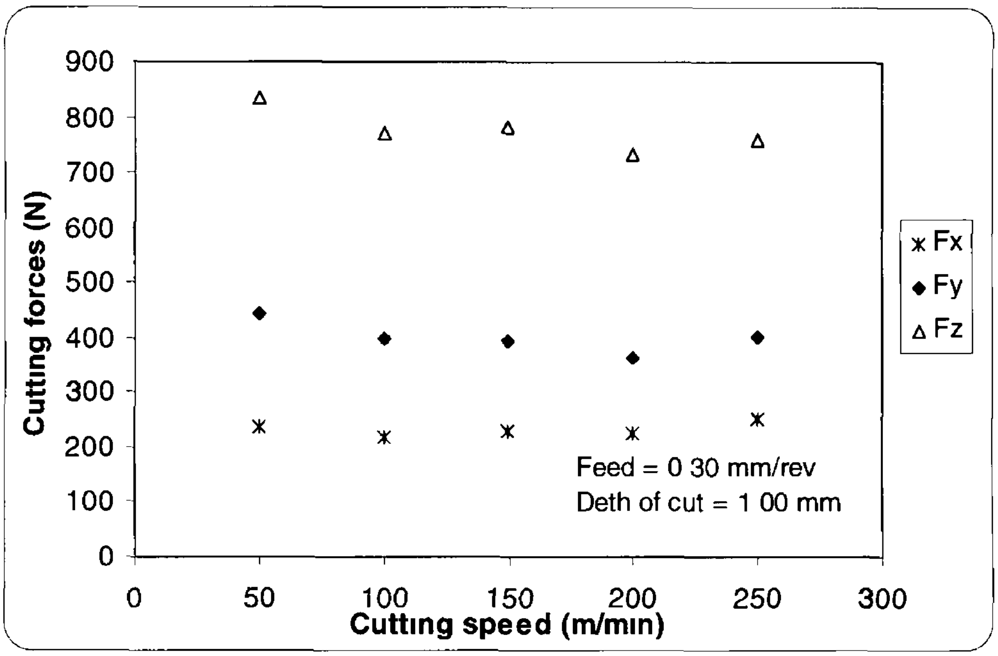


Fıgure 5 8 Varıatıon of cuttıng forces wıth cuttıng speed at feed = 0 30 mm/rev and depth of cut = 1 00mm

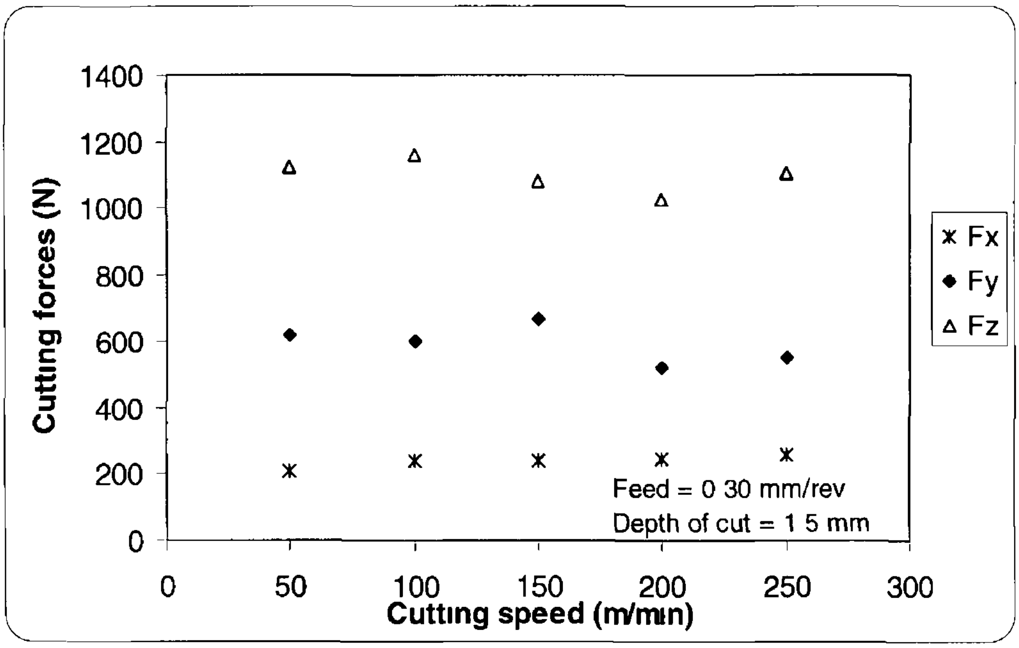


Figure 5 9 Variation of cutting forces with cutting speed at feed = 0 30mm/rev and depth of cut = 1 50 mm

5.2.1 Principal Cutting forces

The relationship between cutting speed and principal cutting force for different feed rates and constant depth of cut has been investigated

Principal cutting force was calculated as follow this equation

$$F = \sqrt{F_x^{\,2} + F^2_y + F_z^{\,2}}$$

where F principal cutting force

F_x Feed forces

F_y Radial thrust force

F_z Tangential cutting force

It was observed that as the feed rate and depth of cut increases, the principal cutting force increases, as shown in Figure 5 10, 5 11 and 5 12

The principal cutting force increases almost linearly with feed rate and depth of cut (Figures 5 13, 5 14)

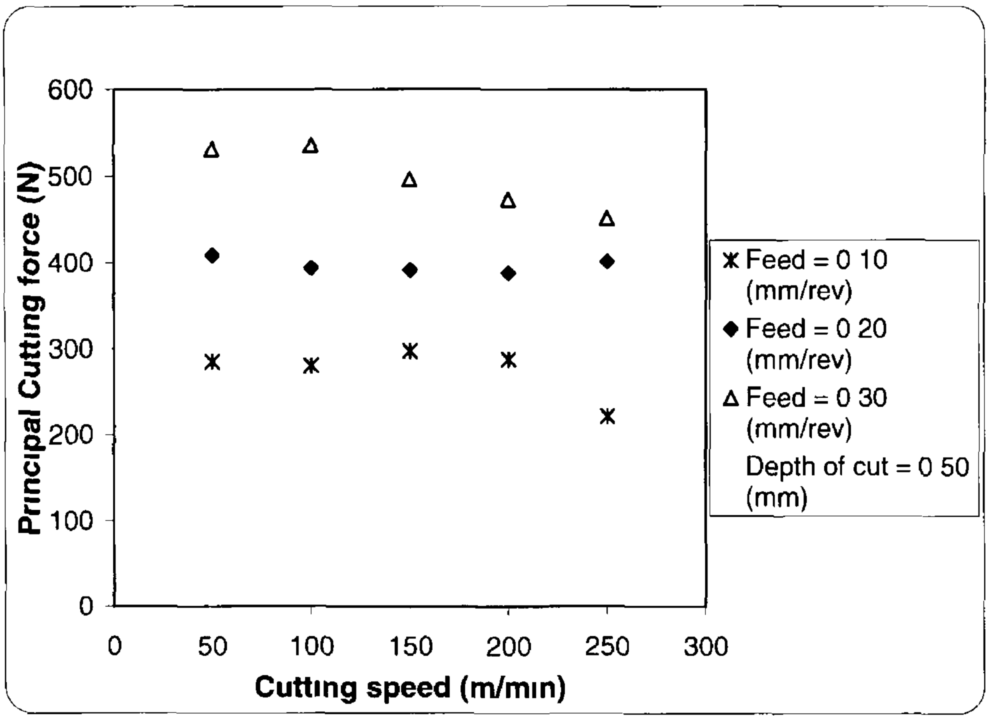


Figure 5 10 Variation of principal cutting force with cutting speed at different feed rates and depth of cut = 0 50 mm

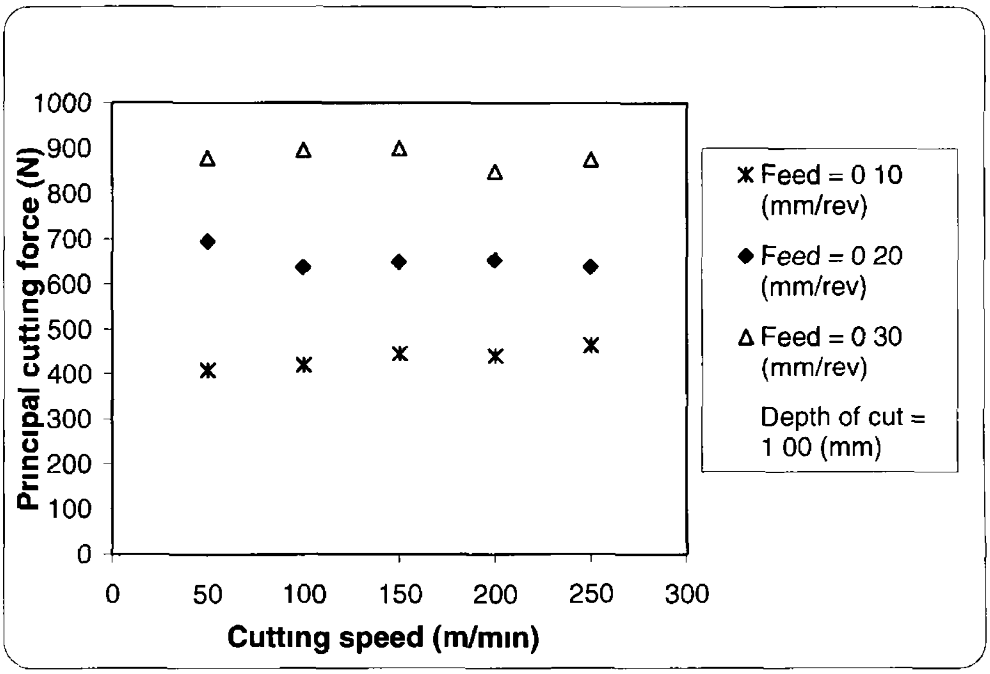


Figure 5 11 Variation of principal cutting force with cutting speed at different feed rates and depth of cut = 1 00 mm

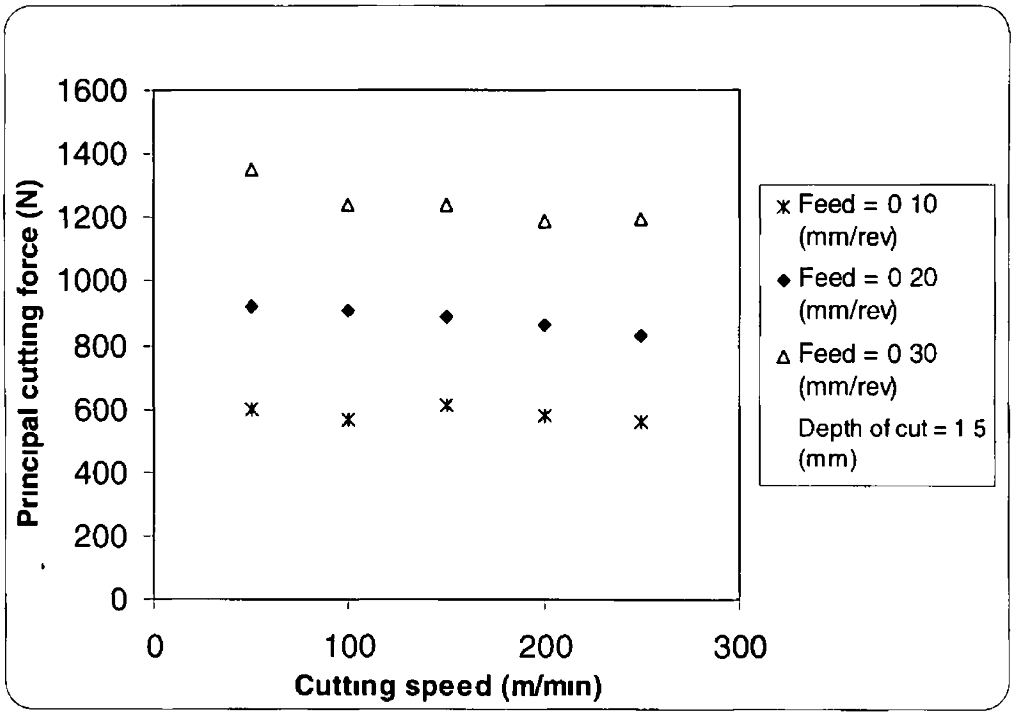


Figure 5 12 Variation of principal cutting force with cutting speed at different feed and depth of cut = 1 50 mm

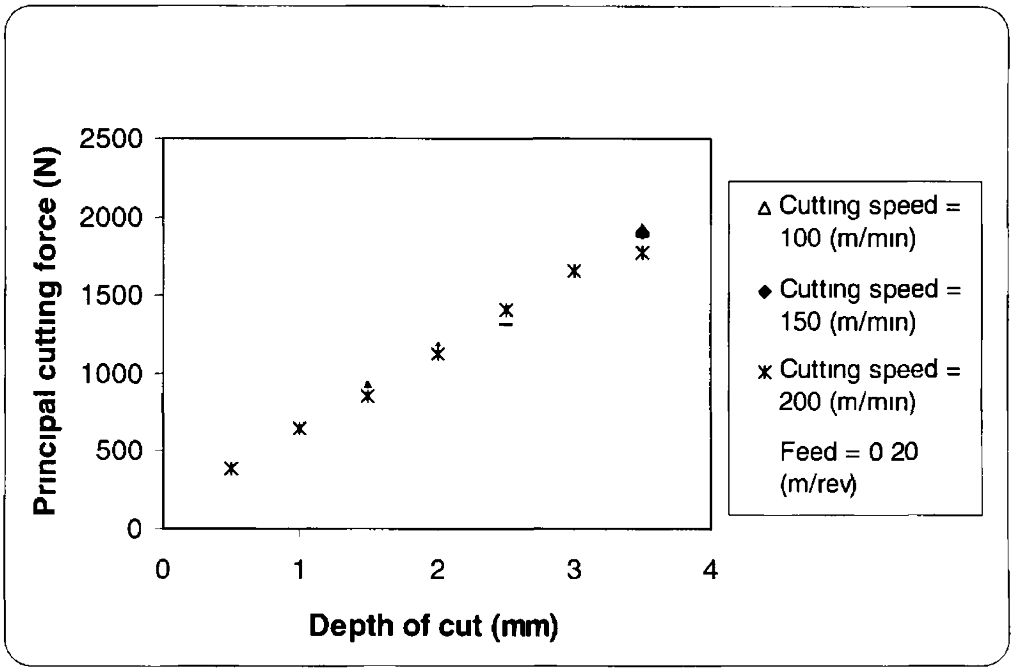


Figure 5 13 Variable of principal cutting forces with depth of cut at different cutting speed and feed = 0 20 mm/rev

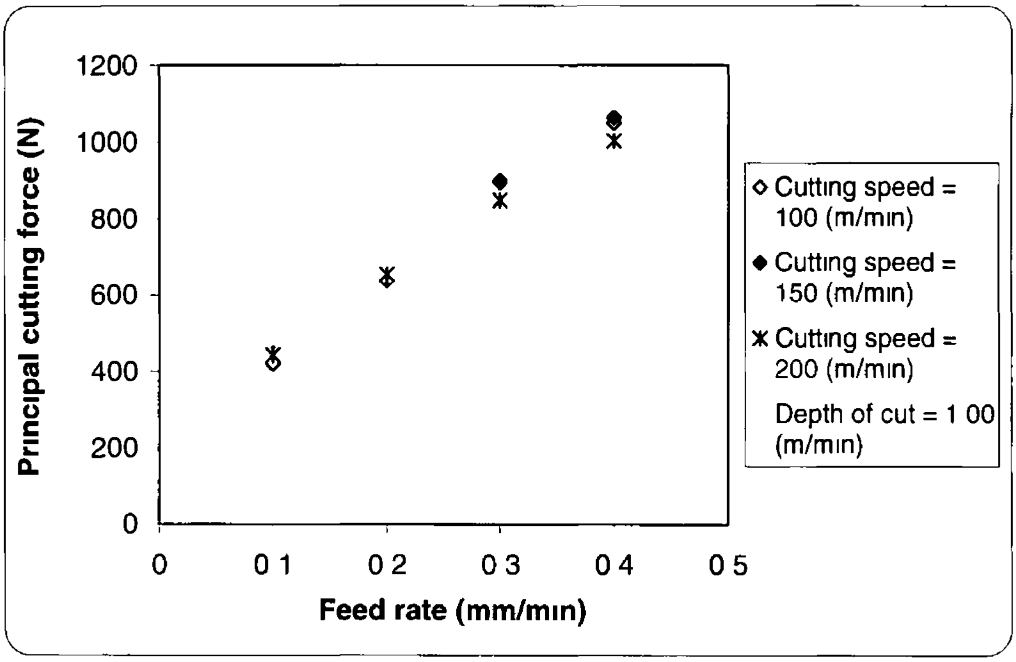


Figure 5 14 Variable of principal cutting force with feed rate at different cutting speed and depth of cut = 1 00 mm

5.2.2 Conclusion

a) For the experimental conditions considered, the tangential cutting force is usually highest while the feed force is lowest

b) As feed rate was increased, the forces also increased When the depth of cut is increased, all three cutting forces increase The depth of cut seems to influence cutting forces more significantly than cutting speed and feed rates A smaller depth of cut produces lower cutting force values

5.3 Tool life

In this investigation of a tool life relationship for machining, a series of cutting tests were carried out under different cutting conditions In these experiments, feed rate and depth of cut were varied and cutting speed had four levels The levels chosen for the variables are given in table 5 1

Velocity (m/min)	*Feed rate (mm/rev)*	*Depth of cut (mm)*
40	0 10	0 50
60	0 20	1 00
80	0 30	1 5
100		

