Machinability Studies of High Strength Materials and the Development of A Data Base System

by

Imtiaz Ahmed Choudhury *B Sc Eng , M Eng , M S*

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Name of the Supervisor Dr M A El-Baradie

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In the Name of God The Compassionate the Merciful

Dedicated to

my Mother and late Father

DECLARATION

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of *Doctor of Philosophy* 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 I Choudhury   ID No 92700063

Imtiaz Ahmed Choudhury

Date December 11, 1995

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AUTHOR

The author received his B Sc in mechanical engineering from the Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh in the year 1977 After graduation, he was in the same department as a teaching assistant for a period of six months Then the author joined the Titas Gas (Natural gas) Transmission and Distribution, Dhaka and was there until June 1978 He was then employed overseas for about three years In the year 1982, the author joined as a lecturer in the Department of Mechanical Engineering of Rajshahi Engineering College (Presently known as Bangladesh Institute of Technology (BIT), Rajshahi) and was promoted to Assistant Professor In 1985, the author went to Asian Institute of Technology (AIT), Thailand for higher degree on a scholarship He received M Eng in Energy Technology in August 1986 and returned to his job at BIT, Rajshahi The author received a research assistantship again from the Arizona State University, USA in 1990 and completed his M S in mechanical engineering in the year 1992 Since March 1993, the author have been pursuing his Ph D study in the Dublin City University and awarded a studentship

ABSTRACT

Machinability assessment of two high strength materials were carried out using uncoated and coated carbide tool inserts The materials investigated were EN24T steel (290 BHN) and inconel 718 (415-444 BHN) The objectives of these investigation were to generate cutting data in relation to the machining responses i e , tool life, surface roughness, and cutting forces The cutting tests were carried out using one-variable-at-a-time and design of experiments

For one-variable-at-a-time experiment, cutting forces and tool life were measured In these tests, the cutting variables i e , cutting speed, feed rate, and depth of cut were varied to study their effects on the tool life and cutting forces The different tool life exponents of the extended Taylor's tool life equation were determined graphically With the design of experiments, the combined effects of the cutting variables were investigated on the machining responses

The experimental data based on the design of experiments were analyzed by the response surface methodology, statistical regression packages, and sequential estimation techniques Various mathematical models were developed using these techniques The adequacy of each model was judged by statistical analysis

Using the mathematical models of different responses, a computerized machinability data base system was developed to facilitate the optimum selection of cutting parameters The selection of cutting parameters is applicable for EN24T steel and inconel 718 only However, the data base could be extended to incorporate different work materials and tool combinations

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NOMENCLATURE

α	augment length
$\mathbf{b}$	matrix of the parameter estimates
BHN	Brinell hardness number
β	parameter to be estimated
d	depth of cut (mm)
ϵ	experimental error
f	feed rate (mm/rev)
F_x	axial (feed) force
F_y	radial force
F_z	tangential force
F	resultant cutting force
KT	crater depth (mm)
MPa	mega pascals
μ_β	parameter vector known from prior information
n	number of observations
n_1	speed exponent
n_2	feed exponent
n_3	depth of cut exponent
N	unit of force (newton)
p	number of parameters
ψ	covariance matrix of the errors
$\mathbf{P}$	covariance matrix of estimates
Q	metal removal rate (cm^3/min)
R_a	observed arithmetic average surface roughness (μm)
$\hat{R}_a$	predicted surface roughness (μm)
t	t- distribution statistics
T	tool life (minutes)
$\hat{T}$	predicted tool life (minutes)
T	charge amplifier sensitivity
V	cutting speed (m/min)
VB_B	average width of flank wear (mm)

VB_N	width of notch wear (mm)
$\mathbf{V}_\beta$	covariance matrix of $\boldsymbol{\mu}_\beta$
$\mathbf{x}$	matrix of independent machining variables
$\mathbf{x}^T$	transpose of $\mathbf{x}$
$(\mathbf{x}^T\mathbf{x})^{-1}$	inverse of the matrix $(\mathbf{x}^T\mathbf{x})$
x_1	coded variable (speed)
x_2	coded variable (feed)
x_3	coded variable (depth of cut)
y	observed logarithmic response (tool life, surface roughness, or cutting force)
$\hat{y}$	predicted response in logarithmic scale
$(y - \hat{y})$	residuals
$\mathbf{y}$	$(n \times 1)$ vector of observations on y

CHAPTER 1

INTRODUCTION

The basic requirements for the automation of the process planning and numerical control programming functions in computer integrated manufacturing (CIM) systems are the machinability data base systems The data base systems provide the information needed for the automatic selection of machining data and this has become an important component in the implementation of CIM With the growing need for industrial production automization and increasing use of expensive machine tools, the need of industry for actual and optimized data is increasing so that these machine tools can be utilized and used economically The increased application of computer aided manufacturing (CAM) to machining operations by the use of CNC machine tools has enhanced the need for the development a machinability data base systems

The need for selection of machine tools, the determination of optimized cutting data and the selection of tools and cutting materials are main problems in planning machining conditions Many researchers in this regard have suggested a machinability data base systems 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 optimization algorithm

The main objectives of this research study are

1— Generation and analysis of cutting test data for high strength EN24T steel of hardness 290 BHN

2— Generation and analysis of cutting tests data for a nickel base super alloy, inconel 718

3— Development of mathematical models for steel and inconel, using different statistical regression model building techniques