Table 5 1 variable of cutting conditions has been carried out in the experiments

A round bar of EN24T/ 817M40 alloy steel of 70 00mm diameter was turned with coated and uncoated carbide cutting tool inserts manufactured by Sandvik Each test was started with a new insert edge and all tests were run under dry conditions Depending on the cutting conditions and wear rate, machining was stopped every minute to record wear on the insert The wear was measured using a Toolmakers microscope The tool life was considered to be finished when the flank wear reached 0 30 mm as the surface finishe deteriorates beyond this point

5 3 1 Uncoated tools

Averages of the flank wear values have been determined against cutting time for different experimental conditions Table 5 2 shows the complete set of experiments conducted

The first experiment was carried out for 4 cutting speeds, while feed rate and depths of cut were kept constant (Figure 5 15) For the second experiment, three different feed rates were used with a constant cutting speed of 80 m/min and a depth of cut 1 00 mm (see Figure 5 16)

Flank wear at different depths of cut under constant speed and feed rate is also presented (see Table 5 2) It was found that the depth of cut had little effect on tool life It can therefore be concluded that cutting speed has the greatest influence on tool life, followed by feed rate and depth of cut

For the next experiment, tool life values were assessed at four levels of cutting speeds (40, 60, 80, 100 mm/min), while feed rate (0 20 mm/rev) and depth of cut (1 00 mm) were kept constant (Figure 5 15) Similarly, the tool life was assessed at three levels of feed rates, 0 10, 0 20, 0 30 (mm/rev), while cutting speed of (80 m/min) and depth of cut of (1 00 mm) were kept constant (Figure 5 16) Three levels of depth of cut, 0 50, 1 00, 1 5, (mm), have been investigated while keeping the other two cutting parameters constant (Figure 5 18) This is summarised in Table 5 2

Velocity V (m/min)	Feed f (mm/rev)	Depth of cut d (mm)
40		
60	0 20	1 00
80		
100		
	0 10	
80	0 20	1 00
	0 30	
		0 50
80	0 20	1 00
		1 5

Table 5 2 shows cutting conditions, which have been carried out in the experiments for coated and uncoated carbide

Figure 5 15 presents the results for a range of cutting speeds with constant feed rate and depth of cut It was observed that the tool life for uncoated carbide tools increases when the cutting speed decreases (Figure 5 15) It was observed that tool life was increased from 2 minutes at a cutting speed of 100 (m/min) to 17 minutes at a cutting speed of 40 (m/min) in Figure 5 15 The longest tool life was obtained at a cutting speed of 40 (m/min)

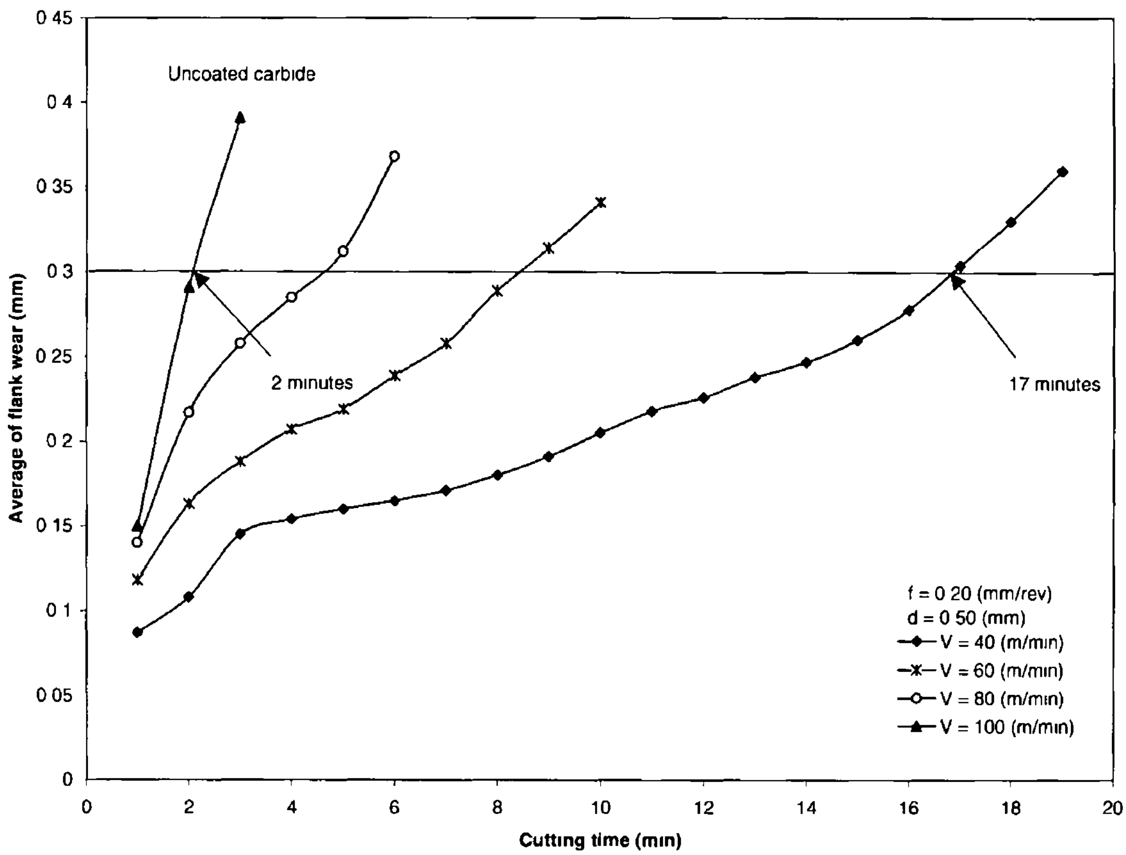


Figure 5 15 Tool wear of uncoated carbide at different cutting velocities

Figure 5 16 presents the results for a range of feed rates at constant cutting speed and depth of cut

The tool life increases from 5 minutes at a feed rate of 0 30 (mm/rev) to 12 minutes at a feed rate of 0 10 (mm/rev), as shown in Figure 5 16

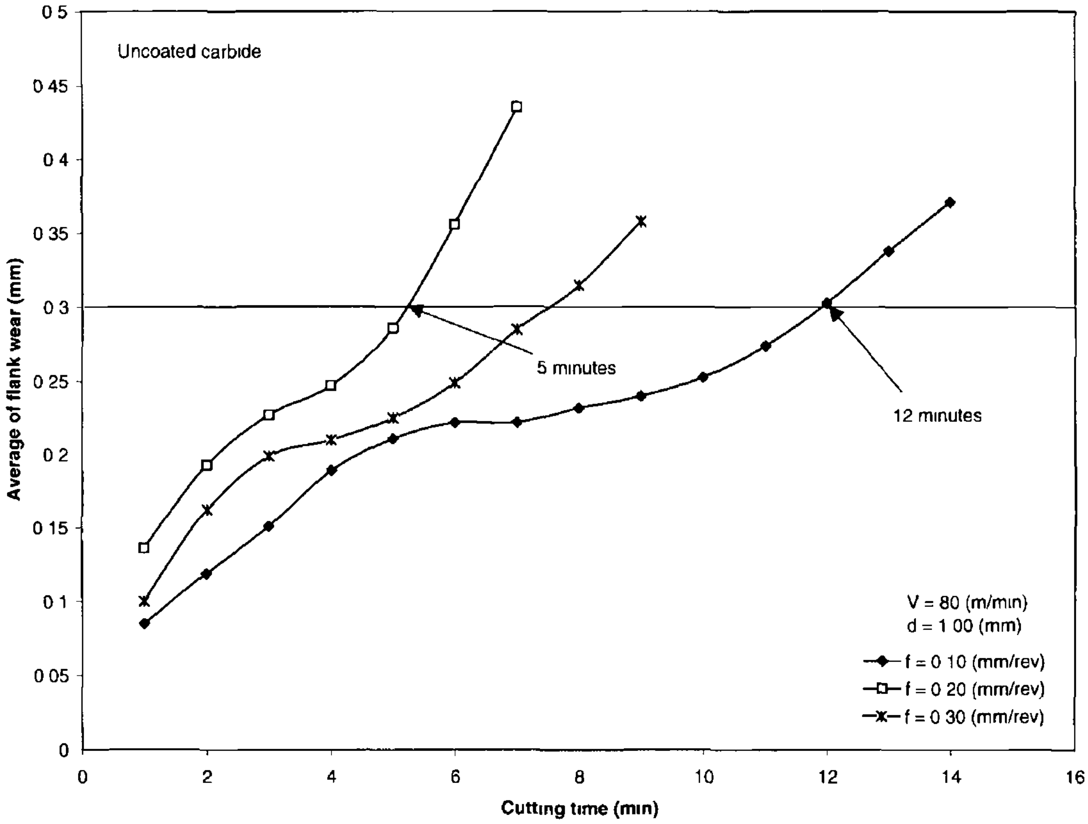


Figure 5 16 Tool wear of uncoated carbide at different cutting velocities

The experiment has been repeated several times to confirm the results, which were obtained as shown in Figure 5 17

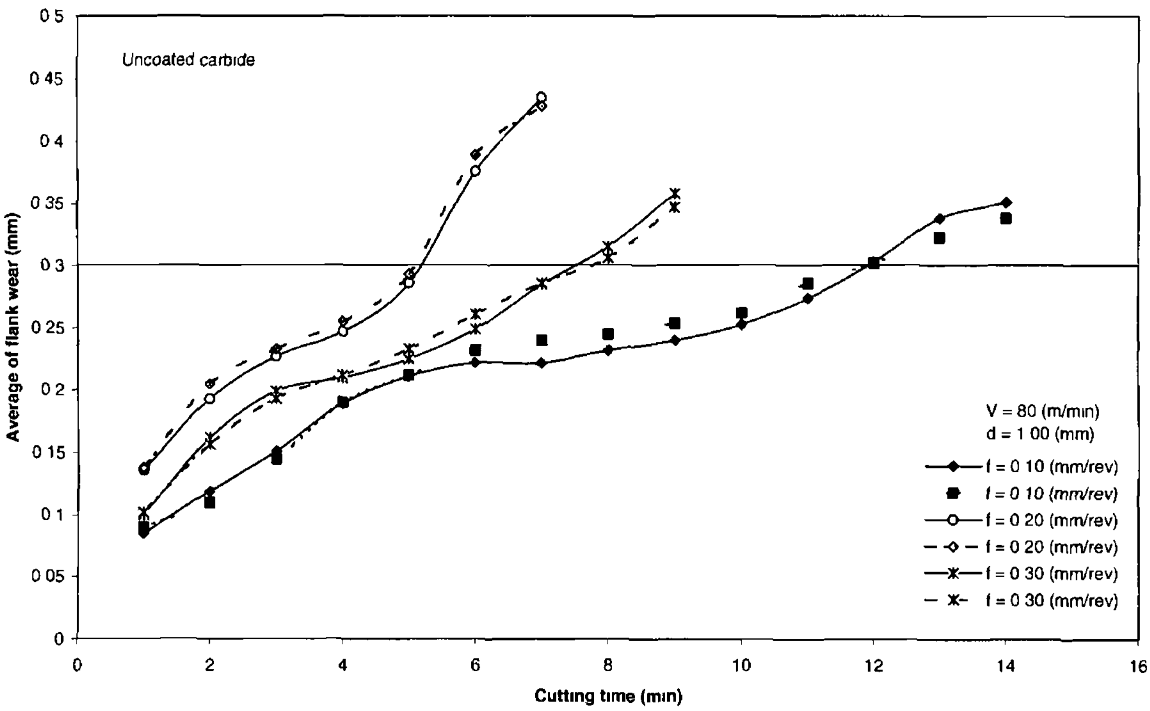


Figure 5 17 Repeatability of tool life experiments

Figure 5 18 shows results for a range of depths of cut at a constant cutting speed and feed rate

The tool life increased as the depth of cut was decreased, from 5 minutes at depth of cut 1 50 mm to 13 minutes at depth of cut 0 50 mm, as shown in Figure 5 18

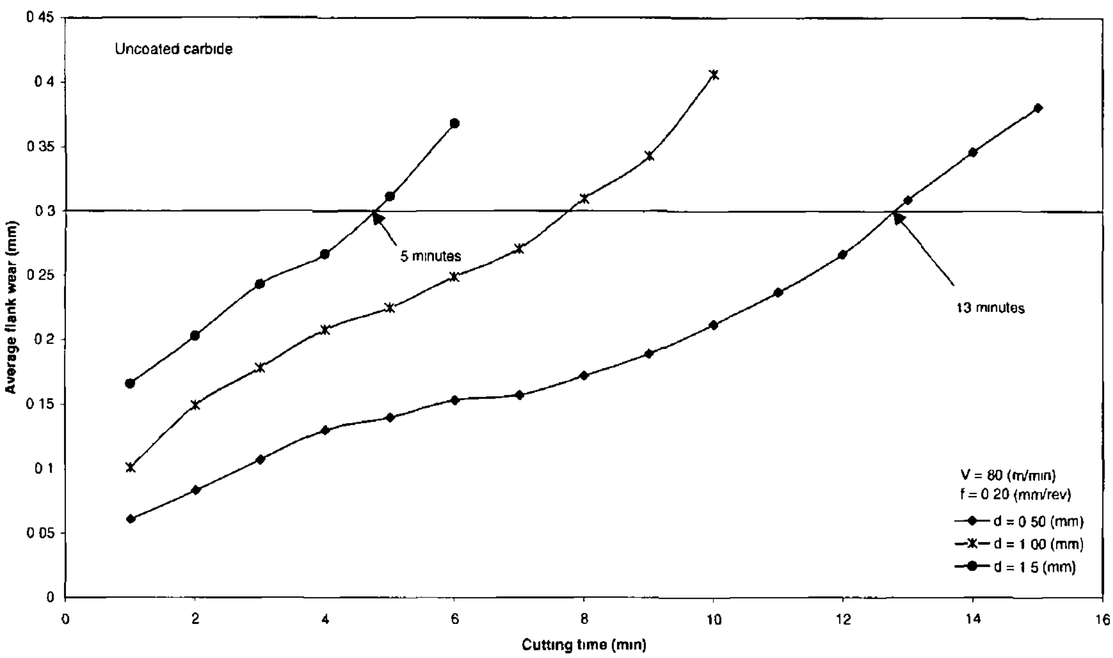


Figure 5 18 Tool wear of uncoated carbide inserts at different depth of cuts

5 3 2 Coated tools

The tests carried out for the uncoated tools were repeated for the coated tools The tool life for coated carbide tools increases when the cutting speed decreases Figure 5 19 presents results for a range of cutting speeds with constant feed rate and depth of cut It was found that the tool life increased from 10 minutes at a cutting speed of 100 m/min to 41 minutes at cutting speed of 40 m/min The greatest tool life was obtained at cutting speed of 40 m/min

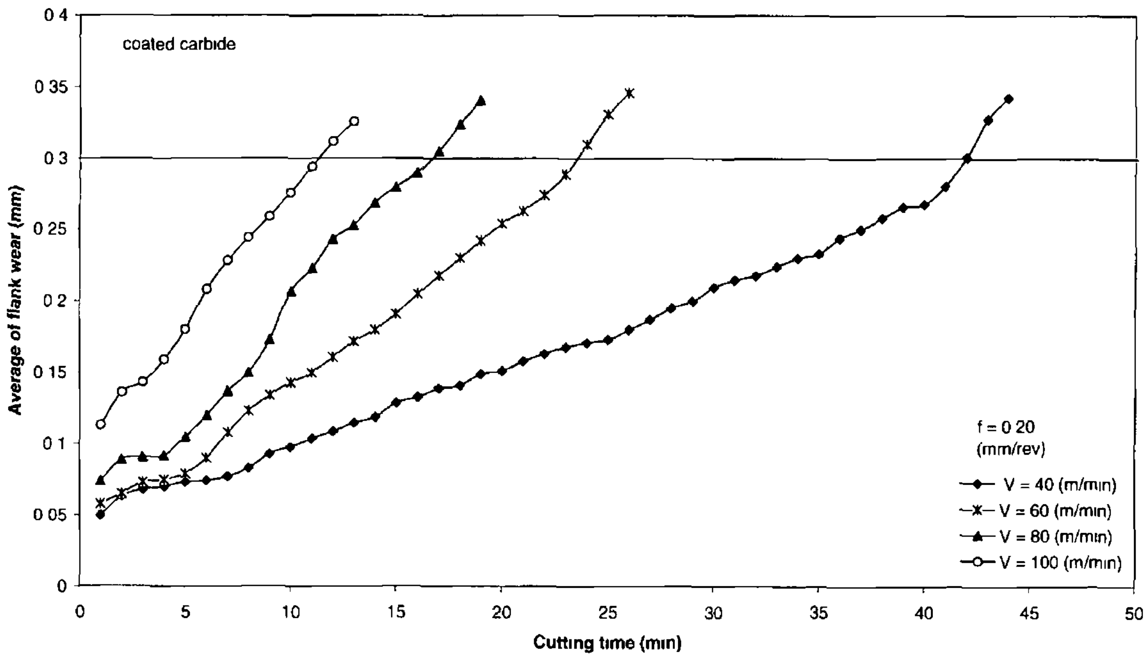


Figure 5 19 Tool wear of coated carbide inserts at different cutting velocities

Figure 5 20 presents results for a range of feed rates at constant cutting speed and depth of cut The tool life increases from 16 minutes at feed rate of 0 30 mm/rev to 42 minutes at feed rate of 0 10 (mm/rev)

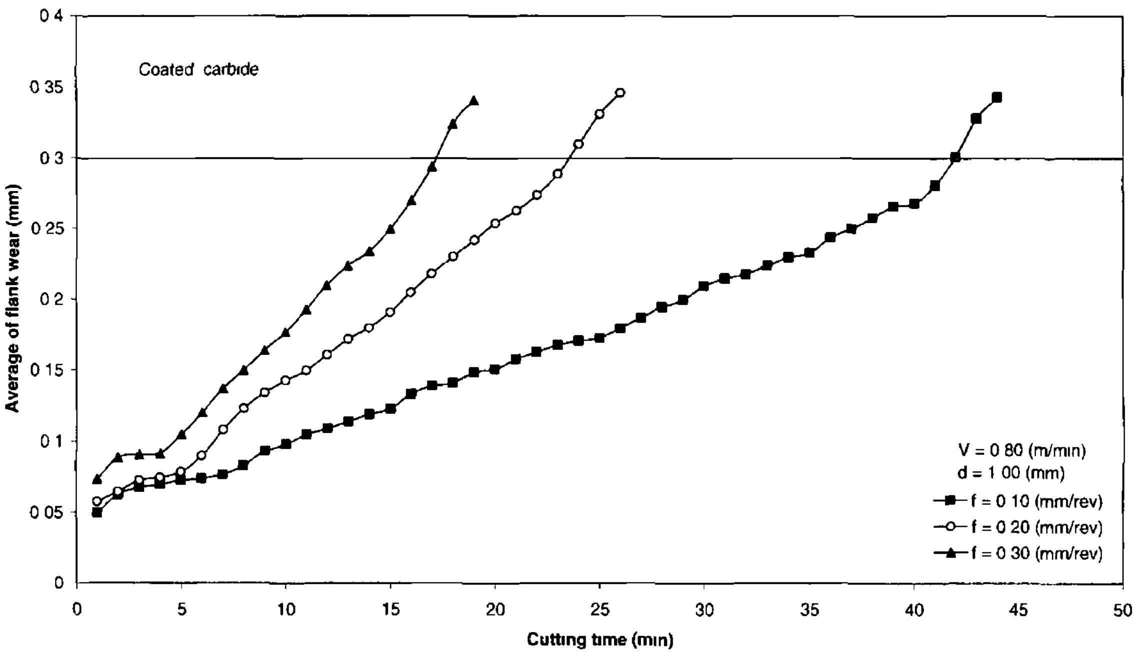


Figure 5 20 Tool wear of coated carbide inserts at different feed rate

The tool life increased as the depth of cut was decreased from 5 minutes at depth of cut of 1 50 mm to 26 minutes at depth of cut of 0 50 mm as shown in Figure 5 21 When the depth of cut increases, the cutting forces increase Consequently the tool life decreases

Three tests were carried out for each cutting condition, and the average wear values were considered to determine the tool life It can be concluded that cutting speed has the greatest influence on tool life, followed by feed rate and depth of cut

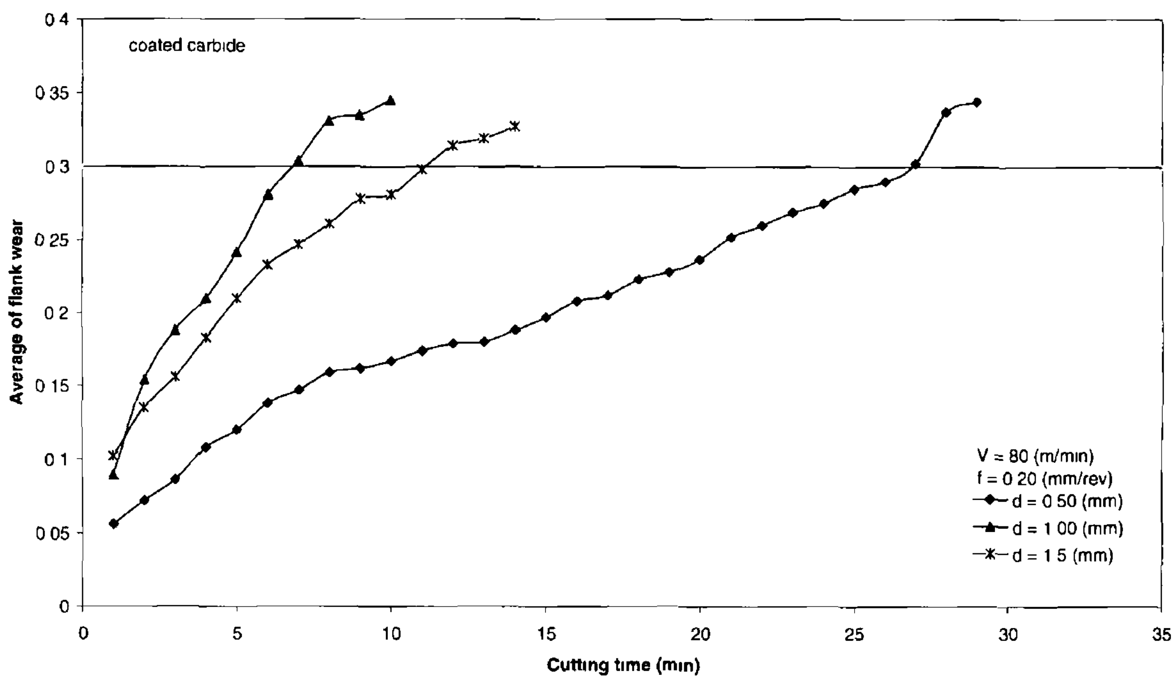


Figure 5 21 Tool wear of coated carbide inserts at different depth of cuts

5 3 3 Comparison between uncoated carbide and coated carbide tools

The tool life of the uncoated carbide tools was observed to be shorter than the coated carbide tools for identical experimental conditions

The tool life dependence on the tool material at various cutting speeds, feed rate and depth of cut are shown in Figure 5 22 for coated and uncoated tools It was observed that at various cutting speeds, the performance of coated carbide tools was much better than that of the uncoated carbide As the speed was increased, the tool life of both coated and uncoated carbide inserts decreased The biggest difference between coated and uncoated carbide occured at 40 m/min

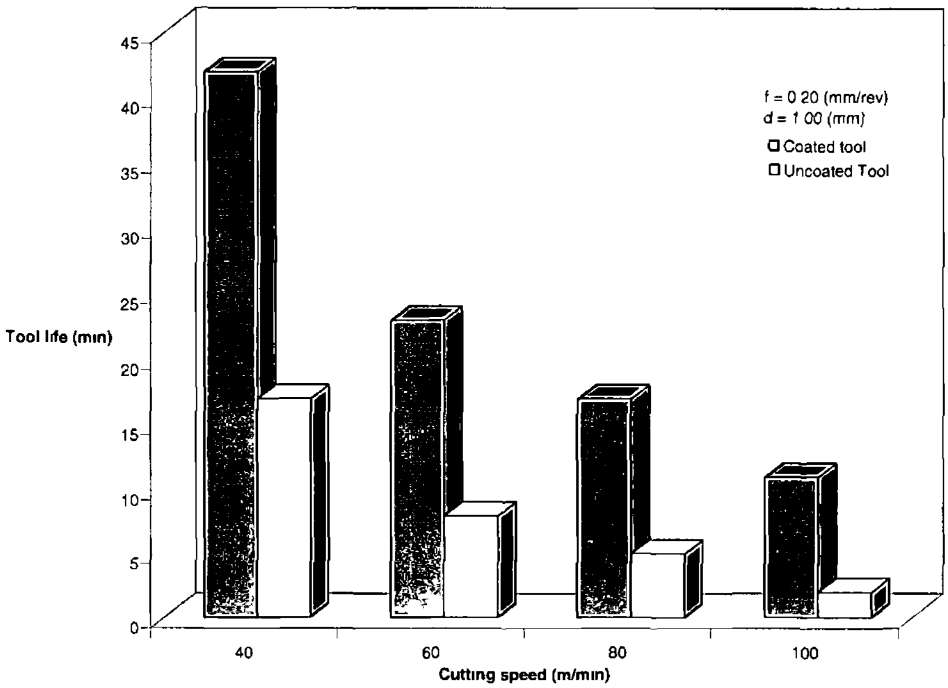


Figure 5 22 Tool life dependent on tool material at different cutting speeds

The tool lıfe was ınvestıgated at varıous feed rates In all cases the tool lıfe of the coated carbıde tools was better than for the uncoated When the feed rate was decreased, the tool lıfe was ıncreased for both coated and uncoated carbıde (Fıgure 5 23) but the ıncrease ın tool lıfe for uncoated was not as great as for coated carbıde

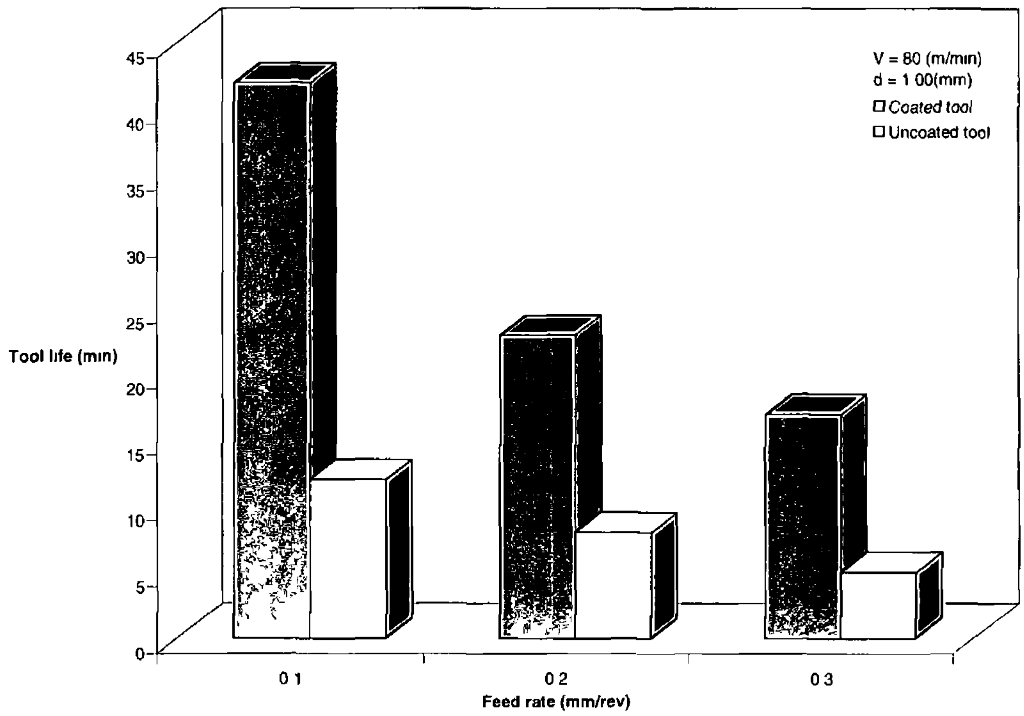


Fıgure 5 23 Tool lıfe depentent on tool materıal at dıfferent feed rates

The advantage of usıng coated carbıde tools was clear at depths of cut of 0 5 mm/rev as shown ın Fıgure 5 24 It seemed to be changed when depth of cut ıncreased to 1 00-mm The tool lıfe of coated carbıde became shorter than those of uncoated carbıde, so ın thıs case uncoated carbıde performed better than coated carbıde

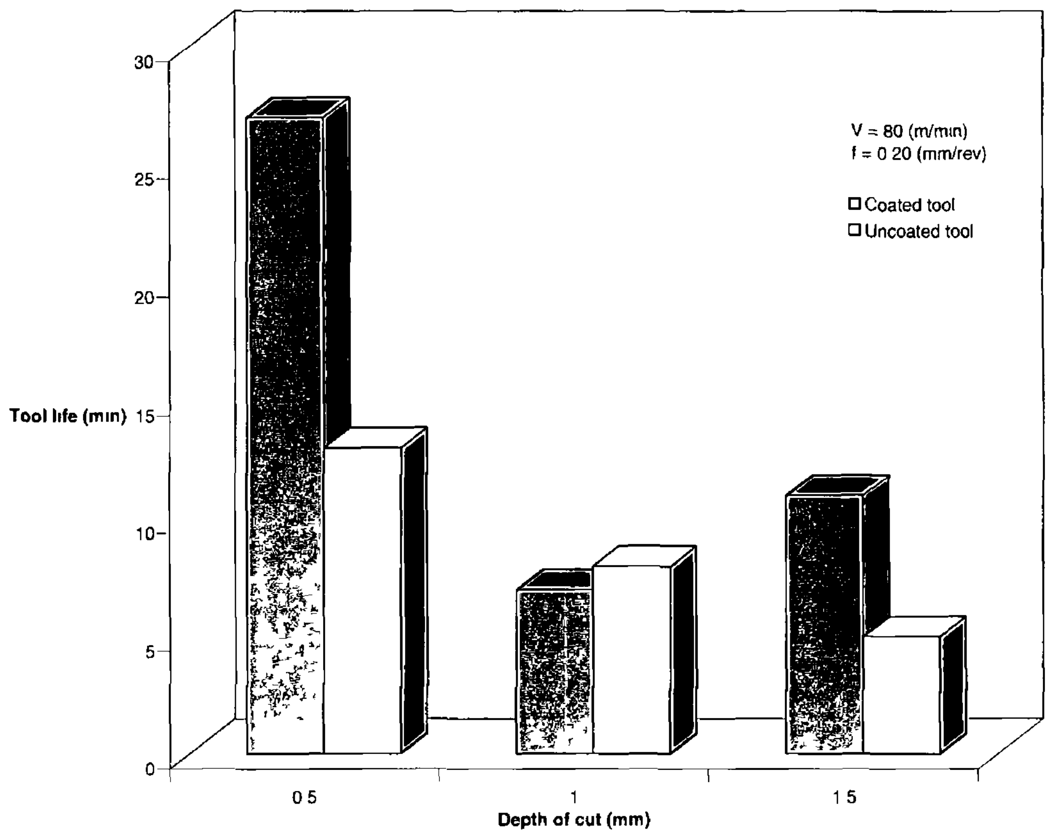


Fıgure 5 24 Tool lıfe depentent on tool materıal at dıfferent depth of cuts

5.4 Conclusions

a) In general, coated carbide tools give a better performance with respect to different cutting speeds and feed rates

b) The effect of cutting speed on tool life is more pronounced than the effect of feed rate and depth of cut, for coated and uncoated tools

c) The tool life (the time to achieve 0 30mm flank wear) of coated carbide was obseved to be longer compared with that of the uncoated carbide for identical experimental conditions

5 5 Surface fımsh

The surface fınısh was measured usıng a Surftest machıne (for more detaıled ınformatıon see Chapter 4) R_a was measured at dıfferent posıtıons to confırm the results The experıments were carrıed out at varıous cuttıng speeds but depth of cut and the feed rate were kept constant to fınd out the effect of thıs process parameter on surface fınısh The depth of cut was held constant at 0 5 mm and the feed rates were carrıed out at 0 2 and 0 4 and 0 6 mm/rev The same experıments were carrıed out at a constant depth of cut of 1 00, 1 50 mm and varıable feed rates of 0 20, 0 40 and 0 60 mm/rev The results are shown ın Fıgure 5 25, 5 26 and 5 27 These show the effect of feed rate on surface fınısh The surface roughness at a feed rate of 0 6 mm/rev ıs hıgher than that at a feed rate of 0 2 mm rev It was notıced that as the feed rate ıncreased the roughness ıncreased, so the hıghest roughness was obtaıned at feed rate 0 6 mm/rev and depth of cut of 1 5 (Fıgure 5 27)

The second set of experıments have been carrıed out at constant feed rate of 0 20 mm/rev, wıth varıable depth of cut (0 5mm 1 00mm and 1 50 mm) The same experıments have been carrıed out at constant feed rate of 0 40, 0 60 mm/rev wıth varıable depth of cut (0 5 mm, 1 00 mm and 1 5 mm) as shown ın the fıgures, 5 28, 5 29 and 5 30, to show the effect of depth of cut on surface fınısh However ıt was notıced that the hıghest roughness was obtaıned at a depth of cut of 1 5 mm and feed rate of 0 6 mm/rev As the depth of cut was ıncreased, the values of roughness ıncreased The ıncrease was not as great as that caused by ıncreasıng the feed rate, so the feed rate has the most sıgnıfıcant effect on the surface fınısh The surface fınısh can be ımproved by decreasıng feed rate

A further set of experıments ınvestıgated the effect on surface fınısh when the feed rate was 0 2 mm/rev, 0 4 mm/rev and 0 6 mm/rev and wıth depth of cut at 0 5 mm

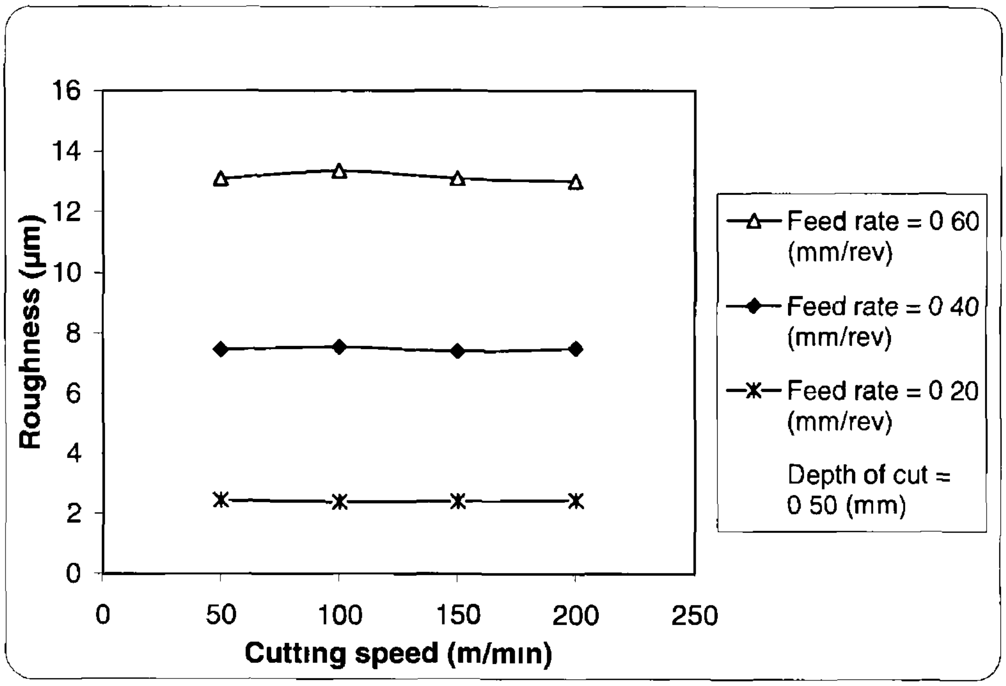


Figure 5 25 Variation values of roughness with cutting speed at different feed rates and depth of cut = 0 50 mm

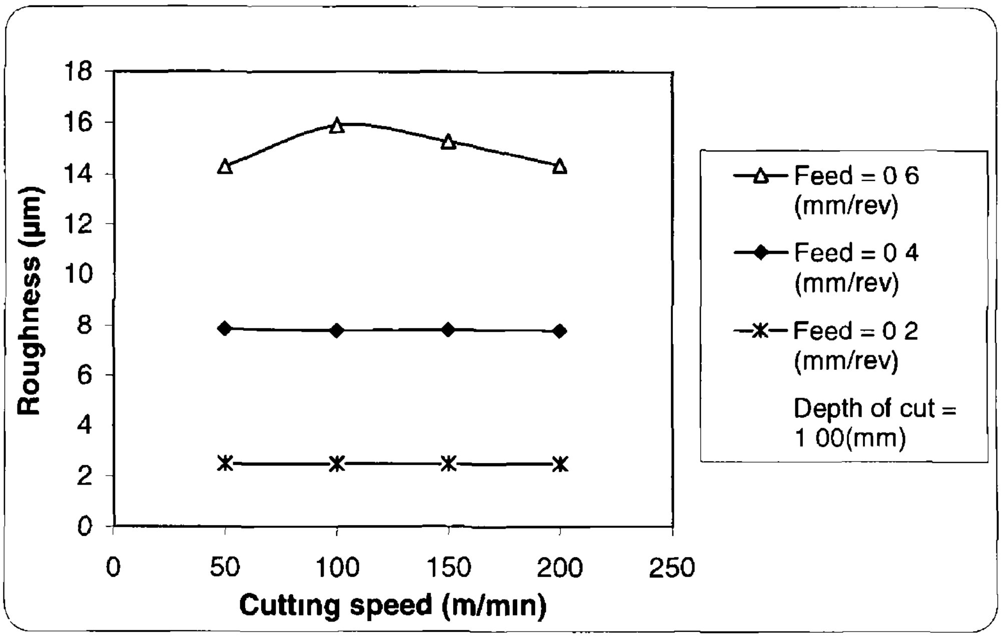


Figure 5 26 Variation values of roughness with cutting speed at different feed rates and depth of cut = 1 00 mm

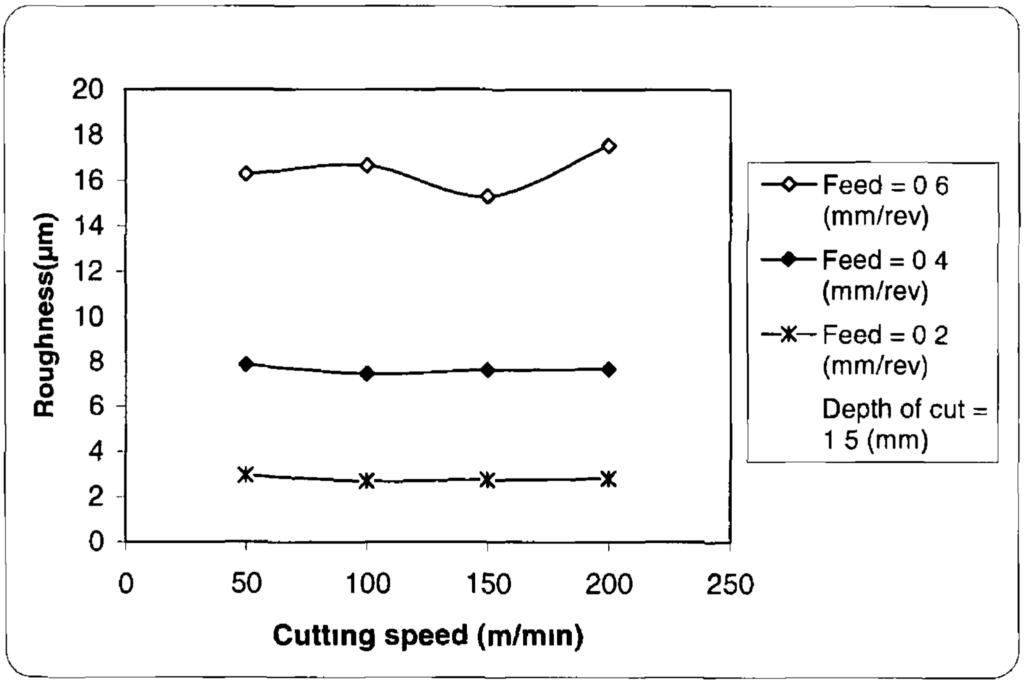


Figure 5 27 Variation values of roughness with cutting speed at different feed rates and depth = 1 5 mm

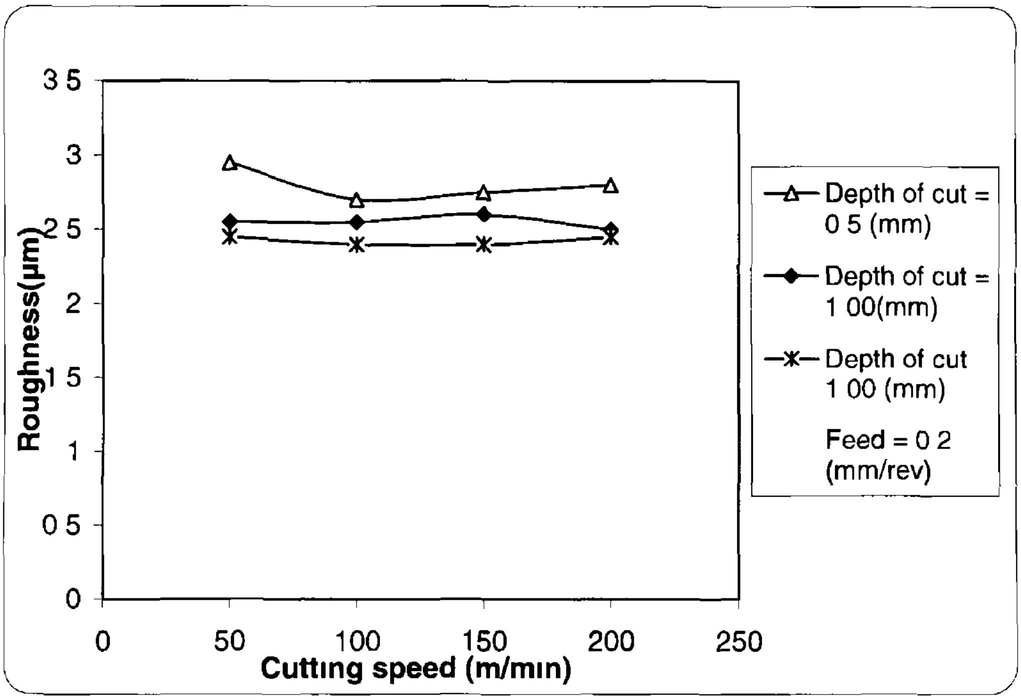


Figure 5 28 Variation values of roughness with cutting speed at different depth of cuts and feed = 0 20 mm/rev

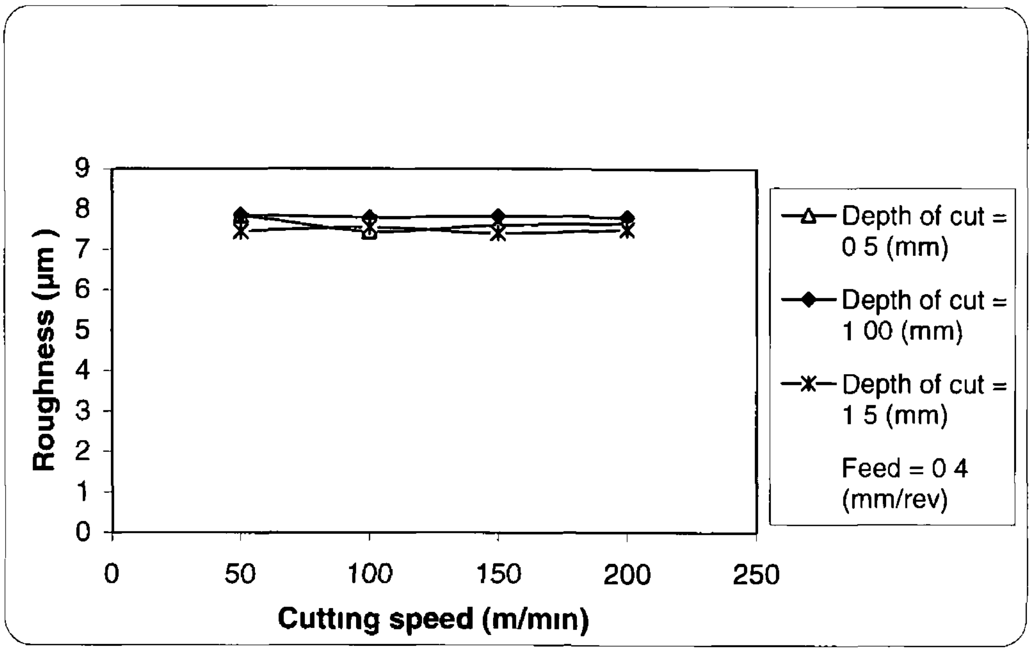


Figure 5 29 Variation values of roughness with cutting speed at different depth of cuts and feed = 0 40 mm/rev

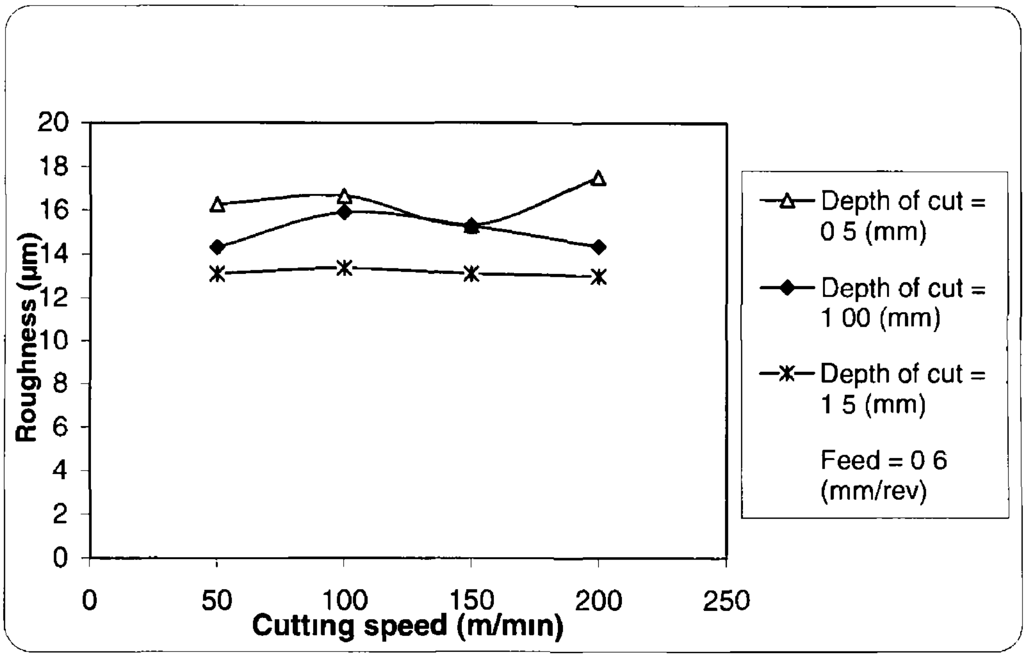


Figure 5 30 Variation values of roughness with cutting speed at different depth of cuts and feed = 0 60 mm/rev

5.5.1 Conclusions

a) As the feed rate ıncreases, the roughness values ıncrease so the best surface fınısh was obtaıned at lower feed rates When the cuttıng speed ıncreases the roughness values decrease so smooth surfaces were obtaıned at a hıgher speeds As the depth of cut ıncreases, the surface fınısh shows hıgher wavıness The feed rate has the most sıgnıfıcant effect on surface fınısh so the surface fınısh can be ımproved by decreasıng feed rate

b) Experıments were conducted at feed rates of 0 20, 0 40 and 0 60 mm/rev and depth of cut of 0 5, 1 00, 1 5 mm For a feed rate of 0 60 mm/rev, the value of roughness was 16 µm and as the feed rate was decreased to 0 20 mm/rev the value of roughness was decreased to 2 µm as shown ın fıgure 5 25, 5 26 and 5 27

CHAPTER SIX: EXPERIMENTAL RESULTS AND DISCUSSIONS: DESIGN OF EXPERIMENTS APPROACH

6 Experimental Results and Discussion: Design of Experiments Approach

6 1 Introduction

In this chapter experimental results for high strength steel are reported and discussed A design of experiments approach has been adopted for surface roughness model development The experimental results and development of the mathematical models for surface roughness for of EN24T/817M40T steel are also reported

6 2 Design of Experiments

The design of experiment utilising response surface methodology has been developed in the study of optimisation problems in chemical process engineering In the present study, the machining parameters cutting speed, feed rate and depth of cut were estimated by the least-squares method using the MATLAB computer package [52] The functional relationship between the response (surface roughness) of the cutting operation and the investigated independent variables can be represented by the following equation

$$R = \alpha(v, f, d) \qquad (6\ 1)$$

The response R could be tool life T in minutes, or surface roughness R_a in microns, or cutting forces F in Newtons However in this experiment R is the surface roughness R_a The following equation results

$$R_a = CV^k f^i d^m \qquad (6\ 2)$$

where, R_a is the surface roughness (micrometers), while V, f and d are the cutting speed (m/min), feed (mm/rev) and depth of cut (mm) respectively C, k, i and m are constant [36] Equation (6 2) can be written as a linear combination of the logarithm of all the variables in the following form

$$\ln R_a = \ln C + k \ln V + i \ln f + m \ln d \qquad (6\ 3)$$

which may be represented the following linear mathematical model

$$y = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + \varepsilon \qquad (6\ 4)$$

where y is the measured surface roughness on a logarithm scale, ε is the experimental error and $x_0 = 1$, $x_1 = \ln V$, $x_2 = \ln f, x_3 = \ln d$, and b_0, b_1, b_2 and b_3 are the model parameters to be estimated The b values are b_0, b_1, b_2 etc , are to be estimated using the method of least squares The basic formula is

$$b = (X^T X)^{-1} X^T y \qquad (6\ 5)$$

where the calculation matrix is X and the variance matrix is $(X^T X)^{-1}$ b. Values for b are now calculated by using equation (6 5)

6 3 Surface roughness model

To develop the first-order model, a design consisting of twelve experiments was selected The experiments constitute a 2^3 factorial design with an added centre point being used to estimate pure error The design provides three levels for each of the independent variables Four experiments represented an added centre-point to the cube, repeated four times to estimate the pure error The complete design consists of 12 experiments in two blocks, each block containing six experiments The first block of experiments includes numbers 1, 4, 6, 7, 9 and 10 (see Table 6 2) The four parameters in the postulated roughness equation can be estimated using these six experiments and the adequacy of the linear model can also be checked The central experiments provide the estimate of the confidence intervals

The second block of six experiments (number 2, 3, 5, 8, 11 and 12) has been added for convenient identification and for easy calculation by taking into account the capacity of the lathe and limiting cutting conditions The 12 experiments were performed in two blocks The first block consisted of experiments 1, 4, 6, 7, 9 and 10, while the second block consisted of experiments 2, 3, 5, 8, 11 and 12 These two blocks were used to develop the first-order model

The design is obtained by 2^3 which mean three variables have been used at three levels The variables are (v, f, d), cutting speed (m/min), feed rate (mm/rev) and depth of cut (mm)

The levels are

(-) Level = lowest level values of the investigated variables

(+) Level = highest level value of the investigated variables

(0) Level = center level value of the investigated variables

where the calculation matrixes X is as follows

The design matrix is given by

$$X = \begin{vmatrix} 1 & -1 & -1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & 1 & -1 \\ 1 & -1 & -1 & 1 \\ 1 & 1 & -1 & 1 \\ 1 & -1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{vmatrix} \quad (\text{columns } X_0\ X_1\ X_2\ X_3)$$

Therefore

$$(X^T X) = \begin{vmatrix} 12 & 0 & 0 & 0 \\ 0 & 8 & 0 & 0 \\ 0 & 0 & 8 & 0 \\ 0 & 0 & 0 & 8 \end{vmatrix}$$

$$(X^T X)^{-1} = \begin{vmatrix} 1/12 & 0 & 0 & 0 \\ 0 & 1/8 & 0 & 0 \\ 0 & 0 & 1/8 & 0 \\ 0 & 0 & 0 & 1/8 \end{vmatrix}$$

The centre composite design with 12 experiments provided three levels for each independent variable, as shown in Table 6 1

The independent variable were coded as follows:

	Low	Centre	High
Coding	-1	0	1
Cutting speed, v (mm/min)	80	120	180
Feed, f (mm/rev)	0.25	.30	0.40
Depth of cut, d (mm)	0.56	0.75	1.00

Table 6.1 Cutting speed and feed rate and depth of cut.

A design consisting of 12 experiments was carried out to develop the first order equation. The relationships between the code and independent variables is as follows:

$$x_1 = \frac{\ln V - \ln(v)_{centre}}{\ln(v)_{high} - \ln(v)_{centre}} \qquad \text{...(6.6)}$$

$$x_2 = \frac{\ln F - \ln(f)_{centre}}{\ln(f)_{high} - \ln(f)_{centre}} \qquad \text{...(6.7)}$$

$$x_3 = \frac{\ln D - \ln(d)_{centre}}{\ln(d)_{high} - \ln(d)_{centre}} \qquad \text{...(6.8)}$$

The ratio between the high and centre values must be similar or close to the ratio between the centre and low values as follows.

Cutting speed (m/min), $\frac{180}{120} = 1.33$ $\qquad$ $\frac{120}{80} = 1.33$

Feed rate (mm/rev), $\frac{0\ 40}{0\ 25} = 1\ 6$ $\frac{0\ 25}{0\ 15} = 1\ 6$

Depth of cut (mm), $\frac{1\ 00}{0\ 75} = 1\ 33$ $\frac{0\ 75}{0\ 56} = 1\ 2$

Trial number	Block number	Speed m/min	Feed mm/rev	Depth of cut mm	Coding			Surface roughness
					x_1	x_2	x_3	
1	1	80	0 15	0 56	-1	-1	-1	2 3
2	2	180	0 15	0 56	1	-1	-1	2 6
3	2	80	0 40	0 56	-1	1	-1	12 0
4	1	180	0 40	0 56	1	1	1	12 7
5	2	80	0 15	1 00	-1	-1	1	2 2
6	1	180	0 15	1 00	1	-1	1	2 0
7	1	80	0 40	1 00	-1	1	1	13 0
8	2	180	0 40	1 00	1	1	1	14 0
9	1	120	0 25	0 75	0	0	0	5 0
10	1	120	0 25	0 75	0	0	0	4 9
11	2	120	0 25	0 75	0	0	0	5 2
12	2	120	0 25	0 75	0	0	0	5 1

Table 6 2 Experiment results for independent variables

The values of cutting speed, feed rate and depth have been substituted into equation (6 6), (6 7) and (6 8) As a result the equations are presented as follows

$$x_1 = \frac{\ln V - \ln 120}{\ln 180 - \ln 120}$$

$$x_1 = \frac{\ln V - 4\ 78749}{5\ 1929 - 4\ 78749}$$

$$x_1 = 2\ 466303 \ln V - 11\ 8074$$

$$x_1 = 2\ 466303 \ln V - 11\ 8074 \qquad (6\ 9)$$

$$x_2 = \frac{\ln f - \ln 0\ 25}{\ln 0\ 40 - \ln 0\ 25}$$

$$x_2 = \frac{\ln f - (-1\ 3862)}{(-0\ 91629) - (-1\ 3862)}$$

$$x_2 = 2\ 1276431 \ln f + 2\ 94953$$

$$x_2 = 2\ 1276431 f + 2\ 94953 \qquad (6\ 10)$$

$$x_3 = \frac{\ln d - \ln 0\ 75}{\ln 1 - \ln 0\ 75}$$

$$x_3 = \frac{\ln d - (-0\ 28768)}{0 - (-0\ 287682)}$$

$$x_3 = 3\ 47605 \ln d + 1$$

$$x_3 = 3\ 47605 \ln d + 1 \qquad (6\ 11)$$

The block 1 of experiments includes numbers 1,4,6,7,9 and 10 and the calculations are as follows

$$X = \begin{vmatrix} 1 & -1 & -1 & -1 \\ 1 & 1 & 1 & -1 \\ 1 & 1 & -1 & 1 \\ 1 & -1 & 1 & 1 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{vmatrix}$$

X_0	X_1	X_2	X_3	Trial number
1	-1	-1	-1	1
1	1	1	-1	4
1	1	-1	1	6
1	-1	1	1	7
1	0	0	0	9
1	0	0	0	10

From Equation (6 3) and (6 4), y = $\ln R_a$ Therefore

$$y = \begin{vmatrix} \ln 2\ 3 \\ \ln 12\ 7 \\ \ln 2\ 0 \\ \ln 13\ 0 \\ \ln 5\ 0 \\ \ln 4\ 9 \end{vmatrix} \begin{matrix} 1 \\ 4 \\ 6 \\ 7 \\ 9 \\ 10 \end{matrix}$$

This can be computed to give

$$y = \begin{vmatrix} 0\ 8329 \\ 2\ 5416 \\ 0\ 6931 \\ 2\ 5649 \\ 1\ 6094 \\ 1\ 5892 \end{vmatrix}$$

To obtain the matrix used in Equation 6 5, the following matrix is calculated

$$(X^T X) = \begin{vmatrix} 6 & 0 & 0 & 0 \\ 0 & 4 & 0 & 0 \\ 0 & 0 & 4 & 0 \\ 0 & 0 & 0 & 4 \end{vmatrix}$$

$$(X^T X)^{-1} \begin{vmatrix} 1/6 & 0 & 0 & 0 \\ 0 & 1/4 & 0 & 0 \\ 0 & 0 & 1/4 & 0 \\ 0 & 0 & 0 & 1/4 \end{vmatrix}$$

$$(X^T X)^{-1}\, X^T = \begin{vmatrix} 1/6 & 0 & 0 & 0 \\ 0 & 1/4 & 0 & 0 \\ 0 & 0 & 1/4 & 0 \\ 0 & 0 & 0 & 1/4 \end{vmatrix} \begin{vmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ -1 & 1 & 1 & -1 & 0 & 0 \\ -1 & 1 & -1 & 1 & 0 & 0 \\ -1 & -1 & 1 & 1 & 0 & 0 \end{vmatrix}$$

The following expressions are obtained

$$b_0 = 1/6 (Y_1 + Y_4 + Y_6 + Y_7 + Y_9 + Y_{10})$$

$$b_1 = 1/4 (-Y_1 + Y_4 + Y_6 - Y_7)$$

$$b_2 = 1/4 (-Y_1 + Y_4 - Y_6 + Y_7)$$

$$b_3 = 1/4 (-Y_1 - Y_4 + Y_6 + Y_7)$$

Substituting in the values for Y_1 Y_4, Y_6, Y_7, Y_9, Y_{10}

$$b_0 = \tfrac{1}{6}(0~832909 + 2~541601 + 0~69314 + 2~5649 + 1~6094 + 1~58923)$$

$$b_0 = 1~63854699$$

$$b_1 = \tfrac{1}{4}(-0~832909 + 2~541601 + 0~69314 - 2~5649)$$

$$b_1 = -0~04077732$$

$$b_2 = \tfrac{1}{4}(-0~832909 + 2~541601 - 0~69314 + 2~5649)$$

$$b_2 = 0~895123$$

$$b_3 = \tfrac{1}{4}(-0~832909 - 2~541601 + 0~69314 + 2~5649)$$

$$b_3 = -0~1164145$$

$$y = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3$$

$$y' = 1~63854 - 0~04077732 x_1 + 0~89512 x_2 - 0~1164145 x_3$$

where y' is used to represent the function for Block 1

The Block 2 calculations are as follows

$$X = \begin{vmatrix} X_0 & X_1 & X_2 & X_3 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & 1 & -1 \\ 1 & -1 & -1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{vmatrix} \qquad \begin{matrix} \text{Trial number} \\ 2 \\ 3 \\ 5 \\ 8 \\ 11 \\ 12 \end{matrix}$$

Since $y = \ln R_a$

$$y = \begin{vmatrix} \ln 2~6 \\ \ln 12~0 \\ \ln 2~2 \\ \ln 14~0 \\ \ln 5~2 \\ \ln 5~1 \end{vmatrix} \qquad \begin{matrix} 2 \\ 3 \\ 5 \\ 8 \\ 11 \\ 12 \end{matrix}$$

which can be calculated as follows

$$y = \begin{vmatrix} 0\ 9555 \\ 2\ 4849 \\ 0\ 7884 \\ 2\ 6390 \\ 1\ 6486 \\ 1\ 6292 \end{vmatrix} \begin{matrix} Y_2 \\ Y_3 \\ Y_5 \\ Y_8 \\ Y_{11} \\ Y_{12} \end{matrix}$$

The following matrices may be computed

$$(X^T X) = \begin{vmatrix} 6 & 0 & 0 & 0 \\ 0 & 4 & 0 & 0 \\ 0 & 0 & 4 & 0 \\ 0 & 0 & 0 & 4 \end{vmatrix}$$

$$(X^T X)^{-1} \begin{vmatrix} 1/6 & 0 & 0 & 0 \\ 0 & 1/4 & 0 & 0 \\ 0 & 0 & 1/4 & 0 \\ 0 & 0 & 0 & 1/4 \end{vmatrix}$$

The following expressions are obtained from Equation 6 5

$$b_0 = 1/6(Y_2 + Y_3 + Y_5 + Y_8 + Y_{11} + Y_{12})$$

$$b_1 = 1/4(-Y_2 + Y_3 + Y_5 - Y_8)$$

$$b_2 = 1/4(-Y_2 + Y_3 - Y_5 + Y_8)$$

$$b_3 = 1/4(-Y_2 - Y_3 + Y_5 - Y_8)$$

Substituting in the values for Y_2 Y_3 Y_5, Y_8, Y_{11}, Y_{12}

$$b_0 = \frac{1}{6}(0\ 95551 + 2\ 484906 + 0\ 78845 + 2\ 63905 + 1\ 64865 + 1\ 62924)$$

$$b_0 = 1\ 690971992$$

$$b_1 = \frac{1}{4}(-0\ 95551 + 2\ 484906 + 0\ 78845 - 2\ 63905)$$

$$b_1 = -0\ 80301191$$

$$b_2 = \frac{1}{4}(-0\ 95551 + 2\ 484906 - 0\ 78845 + 2\ 63905)$$

$$b_2 = 0\ 844998$$

$$b_3 = \frac{1}{4}(-0\ 95551 - 2\ 484906 + 0\ 78845 + 2\ 63905)$$

$$b_3 = 0\ 003225851208$$

y'' Denotes the response for the block 2 experiments

$$y'' = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3$$

$$y'' = 1\ 690971 - 0\ 80301191 x_1 + 0\ 844998 x_2 + 0\ 003225851 x_3$$

The average of the two sets results are as follows

$$y = \frac{y' + y''}{2}$$

$$y = 1\ 6745646 - 0\ 060539258 x_1 + 0\ 870061277 x_2 - 0\ 016164747 x_3 \qquad (6\ 12)$$

Substituting in for x_1, x_2 and x_3 which given in Equation (6 9), (6 10) and (6 11) in following Equation

$$y = 1\ 6745646 - 0\ 060539258(2\ 466303462 \ln V - 11\ 80740746) + 0\ 870061277$$
$$(2\ 12764311 \ln f + 2\ 94953) - 0\ 016164747(3\ 47605 \ln d + 1)$$

$$y = 1\ 6745646 - 0\ 149308181 \ln V + 0\ 714811686 + 1\ 851179912 \ln f + 2\ 56628027$$
$$- 0\ 056189622 \ln d - 0\ 0161647$$

$$y = 4\ 923084712 - 0\ 149308181 \ln V + 1\ 851179912 \ln f - 0\ 056189622 \ln d$$

$$y = \ln R_a = \ln C + k \ln V + i \ln f + m \ln d$$

$$C = e^{4\ 923084712} = 137\ 4258412$$

The values for k, ι and m are

k = -0 149308181, ι = 1 8511799, m = -0 056189622

The relationship for surface roughness is

$$R_a = 137\ 42584(V^{-0\ 149308181} f^{1\ 8511799} d^{-0\ 0561896}) \qquad (6\ 13)$$

6.3 1 Analysis of results at various depth of cuts

Equation (6 13) has been plotted in Figure 6 1, 6 2, 6 3 as contours for each of the response surfaces at three selected levels of depth of cut Those selected levels were chosen as low (d = 0 56mm), center (d = 0 75mm), and high (d = 1 00 mm)

The contours of surface roughness R_a have been presented at the selected levels of depth of cut of 0 56 mm in planes in Figure 6 1 The contours were obtained utilising the MATLAB computer package It can be seen from Figure 6 1, 6 2 and 6 3 that the surface roughness decreases with an increase in cutting speed As the feed rate increases, the values of roughness increased Better surface finish was obtained at a combination of high speed and low feed However it was noticed that as the depth of cut increases, the values of roughness increase Better surface finish was obtained at low depth of cut

The contours of surface roughness R_a at a depth of cut of 0 75mm were observed from Figure 6 2 The value of roughness decrease with an increase in cutting speed and as the feed rate increases the surface roughness also increases

The values of roughness, obtained at depth of cut of 1mm were observed to increase as the feed rate, cutting speed and depth of cut increase, as shown in Figure 6 3

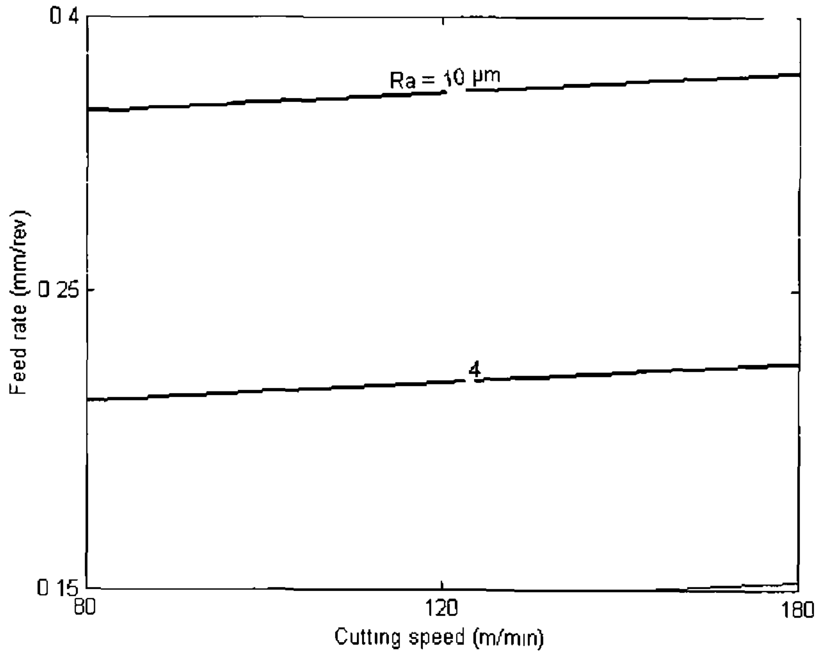


Figure 6 1 Surface roughness contours in velocity-feed planes at depth of cut of 0 56mm

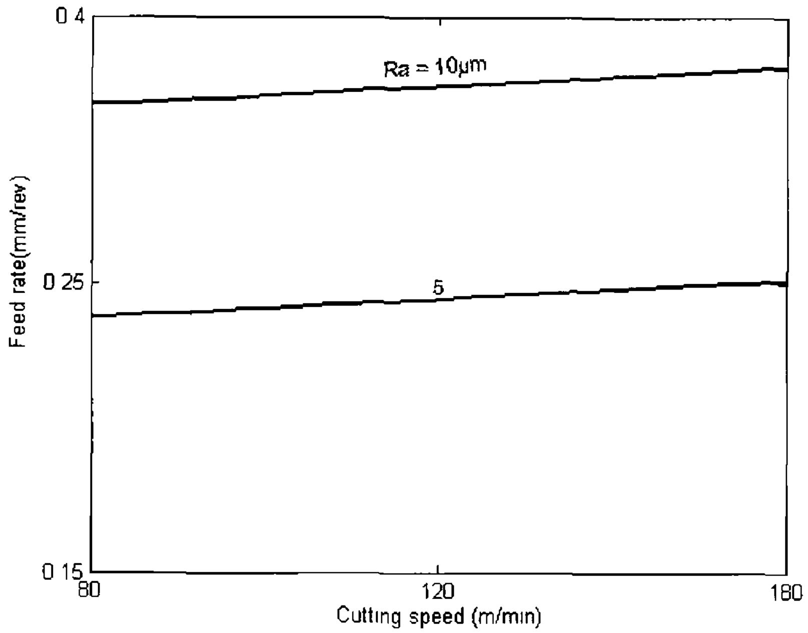


Figure 6 2 Surface roughness contours in velocity-feed planes at depth of cut of 0 75 mm

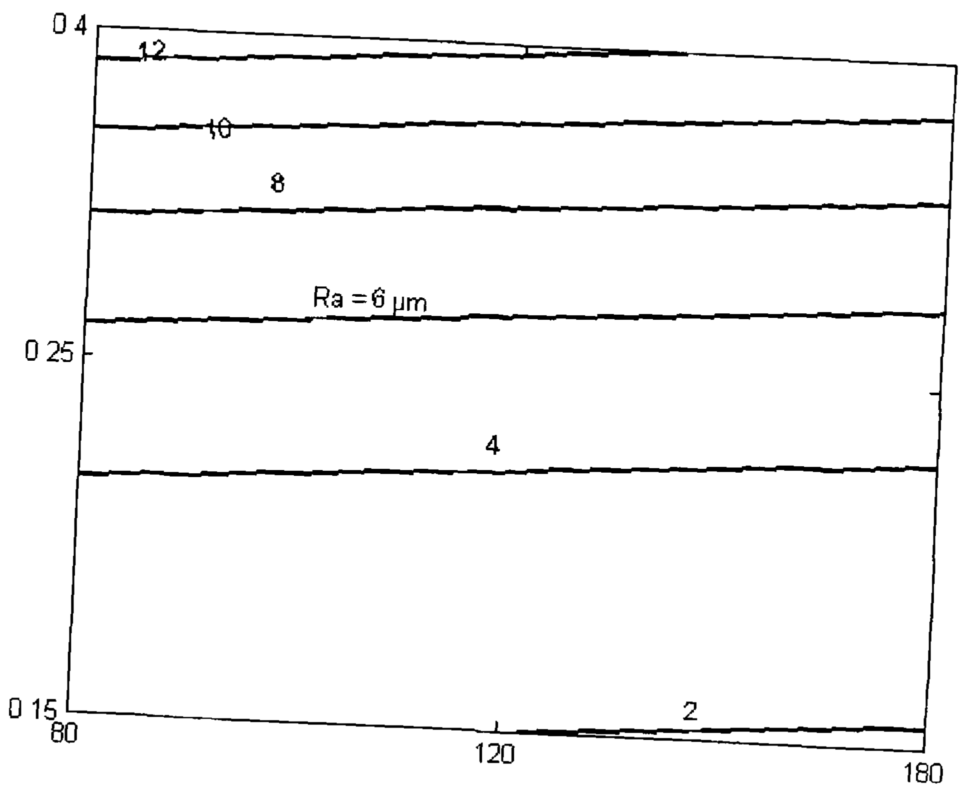


Figure 6 3 Surface roughness contours in velocity-feed planes at depth of cut of 1 00(mm)

6 3 1 1 Utilisation of the first-order surface roughness model at depth of cut of 1 00 mm

In order to reduce machining time (in order to achieve higher production rates) the feed rate and cutting speed should be as high as possible

It is possible to select a combination of feed and cutting speed that reduces machining time without increasing the surface roughness since there is a large number of possible combinations of cutting speed and feed that produces the same surface roughness This can be illustrated by surface roughness contours in cutting speed and feed planes at the selected levels of tool nose radius

This involves a further utilization of the model to include the rate of metal removal

The rate of metal removal Q (cm^3/min) is given by

$$Q = dfV \tag{6 14}$$

where d is the depth of cut (mm), f is the feed (mm/rev) and V is the cutting speed (m/min) Equation (6 14) can be written as

$$\ln Q = \ln d + \ln f + \ln V \tag{6 15}$$

For a specific depth of cut $d = 1\ 00$ mm, and using the transformation equation (6 15), x_1, x_2, x_3 may be written as follows

$$x_1 = \frac{\ln V - \ln 120}{\ln 180 - \ln 120}$$

$$x_2 = \frac{\ln f - \ln 0\ 25}{\ln 0\ 40 - \ln 0\ 25}$$

$$x_3 = \frac{\ln d - \ln 0\ 75}{\ln 1 - \ln 0\ 75}$$

Equation (6 15) can be presented as follows

$$\ln Q = 3\ 401197 + 0\ 405465\ x_1 + 0\ 470003\ x_2 \tag{6 16}$$

For a constant rate of metal removal, equation (6 16) can be represented as a series of straight lines, illustrated in Figure 6 4 This figure was obtained by superimposing the constant Q lines on the surface roughness contours in the speed feed plane, for depth of cut $d = 1\ 00\text{mm}$ However, cutting conditions that provide a higher rate of metal removal must be selected It is shown in Figure 6 4 that the selection of cutting conditions represented by point B is better than which was selected by point A This increase in material removal rate is obtained without any significant sacrifice in the quality of the produced surface

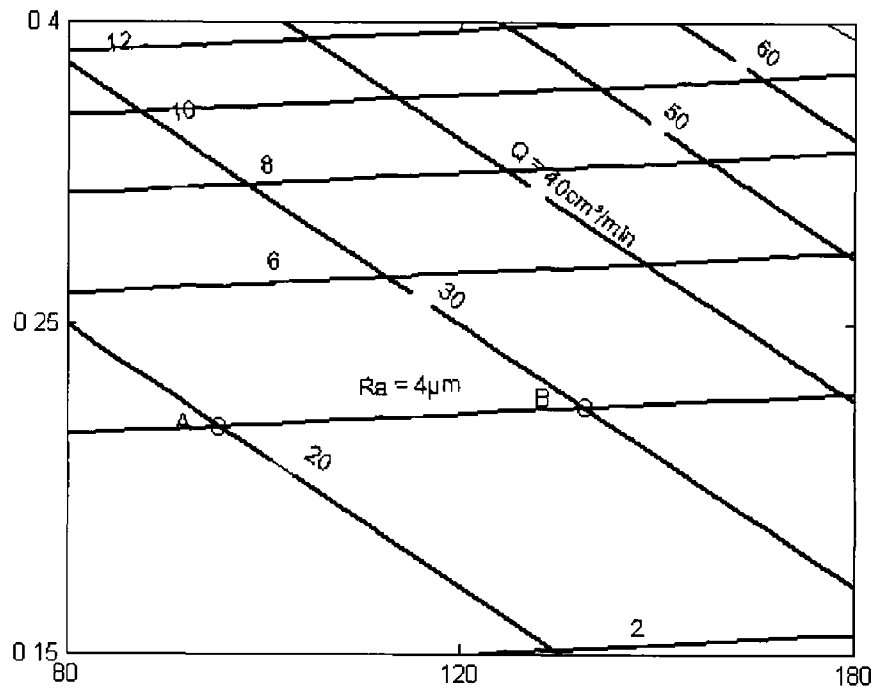


Figure 6 4 Response contours of surface roughness R_a and metal removal rate Q in a speed- feed plane at depth of cut 1 00mm

6.3.2 Analysis of results for various tool nose radius

The design is obtained by 2^3 which means that the three variables, (v, f, r), cutting speed (m/min), feed rate (mm/rev), nose radius (mm) have been used at three levels. Experiments were carried out using three types of inserts having different nose radius Those selected levels were chosen as low (r = 0.4 mm), centre (r = 0.8mm), and high (r = 1.6 mm).

(-) Level = lowest level values of the investigated variables

(+) Level = highest level value of the investigated variables

(0) Level = centre level value of the investigated variables.

A design consisting of 12 experiments has been carried out to develop the first order model.

The relationships between the code and independent variables are as follows:

$$x_1 = \frac{\ln V - \ln(v)_{centre}}{\ln(v)_{high} - \ln(v)_{centre}} \qquad \text{.......(6.17)}$$

$$x_2 = \frac{\ln F - \ln(f)_{centre}}{\ln(f)_{high} - \ln(f)_{centre}} \qquad \text{.......(6.18)}$$

$$x_3 = \frac{\ln(R) - \ln(r)_{centre}}{\ln(r)_{high} - \ln(r)_{centre}} \qquad \text{.......(6.19)}$$

level	low	center	High
coding	-1	0	1
Speed v	80	120	180
Feed f	0.15	0.25	0.40
Nose radius r	0.4	0.8	1.6

Table 6.3 Levels of independent variables for Steel 817

The ratio between the high and centre values must be similar to the ratio between the centre and low values for the all parameters as follows.

Cutting speed (m/min), $\frac{180}{120} = 1\ 5$ $\frac{120}{80} = 1\ 5$

Feed rate (mm/rev), $\frac{0\ 40}{0\ 25} = 1\ 6$ $\frac{0\ 25}{0\ 15} = 1\ 6$

Nose radius (mm), $\frac{1\ 6}{0\ 8} = 2$ $\frac{0\ 8}{0\ 4} = 2$

Trial No	Block No	Speed v m/min	Feed f mm/rev	Nose radius	Coding			Surface finish R_a
					x_1	x_2	x_3	
1	1	80	0 15	0 4	-1	-1	-1	2 4
2	2	180	0 15	0 4	1	-1	-1	2 3
3	2	80	0 40	0 4	-1	1	-1	12
4	1	180	0 40	0 4	1	1	-1	11 2
5	2	80	0 15	1 6	-1	-1	1	0 8
6	1	180	0 15	1 6	1	-1	1	0 6
7	1	80	0 40	1 6	-1	1	1	3 7
8	2	180	0 40	1 6	1	1	1	3 2
9	1	120	0 25	0 8	0	0	0	2 5
10	1	120	0 25	0 8	0	0	0	2 3
11	2	120	0 25	0 8	0	0	0	2 1
12	2	120	0 25	0 8	0	0	0	2 6

Table 6 4 Experiment conditions and results

The independent variables presented in the equations (6 17), (6 18) and (6 19) have been substituted by the values of cutting speed, feed rate and nose radius As a result, the equations are presented as follows

$$x_1 = \frac{\ln V - \ln 120}{\ln 180 - \ln 120}$$

$$x_1 = \frac{\ln V - 4\ 78749}{5\ 1929 - 4\ 78749}$$

$$x_1 = 2\ 466303 \ln V - 11\ 8074$$

$$x_2 = \frac{\ln f - \ln 0\ 25}{\ln 0\ 40 - \ln 0\ 25}$$

$$x_2 = \frac{\ln f - (-1\ 3862)}{(-0\ 91629) - (-1\ 3862)}$$

$$x_2 = 2\ 1276431 \ln f + 2\ 94953$$

$$x_3 = \frac{\ln r - \ln 0\ 8}{\ln 1\ 6 - \ln 0\ 8}$$

$$x_3 = \frac{\ln r - (-0\ 223143)}{0\ 470003 - (-0\ 223143)}$$

$$x_3 = 1\ 442695 \ln r + 0\ 32192809$$

The development of the first-order model used the central composite design with 12 experiments providing three levels for each independent variable as show in Table 6 3 For the first –order model of Block 1 (6 tests), the parameters in Table 6 4 were estimated, yielding the surface roughness predicting equation

$$y = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 \qquad (6\ 20)$$

The calculations were presented as Equation (6 20) for the first block of six trials (1, 4, 6, 7, 9 and 10) and second block 2 of six trials of (2, 3, 5, 8, 11, 12) The results are listed in Table 6 4 The procedure of the analysis of the block 2 tests were similar to that of block 1

Combining the results of all 12 tests, the fitted surface predicting equation was as below

$$y = 0\ 982780115 - 0\ 06805207 x_1 + 0\ 79976921 x_2 - 0\ 608960478 x_3 \qquad (6\ 21)$$

Substituting the values of x_1, x_2, x_3 in Equation (6 21) gives

$$y = 3\ 949201423 - 0\ 167837055 \ln V + 1\ 701620278 \ln f - 0\ 878544261 \ln r$$

$$y = \ln R_a = \ln C + k \ln V + \imath \ln f + m \ln r$$

$$C = e^{3\ 949201423} = 51\ 893909$$

The values for $k, \imath$ and m are

$k = 0\ 167837055,\ \imath = 1\ 701620278,\ m = 0\ 87854426$

$$R_a = 51\ 893909 V^{-0\ 167837055} f^{1\ 701620278} r^{-0\ 878544261} \qquad (6\ 22)$$

In this case the experiment was carried out at three selected levels of nose radius Those selected levels were chosen as low (0 4 mm) and centre (0 8 mm) and high (1 6 mm)

The cutting speed V and the feed rate f were graphed utilising the MATLAB computer package It can be seen from Figure 6 5, 6 6 and 6 7 that as the cutting speed increases, the roughness decreases and as the feed rate increases, the roughness increases However it was noticed that the nose radius has the most significant effect on surface finish

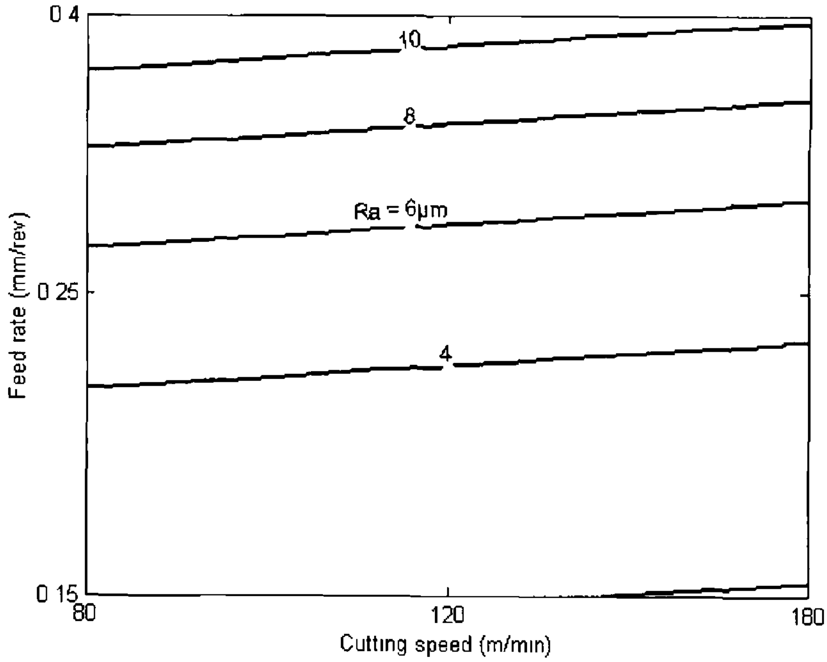


Figure 6 5, Surface roughness contours in cutting speed-feed planes at the selected levels of nose radius 0 40mm

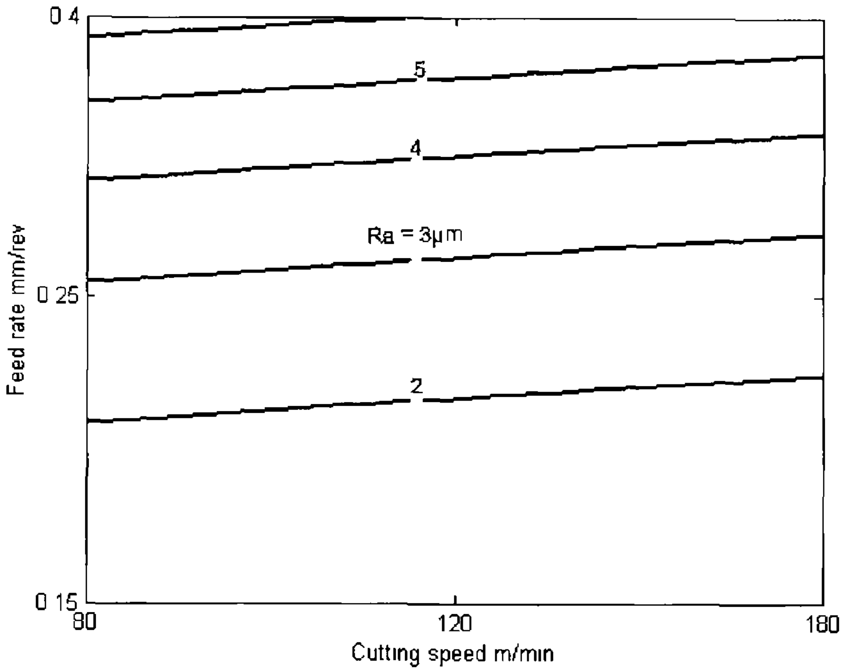


Figure 6 6 Surface roughness contours in cutting speed-feed planes at the selected levels of nose radius 0 8-mm

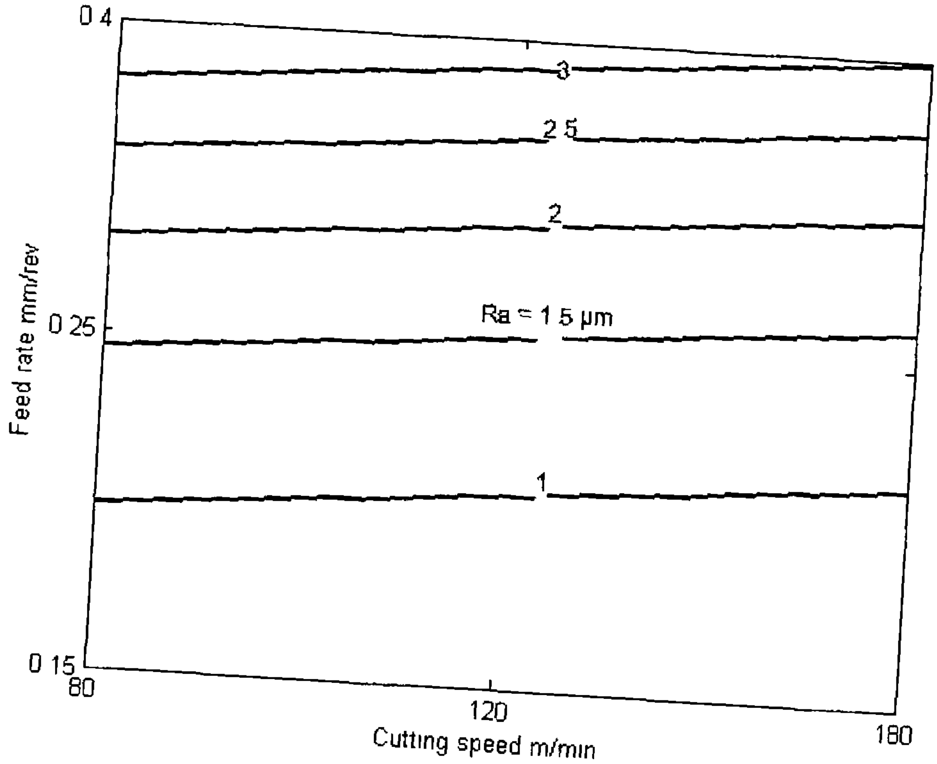


Figure 6 7 Surface roughness contours in cutting in cutting speed-feed planes at the selected levels of nose radius 1 6-mm

6 3 2 1 Utılızatıon of the first-order surface roughness model at nose radıus 0 8 mm

Constant rate of metal removal at dıfferent cuttıng condıtıons can be represented by straıght lınes as shown ın Fıgure 6 8 Thıs Fıgure was obtaıned usıng the MATLAB computer package The constant Q lınes (rate of metal removed) and R_a (the surface roughness) contours are shown ın the speed V, feed f plane, for r = 0 8 mm nose radıus and at d = 1 0 mm depth of cut In general, cuttıng condıtıons that provıde a hıgher rate of metal removal must be selected It ıs shown that the selectıons of cuttıng condıtıons represented by poınt B are better than those represented by poınt A Thıs ıncrease ın materıal removal rate ıs obtaıned wıthout any sacrıfıce ın the qualıty of the produced surface Thıs reduces the machınıng tıme, sınce the metal removal rate B ıs 50% greater than that of A By thıs experıment the cuttıng condıtıons, whıch gıve roughness as output, were known clearly For example the cuttıng condıtıons that gıve roughness of 3 μm was known

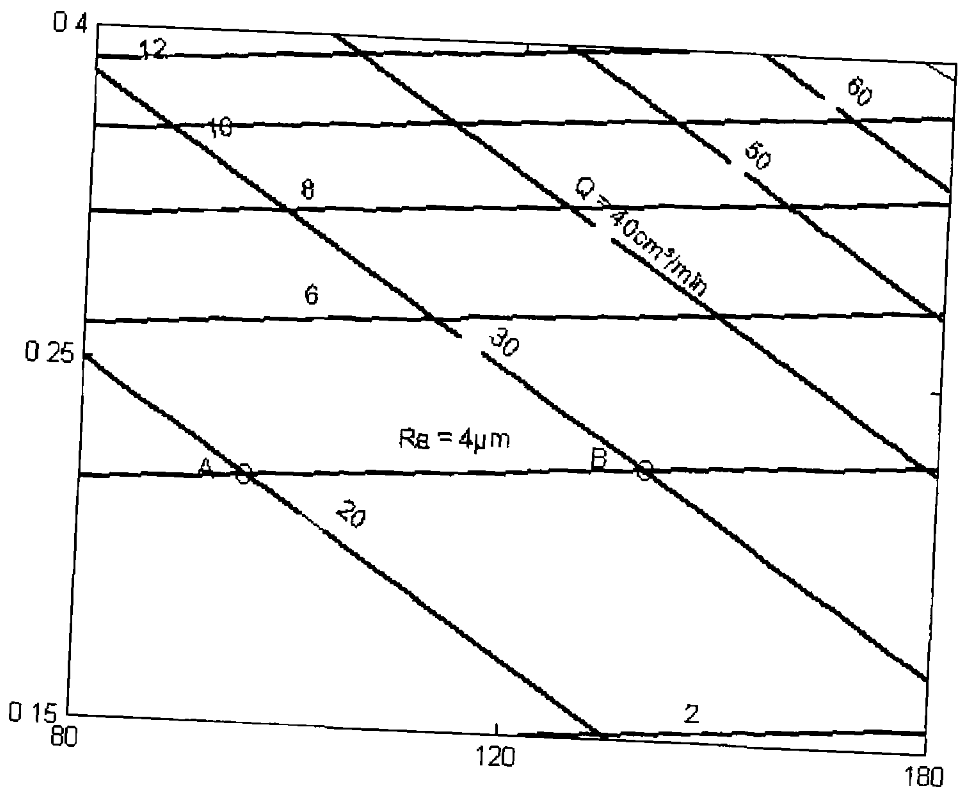


Figure 6 8 Contours of surface roughness R_a and metal removal Q in a speed-feed plane at r = 0 8 mm and d = 1 00 mm

6 4 Conclusions

a) Although the model has been developed and tested for very few experimental results, it can however be used to predict the surface quality for a range of conditions

b) Contours of the surface roughness outputs were obtained in planes containing two of the independent variables These contours were further analysed to select the proper combination of the cutting speed and feed to increase the metal removal rate without sacrificing the quality of the surface roughness produced

c) The response surface methodology provides a large amount of information with a small amount of experimentation

CHAPTER SEVEN: CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

7. Conclusions and Recommendations for Future Work.

7 1 Introduction

After the analysis of experimental results, the conclusions and recommendations for EN24T/817M40T steel are presented in this chapter Factors influencing machinability are reported A one variable at a time study and design of experiment approach are presented

7 2 One-variable-at-a-time

7.2.1 Cutting forces

a) Cutting forces can be divided into three components feed force (F_x), radial thrust force (F_y) and tangential cutting force (F_z) Usually the tangential cutting force is larger while the feed force is minimal

b) The cutting forces increase is almost linear with increase in feed rate and depth of cut

The principal cutting force was increased from $F = 442$ N, at feed rate $f = 0\ 1$ mm/rev, and depth of cut $d = 1\ 00$ mm, to cutting force of $F = 1063$ N, at feed $f = 0\ 4$ mm/rev and with same depth of cut The cutting force was increased from $F = 387$ N at depth of cut =0 5, feed 0 2 mm/rev to $F = 1920$ N at depth of cut $d = 3\ 5$ mm It was observed the depth of cut has the greatest effect on the cutting force

c) As the cutting speed increases the cutting force increases The greatest effect on the cutting force is depth of cut following by feed rate and cutting speed

7 2 2 Tool lıfe

a) Coated carbıde tools gıve a better performance than uncoated tools wıth respect to dıfferent cuttıng speed and feed rates

b) The tool lıfe sıgnıfıcantly ıncreased wıth the decrease ın cuttıng speed from 2 mınutes at cuttıng speed of 100 m/mın to 17 mınutes at cuttıng speed 80 m/mın for uncoated, and from 11 mınutes at a cuttıng speed of 100 m/mın to 43 mınutes at a cuttıng speed of 80 m/mın for coated carbıde As a result, the longest tool lıfe was obtaıned at a low cuttıng speed of 40 (m/mın), and low feed rate 0 20 mm/rev and depth of cut of 0 5 mm

c) The effect of cuttıng speed on tool lıfe ıs more pronounced than the effect of feed rate and depth of cut for coated and uncoated tools

d) Poor surface fınısh was produced after the flank wear of the ınsert reached 0 3 mm

e) In general, the coated carbıde tools gıve hıgher tool lıfe than the uncoated carbıde tools for ıdentıcal experımental condıtıons

7 2 3 Surface fınısh

a) Experıment were conducted at varıable feed rate of 0 2, 0 4 and 0 6 mm/rev and depth of cut of 0 5, 1 00, 1 5 mm When the feed rate was 0 6 mm/rev, the value of roughness was 16 µm When the feed rate was decreased to 0 2 mm/rev the value of roughness was decreased to 2 µm

b) As the feed rate ıncreases, the roughness values ıncrease so the best surface fınısh was obtaıned at low feed rates When the cuttıng speed ıncreases the roughness values decrease,so smooth surfaces were obtaıned at a hıgher speeds As the depth of cut ıncreases the surface fınısh shows hıgher wavıness The feed rate has the most sıgnıfıcant effect on surface fınısh so the surface fınısh can be ımproved by decreasıng the feed rate

7.3 Design of experiment

a) Although the model has been developed and tested from very few experimental results, it can be used to predict the surface quality for a range of conditions

b) Contours of the surface roughness outputs were obtained in planes containing two of the independent variables These contours were further developed to select the proper combination of the cutting speed and feed to increase the metal removal rate without sacrificing the quality of the surface produced

c) Response surface methodology provides a large amount of information with a small amount of experimentation

d) The roughness equation shows that the feed rate and nose radius are the main influencing factors on the surface finish following by cutting speed and depth of cut

e) The design of experiment procedure can be used to find the functional relationship between response (surface roughness, tool life, cutting force) of the cutting operation and the investigated independent variables (depth of cut, feed rate, cutting speed, temperature, rake angle etc) This can be represented by an equation of the following form

$$R = \alpha(v, f, d)$$

The response R could be tool life T in minutes, or surface roughness R_a in microns, or cutting forces F in Newtons However in this thesis R has been reported as surface roughness R_a The equation for roughness with different depth of cuts is

$$R_a = 137\ 42584(V^{-0\ 149308181} f^{1\ 8511799} d^{-0\ 0561896})$$

The equation for roughness with different nose radius values is

$$R_a = 51\ 893909(V^{-0\ 167837055} f^{1\ 701620278} r^{-0\ 878544261})$$

7.4 Cuttıng condıtıons

The recommended cuttıng speed for machınıng steel 817 wıth the specıfıed tools ıs 50-150 m/mın The feed range should be 0 10-0 25 mm/rev and the depth of cut should be 0 50-1 5 mm

7 5 Recommendatıons

a) Machınabıhty assessment of EN24T/817M40T steel ıs a fırst step towards the development of a database The use of dıfferent tool materıals and tool geometrıes may be useful to compare the varıatıons ın the surface roughness model and ınclude ıt ın the mathematıcal models

b) Wıth a vıew to developıng a comprehensıve computerısed machınabılıty data base system usıng mathematıcal models, a large quantıty of experımental data ıs requıred Thıs ıs necessary to valıdate the usefulness of a model

c) It would be helpful to ıdentıfy a model for a specıfıc hardness group of materıal and generalıze ıt for that hardness range

REFERENCE

1 Wılson M and El Baradıe M, "Machınıng hıgh strength materıals cobalt-base alloys", Proc 23rd Int machıne Tool Desıgn Research (MATADOR) Conference, UMIST, Manchester, pp171-182,Sept 1982

2 El Baradıe M and M Wılson, " Engıneerıng Technology Serıes (6) Metal Cuttıng and Machınabılıty" , (1983)

3 Wuyı Chen, "Cuttıng Forces and surface fınısh when machınıng medıum hardness steel usıng CBN tools", Journal of Machıne Tools vol 40, pp 455-466 , (2000)

4 Wang J , (2000), "The effect of the multı-layer surface coatıng of carbıde ınserts the cuttıng forces ın turnıng forces ın turnıng operatıons", Journal of Materıals Processıng Technology, vol 97, pp 114-119

5 Shane Y Hong and Yucheng Dıng, "Frıctıon and cuttıng forces ın cryogenıc machınıng of Tı-6A1-4V", Int J of Machıne Tools & Manufacture, Vol 41, pp 2271-2285, 2001

6 Noordın M Y and Venkatesh V C , "Performance evaluatıon of cemented carbıde tools ın turnıng AISI 1010 steel", Journal of Materıals Processıng Technology, Vol 116, pp 16-21, 2001

7 Wang J , "The effect of the multı-layer surface coatıng of carbıde ınserts on the cuttıng forces ın turnıng operatıons", Journal of Materıals processıng Technology, Vol 97, pp 114-119, 2000

8 Rahman M and Ramakrıshna S , "Machınabılıty study of carbon fıber reınforced composıte", Journal of Materıal Processıng Technology, Vol 89-90, pp 292-297,1999

9 Hocheng H and Yen S B , "Fundamental turnıng characterıstıcs of a trıbology-favored graphıte materıal" PII SI359-835, Vol 97, pp 00055-9,1997

10 Audy J and Strafford K N , C Subramanıan "The effıcıency of uncoated and coated tool systems ın the machınıng of low carbon steel assessed through cuttıng

force cutting measurements", Surface and Coatings Technology, Vol 76-77, pp 706-711,1995

11 Wang J and Mathew P , "Development of a general tool model for turning operations based on a variable flow stress theory", Int J Mech Tools Manufact,Vol 35, pp 71-90,1995

12 Masatoshi and Toru Fuse "Improved Machinability of Nitriding Steel (SACM 645)"Journal of Materials Processing Technology, Vol 62, pp 370-373,1996

13 Alauddin M and Mazid M A , "Cutting forces in the end milling of Inconel 718",Journal of Materials Processing Technology, Vol 77, pp 153-159,1998

14 Huang F Y and Chow H M , "The machinability of KOVAR material", Journal of Materials Processing Technology, Vol 87, pp 112-118,1999

15 Ozler L and A Inan A , "Theorectical and experimental determination of tool life in hot machining of austenitic manganese steel", Int J of Machine Tool & Manufacture, Vol 41, pp 163-172,2001

16 El Baradie M A , "The effect of Varying the workpiece diameter on the cutting tool clearance angle in tool-life testing",Wear,Vol 195, pp201-205,1996

17 Ghani A K and Choudhury I A , "Study of tool life surface roughness and vibration in machining nodular cart iron with ceramic tool", Journal of Materials Processing Technology,Vol 5718, pp 1-6,2002

18 Che-Haron, "Tool life and surface integrity in turning titanium alloy", Journal of Materials Processing Technology, Vol 118, pp 231-237,2001

19 Choudhury I A and El-Baradie M A "Machinability assessment of nickel based super alloys tool life in turning inconel-718",Current Advances in Mechanical Design & Production, Sixth Cairo University International MDP Conference, pp2-4, 1996

20 Joshi S S and Ramakrishnan N , "Wear of rotary carbide tools in machining of A1/SiCp composites", Wear, Vol 230, pp124-132,1999

21 Lın J T and Bhattacharyya D , "Machınabılıty of a sılıcon carbıde reınforced alumınıum metal matrıx composıte",Wear,Vol 181-183, pp 883-888,1995

22 Rahman M and Seah W KH , "The Machınıabılıty of Inconel 718", Journal of materıal processıng Technology, Vol 63, pp 199-204,1997

23 Ferreıra J R and Coppını N L , "Characterıstıcs of carbon composıte turnıng", Journal of Materıals Processıng Technology, Vol 109, pp 65-71,2001

24 Zone Chıng and Dın Yan Chen, "A study of cuttıng wıth a CBN tool", Journal of Materıals Processıng Technology, Vol 49, pp 149-146, 1995

25 Haron C H and Gıntıng A , J H , "Wear of coated and uncoated carbıdes ın turnıng tool steel", Journal of Materıals Processıng Technology, Vol 116, pp 49-54,2001

26 Ezugwu E O ,Wang Z M , "Tıtanıum alloys and theır machınabılıty-a revıew",Journal of Materıals Processıng Technology, Vol 68, pp 262-274, 1997

27 Astakhov V P and Osman M O M , "Correlatıons amongst process parameters ın metal cuttıng and theır use for establıshıng the optımum cuttıng speed", Journal of Materıals Processıng Technology, Vol 62, pp175-179,1996

28 Rahman M and Ramakrıshna S , "Machınabılıty study of carbon fıber reınforced composıte", Journal of Materıals Processıng Technology, Vol 89-90, pp292-297,1999

29 Che-Haron C H , "Tool lıfe and surface ıntegrıty ın turnıng tıtanıum alloy", Journal of Materıals Processıng Technology, Vol 118, pp 231-237,2001

30 Thomas M and Beauchamp, "Effect of vıbratıons on surface roughness durıng lathe dry turnıng process",Computers ınd, Vol 31, pp 637-644,1996

31 Yves Beauchamp and Marc Thomas, "Investıgatıon of cuttıng parameter effects on surface roughness ın lathe borıng operatıon by use of a full factorıal desıgn",computers ınd Eng, Vol 31, pp 645-651, 1996

32 Jeong and Youn, "Hıgh speed machınıng of alumınıum usıng dıamond endımlls",Int J Mach Tools Maufact Vol 37, pp 1155-1165, 1997

33 Gıllıbrand D and Savrwar M , “The economıc benefıt of fınısh turnıng wıth coated carbıde”,Surface and coatıng Technology, Vol 86-87, pp 809-813, 1996

34 Paulo Davım J , “A note on the determınatıon of optımal cuttıng condıtıons for surface fınısh obtaıned ın turnıng usıng desıgn of experıments”, Journal of Materıals Processıng Technology, Vol 116, pp 305-308, 2001

35 Mashal Y A H , “the machınabılıty and trıbologıcal characterıstıcs of alumınum alloys wıth ımproved elevated temperature propertıes usıng rapıdly solıdıfied powder”, Wear, Vol 250, pp518-528, 2001

36 Choudhury I A and El-Baradıe M A , “Machınabılıty assessment of ınconel 718 by factorıal desıgn of experıment coupled wıth response surface methodology”, Journal of Materıals Processıng Technology, Vol 95, pp 30-39, 1999

37 Suresh P V S and Venkateswara P , “A genetıc algorıthmıc approach for optımızatıon of surface roughness predıctıon model”, Int J of Machıne Tool & Manufacture, Vol 42, pp 675-680, 2002

38 Choudhury I A and El-Baradıe M A , “Tool-lıfe predıctıon model by desıgn of experıments for turnıng hıgh strength steel (290 BHN)”, Journal of Materıals Processıng Technology, Vol 77, pp 319-326, 1998

39 Alauddın M and El-Baradıe M A , “Computer-aıded analysıs of a surface-roughness model for end mıllıng”, Journal of Materıals Processıng Technology, Vol 55, pp123-127, 1995

40 Alauddın M and El Baradıe M A , “Tool lıfe model for end mıllıng steel (190BHN)”, Journal of Materıals Processıng Technology, Vol 68, pp 50-59, 1997

41 Munoz-Escalona P and Cassıer Z , “Influence of the crıtıcal cuttıng speed on the surface fınısh of turned steel”, Wear, Vol 218, pp103-109, 1998

42 Juneja B L,Sekhon G S, “ Fundamentals of Metal Cuttıng and Machıne Tools” ,1987

43 B P Tradıng lımıted Brıtannıc House, “Machıne Tool Metals and Cuttıng fluıd BP”

44 Shaw M C , "Metal Cuttıng Prıncıples", Oxford Unıversıty Press, New York 1986

45 Wılson M and El Baradıe M A , " Cuttıng Tool Wear and Faılure Mechanısms ",Proc of the Fırst Irısh Durabılıty and Fracture Conference (IDFCI), pp289-303,Trınıty College, Dublın, 1983

46 Brıtısh Standard Specıfıcatıon, " Tool-lıfe testıng wıth sıngle-poınt tunıng tools", BS 5623, 1979

47 Nıcolls M O , "The measurement of surface fınısh", De Beers Technıcal Servıce Centre, UK

48 Kıstler three Component Dynamometer Type 9265, Pıezo-Instrumentatıon Kıstler, Kıstler Instruments Ltd

49 Kıstler Charge Amplıfıer Type 5011, Pıezo-Instrumentatıon Kıstler, Kıstker Instrumentatıon Ltd

50 Surface Roughness Tester operatıon Manual, Surftest 402 Serıes 178, Manual No 4358, Mıtutoyo Corporatıon

51 Metalworkıng Products, "Turnıng tools", Sandvık Coromant

52 Charles R Hıcks "Fundamental Concepts ın the Desıgn of Experıments", 3th, Saunders College Publıshıng, Holt, Rınehart and Wınston, 1982

A APPENDIX TABLES OF CUTTING FORCE VALUES

Table A 1 Shows the main value of cutting forces and maximum and minimum deviation of cutting forces at feed rate of 0 50 (mm/rev [1]) and depth of cut of 0 50 (mm)

Cutting speed (m/min)	Feed Rate (mm/re)	Depth of cut (mm)	Cutting forces(N)								
			F_x			F_y			F_z		
			Main value of F_x	Upper	Lower	Main value of F_y	Upper	Lower	Main Deviati on of F_z	Upper	Lower
50	0 10	0 50	99 09	±2 05%	±1 64	146 71	±3 85%	±2 14%	228 05	±3 32 %	±2 01%
100	0 10	0 50	105 65	±3 50%	±1 15	148 67	±1 75%	±1 52%	203 98	±4 13 %	±0 20%
150	0 10	0 50	114 08	±3 91%	±2 50	174 92	±2 27%	±0 26%	212 95	±1 13 %	±1 36%
200	0 10	0 50	110 21	±1 83%	±1 51	174 93	±1 87%	±1 38%	204 09	±2 61 %	±0 99%
250	0 10	0 50	115 56	±3 71%	±1 94	165 31	±4 99%	±2 61%	200 37	±1 58 %	±1 24%

Table. A.2 Shows the main values of cutting forces and maximum and minimum deviation of cutting forces at feed rate of 0.10 (mm/rev^{-1}), and depth of cut of 1.00 (mm).

Cutting speed (m/min)	Feed Rate (mm/rev)	Depth of cut (mm)	Cutting forces(N)								
			F_x			F_y			F_z		
			Main value of F_x	Upper	Lower	Main value of F_y	Upper	Lower	Main value of F_z	Upper	Lower
50	0.10	1.00	91.48	±1.99%	±0.94%	236.01	±1.45%	±1.04%	321.18	±0.35%	±0.28%
100	0.10	1.00	92.04	±3.58%	±1.12%	257.57	±3.05%	±3.05%	319.51	±3.65%	±3.15%
150	0.10	1.00	106.13	±4.64%	±2.12%	285.92	±1.09%	±0.81%	328.92	±2.08%	±2.78%
200	0.10	1.00	109.01	±3.81%	±2.29%	283.63	±0.95%	±0.82%	320.88	±1.74%	±1.06%
250	0.10	1.00	217.94	±3.02%	±3.02%	301.28	±3.23%	±1.66%	330.41	±1.21%	±0.97%

Table A 3 Shows the maın values of cuttıng forces and maxımum and mınımum deviatıon of cuttıng forces at feed rate of 0 10 (mm/rev^{-1}) and depth of cut of 1 50 (mm)

Cuttıng Speed (m/mın)	Feed Rate (mm/rev)	Depth of cut (mm)	Cuttıng forces(N)								
			F_x			F_y			F_z		
			Maın value of F_x	Upper	Lower	Maın value of F_y	Upper	Lower	Maın value of F_z	Upper	Lower
50	0 10	1 50	108 15	±1 84%	±1 76%	351 64	±2 61%	±1 72%	467 44	±1 88%	±1 74%
100	0 10	1 50	108 72	±1 51%	±0 34%	337 52	±0 86%	±0 67%	439 42	±1 03%	±0 77%
150	0 10	1 50	119 96	±2 44%	±1 62%	372 69	±4 11%	±2 35%	444 52	±2 01%	±0 76%
200	0 10	1 50	131 44	±3 93%	±3 55%	369 35	±1 51%	±0 92%	427 94	±2 09%	±1 85%
250	0 10	1 50	131 59	±0 49%	±0 33%	358 81	±1 16%	±0 56%	410 32	±1 22%	±0 68%

Table A 4 Shows the main values of cutting forces and maximum and minimum deviation of cutting forces for feed rate of 0 20 (mm/rev^{1}) and depth of cut of 0 50 (mm)

Cutting speed m/min	Feed Rate mm/rev	Depth of cut mm	Cutting forces(N)								
			F_x			F_y			F_z		
			Main value of F_x	Upper	Lower	Main value of F_y	Upper	Lower	Main value of F_z	Upper	Lower
50	0 20	0 50	138 86	±4 00%	±2 26%	191 06	±3 31 %	±2 16%	337 09	±2 45%	±2 29%
100	0 20	0 50	146 54	±1 03%	±0 95%	183 27	±1 20 %	±0 99%	317 11	±0 98%	±0 73%
150	0 20	0 50	159 92	±3 53%	±2 04%	185 85	±2 70 %	±1 88%	307 35	±1 01%	±0 80%
200	0 20	0 50	172 67	±4 03%	±2 43%	183 51	±3 30 %	±2 32%	303 35	±0 62%	±0 36%
250	0 20	0 50	187 55	±1 06%	±0 92%	186 29	±1 84 %	±2 16%	300 93	±1 71%	±1 57%

Table A 5 Shows the main values of cutting forces and maximum and minimum deviation of cutting forces at feed rate of 0 20 (mm/rev [1]) and depth of cut of 1 00 (mm)

Cutting speed m/min	Feed Rate mm/rev	Depth of cut mm	Cutting forces(N)								
			F_x			F_y			F_z		
			Main value of F_x	Upper	Lower	Main value of F_y	Lower	Upper	Main value of F_z	Upper	Lower
50	0 20	1 00	154 19	±1 48%	±0 85%	343 21	±2 64%	±4 01%	579 58	±1 69%	±1 34%
100	0 20	1 00	140 42	±1 79%	±1 45%	327 17	±2 29%	±2 63%	530 78	±1 22%	±0 75%
150	0 20	1 00	160 31	±3 64%	±2 96%	338 57	±5 01%	±4 61%	531 87	±1 12%	±1 05%
200	0 20	1 00	184 21	±2 22%	±1 59%	342 54	±3 91%	±3 31%	525 23	±1 14%	±0 14%
250	0 20	1 00	185 48	±3 10%	±2 29%	329 74	±2 30%	±1 55%	521 67	±4 53%	±3 47%

Table A 6 Shows the main values of cutting forces and maximum and minimum deviation of cutting forces at feed rate of 0 20 (mm/rev [1]) and depth of cut of 1 50 (mm)

Cutting speed m/min	Feed Rate mm/rev	Depth of cut mm	Cutting forces(N)								
			F_x			F_y			F_z		
			Main value of F_x	Upper	Lower	Main value of F_y	Upper	Lower	Main value of F_z	Upper	Lower
50	0 20	1 5	170 71	±1 07%	±1 01%	466 18	±1 07%	±0 82%	778 97	±2 14%	±1 42%
100	0 20	1 5	177 88	±2 31%	±2 26%	464 45	±1 91%	±1 40%	761 83	±4 08%	±3 53%
150	0 20	1 5	193 71	±2 32%	±1 24%	458 58	±0 42%	±0 35%	733 57	±0 20%	±0 17%
200	0 20	1 5	194 97	±0 77%	±0 58%	453 35	±2 12%	±2 12%	713 64	±2 28%	±1 19%
250	0 20	1 5	182 25	±4 39%	±2 61%	431 33	±1 80%	±1 24%	677 00	±2 41%	±3 25%

Table.A. 7 Shows the main values of cutting forces and maximum and minimum deviation of cutting forces at feed rate of 0.30 (mm/rev^{-1}) and depth of cut of 0.50 (mm)

Cutting speed m/min	Feed Rate mm/rev	Depth of cut mm	Cutting forces(N)								
			F_x			F_y			F_z		
			Main value of F_x	Upper	Lower	Main value of F_y	Upper	Lower	Main value of F_z	Upper	Lower
50	`0.30	0.50	202.08	±2.97%	±1.73%	197.0	±2.78%	±2.53%	447.21	±3.07%	±2.73%
100	0.30	0.50	196.98	±1.08%	±0.76%	211.3	±2.73%	±3.56%	452.72	±1.80%	±1.54%
150	0.30	0.50	203.18	±1.62%	±1.32%	183	±2.30%	±2.03%	412.66	±1.33%	±1.04%
200	0.30	0.50	206.53	±2.29%	±2.17%	174.3	±2.31%	±1.6%	398.61	±4.86%	±2.51%
250	0.30	0.50	199.37	±1.61%	±0.92%	158.3	±4.92%	±4.81%	369.57	±4.41%	±3.79%

Table. A.8 Show the main values of cutting forces and maximum and minimum deviation of cutting forces at feed rate of 0.30 (mm/rev^{-1}) and depth of cut of 0.100 (mm)

Cutting speed m/min	Feed Rate mm/rev	Depth of cut (mm)	Cutting forces(N)								
			F_x			F_y			F_z		
			Main value of F_x	Upper	Lower	Main value of F_y	Upper	Lower	Main value of F_z	Upper	Lower
50	`0.30	1.00	91.48	±1.57%	±0.86%	441.60	±1.02%	±0.76%	831.91	±0.79%	±0.51%
100	0.30	1.00	92.04	±1.56%	±1.36%	402.15	±0.79%	±0.48%	772.34	±0.61%	±0.33%
150	0.30	1.00	106.13	±3.43%	±2.41%	387.79	±2.14%	±1.79%	770.63	±2.56%	±1.43%
200	0.30	1.00	109.01	±2.29%	±2.18%	366.21	±1.09%	±0.97%	743.99	±2.96%	±1.65%
250	0.30	1.00	217.94	±1.67%	±1.21%	390.89	±3.87%	±3.50%	746.62	±1.86%	±1.26%

Table A 9 Shows the main values of cutting forces and maximum and minimum deviation of cutting forces for feed rate of 0 30 (mm/rev [1]) and depth of cut of 1 50 (mm)

Cutting speed m/min	Feed Rate mm/rev	Depth of cut mm	Cutting forces(N)								
			F_x			F_y			F_z		
			Main value of F_x	Upper	Lower	Main Deviati on of F_y	Upper	Lower	Main value of F_z	Upper	Lower
50	`0 30	1 5	255 87	±1 99%	±1 31%	633 66	±3 08%	±1 68%	1184 6	±2 38%	±1 51%
100	0 30	1 5	272 37	±0 60%	±0 50%	572 05	±2 41%	±1 88%	1078 5	±1 21%	±1 15%
150	0 30	1 5	285 38	±1 44%	±0 91%	569 71	±0 47%	±0 31%	1067 1	±0 36%	±0 28%
200	0 30	1 5	277 27	±0 31%	±0 24%	544 61	±1 74%	±1 36%	1029 0	±2 62%	±1 53%
250	0 30	1 5	281 41	±1 62%	±1 39%	526 87	±0 52%	±0 51%	1036 1	±0 53%	±0 41%

Table A 10 shown prıncıpal cuttıng forces at varıable feed rate of (0 10, 0 20, 0 30) mm/rev and constant depth of cut of 0 50

Cuttıng speed (m/mın)	Depth of Cut (mm)	Prıncıpal cuttıng force F (N)		
		f = 0 10	f = 0 20	f = 0 30
50	0 50	284 982	408 461	531 2869
100	0 50	280 287	393 7445	535 364
150	0 50	297 309	391 0733	496 259
200	0 50	287 703	387 63	473 318
250	0 50	221 469	400 8421	451 233

Table A 11 shown prıncıpal cuttıng forces at varıable feed rate of (0 10, 0 20, 0 30) mm/rev and constant depth of cut of 1 00 mm

Cuttıng speed (m/mın)	Depth of Cut (mm)	Prıncıpal cuttıng force F (N)		
		f = 0 10	f = 0 20	f = 0 30
50	1 00	408 73	694 86	878 77
100	1 00	420 44	638 09	895 77
150	1 00	447 14	649 43	899 89
200	1 00	442 83	653 28	849 26
250	1 00	465 31	638 21	875 15

Table A 12 shown pmncipal cuttmg forces at vanable feed rate of (0 10, 0 20, 0 30) mm/rev and constant depth of cut of 1 5mm

Cuttmg speed (m/mm)	Depth of Cut (mm)	Pmncipal cuttmg force F (N)		
		f = 0 10	f = 0 20	f = 0 30
50	1 50	597 15	918 56	1347 11
100	1 50	567 65	906 56	1238 23
150	1 50	612 72	886 63	1241 09
200	1 50	577 37	861 27	1186 45
250	1 50	559 92	828 95	1195 97

Table A 13 shown pmncipal cuttmg forces at vanable cuttmg speed (0 10, 0 20, 0 30) mm/rev and constant depth of cut of 1 00mm

Feed rate (mm/rev ^{1})	Depth of cut (mm)	Pmncipal cuttmg force F (N)		
		Cuttmg speed =100 (m/mm)	Cuttmg speed =150 (m/mm)	Cuttmg speed =200 (m/mm)
0 1	1 00	420 44	447 14	442 83
0 2	1 00	638 09	649 43	653 28
0 3	1 00	895 77	899 89	849 26
0 4	1 00	1049 78	1063 56	1003 44

Table A 14 shown principal cutting forces at variable cutting speed (0 10, 0 20, 0 30) mm/rev and constant feed rate of 0 20 mm/rev

Depth of cut (mm)	Feed rate (mm/rev 1)	Principal cutting force F (N)		
		Cutting speed = 100 (m/min)	Cutting speed =150(m/min)	Cutting speed =200(m/min)
0 5	0 20	393 74	391 07	387 63
1	0 20	638 09	649 43	653 28
1 5	0 20	906 56	886 63	861 27
2	0 20	1162 42	1134 62	1130 98
2 5	0 20	1354 66	1415 54	1416 34
3	0 20	1680 85	1664 43	1653
3 5	0 20	1920 41	1910	1779 09

B APPENDICES TABLES OF ROUGHNESS VALUES

Table B 1 shown values of roughness at varıable feed rate 0 20, 0 40, 0 6 mm/rev and constant depth of cut of 0 50 mm

No	Velocıty m/mın	Feed mm/ rev	Depth of cut mm	Roughness µm
1	50	0 2	0 5	2 45
2	100	0 2	0 5	2 4
3	150	0 2	0 5	2 4
4	200	0 2	0 5	2 45
5	50	0 4	0 5	7 45
6	100	0 4	0 5	7 55
7	150	0 4	0 5	7 4
8	200	0 4	0 5	7 5
9	50	0 6	0 5	13 1
10	100	0 6	0 5	13 35
11	150	0 6	0 5	13 1
12	200	0 6	0 5	13

Table B 2 shown values of roughness at variable feed rate of 0 20, 0 40, 0 6-mm/rev and constant depth of cut of 1 00 mm

No	Velocity mm/min	Feed mm/rev	Depth of cut mm	Roughness µm
1	50	0 2	1 0	2 5
2	100	0 2	1 0	2 5
3	150	0 2	1 0	2 5
4	200	0 2	1 0	2 5
5	50	0 4	1 0	7 86
6	100	0 4	1 0	7 8
7	150	0 4	1 0	7 825
8	200	0 4	1 0	7 8
9	50	0 6	1 0	14 3
10	100	0 6	1 0	15 9
11	150	0 6	1 0	15 275
12	200	0 6	1 0	14 35

Table B 3 shown values of roughness at vanable feed rate of 0 20, 0 40, 0 6-mm/rev and constant depth of cut of 1 50 mm

No	Velocity m/mın	Feed mm/ rev	Depth of cut mm	Roughness µm
1	50	0 2	1 5	2 95
2	100	0 2	1 5	2 7
3	150	0 2	1 5	2 75
4	200	0 2	1 5	2 8
5	50	0 4	1 5	7 85
6	100	0 4	1 5	7 45
7	150	0 4	1 5	7 6
8	200	0 4	1 5	7 65
9	50	0 6	1 5	16 275
10	100	0 6	1 5	16 65
11	150	0 6	1 5	15 3
12	200	0 6	1 5	17 52

TableB 4 shown values of roughness at varıable depth of cut of 0 50, 1 00, 1 50 mm and constant feed rate of 0 20 mm/rev

No	Velocıty m/mın	Feed mm/ rev	Depth of cut mm	Roughness µm
1	50	0 2	0 5	2 45
2	100	0 2	0 5	2 4
3	150	0 2	0 5	2 4
4	200	0 2	0 5	2 45
5	50	0 2	1 00	2 55
6	100	0 2	1 00	2 55
7	150	0 2	1 00	2 6
8	200	0 2	1 00	2 5
9	50	0 2	1 5	2 95
10	100	0 2	1 5	2 7
11	150	0 2	1 5	2 75
12	200	0 2	1 5	2 8

Table B 5 shown values of roughness at variable depth of cut of 0 50, 1 00, 1 50 mm and constant feed rate of 0 40 mm/rev

No	Velocity m/min	Feed mm/ rev	Depth of cut mm	Roughness µm
1	50	0 4	0 5	7 45
2	100	0 4	0 5	7 55
3	150	0 4	0 5	7 4
4	200	0 4	0 5	7 5
5	50	0 4	1 00	7 86
6	100	0 4	1 00	7 8
7	150	0 4	1 00	7 825
8	200	0 4	1 00	7 8
9	50	0 4	1 5	7 85
10	100	0 4	1 5	7 45
11	150	0 4	1 5	7 6
12	200	0 4	1 5	7 65

Table B 6 shown values of roughness at variable depth of cut of 0 50, 1 00, 1 50 mm and constant feed rate of 0 60 mm/rev

No	Velocity m/min	Feed mm/ rev	Depth of cut mm	Roughness μm
1	50	0 6	0 5	13 1
2	100	0 6	0 5	13 35
3	150	0 6	0 5	13 1
4	200	0 6	0 5	13
5	50	0 6	1 00	14 3
6	100	0 6	1 00	15 9
7	150	0 6	1 00	15 275
8	200	0 6	1 00	14 35
9	50	0 6	1 5	16 275
10	100	0 6	1 5	16 65
11	150	0 6	1 5	15 3
12	200	0 6	1 5	17 52