4— Development of a computerized machinability data base system

The work programme of this project is outlined in the following diagram

Machinability Studies / Data Base Systems

Work-material	Steel EN24T (290 BHN)	Nickel-base Alloy (Inconel 718)
Experimental investigation	One-variable-at-a-time - Cutting force - Tool life	One-variable-at-a-time - Cutting force - Tool life
- Cutting Tool	- Uncoated carbide	- Uncoated carbide - Coated carbide
	Design of experiments - Cutting force - Tool life - Surface finish	Design of experiments - Cutting force - Tool life - Surface finish
- Cutting Tool	- Uncoated carbide	- Uncoated carbide - Coated carbide
Model building	- Regression by ordinary least square - Statistical regression techniques - Sequential estimation	- Regression by ordinary least square - Statistical regression techniques - Sequential estimation
Data Base	Output (Recommended cutting conditions)	

Chapter 2 titled literature survey gives a general introduction to nickel base super alloys and their applications It also covers the literature survey of the following two main areas i e , i) high strength materials, focusing mainly on the machinability of inconel and ii) machinability data base systems

While Chapter 3 on the machinability of nickel base super alloys, gives a general discussion on the machinability assessment and the factors affecting machinability The machinability parameters i e tool life, surface roughness, and cutting forces generally investigated in the machinability of a material are discussed Also, the different cutting tools and their application in relation to the turning of inconel have been discussed

The development of machinability models are presented in Chapter 4 It includes an analysis for developing mathematical models using response surface methodology The different regression model building techniques i e , i) backward elimination, ii) stepwise regression, iii) forward selection, and iv) all possible subset regression for developing mathematical models are also discussed

Also, another different technique known as, sequential estimation technique, which can be used for building model equations is also discussed in this chapter

The experimental facilities are described in Chapter 5, in which the experimental set-up used for the cutting tests are outlined These include the description of Kistler 3-component dynamometer, surface roughness tester, and tool maker's microscope The chemical and mechanical properties of the work materials used for the tests are presented The cutting tool material and tool geometry are also described

Chapter 6 covers the experimental results based on one-variable-at-a-time for EN24T steel and inconel 718 The cutting forces and tool life results are presented and analyzed The effects of speed, feed, and depth of cut on cutting forces and tool lives are discussed Variation of the cutting forces with respect to speed, feed, and depth of cut are also shown in different plots The range of the cutting variables are established from these figures which have been used as a guide line for the design of experiment in the following chapter

Also in Chapter 6, the tool wear of uncoated carbides are investigated when turning EN24T steel and inconel 718 Moreover, wear of coated carbides are studied when turning inconel 718 and compared with those of the uncoated carbide inserts for the same machining conditions Finally, the tool life exponents for velocity, feed, and depth of cut in the extended Taylor's tool life equation have been determined graphically and presented

In Chapter 7, the experimental results based on the design of experiments are presented for EN24T steel and inconel 718 Tool lives, surface roughness, and cutting forces have been measured/recorded when the uncoated carbide inserts were used to machine both steel and inconel In the case of turning of inconel 718 with coated carbide inserts, only the tool life and surface roughness have been investigated and recorded Mathematical models of tool life, surface roughness, and cutting force based on the response surface methodology are given Response contours of tool life, surface roughness, and cutting force are also shown in different plots Dual response contours of metal removal rate and the different responses are also shown

Chapter 8 uses the statistical regression model building techniques and sequential estimation technique outlined in Chapter 4 and analyses of the experimental results of Chapter 7 Model equations obtained by the regression model building techniques have been presented in this chapter The criteria used in the selection of machining variables are also discussed Moreover, the experimental tool life data set of Table 7 2 has been analyzed using the sequential estimation technique The model equation obtained in the case of EN24T steel has been compared with that obtained by the multiple linear regression analysis The advantages of sequential estimation as a model building technique for the development of machinability data base systems are also discussed

A machinability data base system has been developed in Chapter 9, using the results and analysis of Chapters 7 and 8 In this chapter various types of machinability data base systems are discussed The data base system that has been developed in this chapter, is applicable for a combinations of EN24T steel and uncoated carbide, inconel 718 and uncoated carbide, and inconel 718 and coated carbide tools only

Depending on the user's selection (input) of operation, work material, tool material and a given tool life, the system provides an output where it displays a set of recommended cutting conditions (speed, feed, depth of cut) Also, it calculates the surface finish to be achieved and the power requirement

Finally, conclusions and recommendations for further work have been discussed in chapter 10 These are in relation to the machinability assessment of the nickel base super alloys and the development of machinability data base systems

CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

A reasonable amount of work has been reported so far with regard to the machining of high strength materials But the literature in the areas of inconel is yet very much limited The following review is based on the turning of high strength materials especially with regard to turning of inconel 718

The use and advantages of high strength materials have been highlighted followed by a review of literatures related to our work Finally, some works have been reported on the machinability data base systems

2.2 High Strength Materials

The difficult to machine materials are often referred to as space age materials, or high strength temperature resistant (HSTR) materials, or corrosion and oxidation resistance materials [1] These difficult to machine materials have high hardness, high strength at high temperature, an affinity to react with the tool materials, and low thermal diffusivity These give rise to higher cutting temperature The high strength temperature resistant materials are alloys of nickel, nickel-iron or cobalt that exhibit a combination of mechanical strength and resistance to surface degradation generally unmatched by other metallic compounds These materials are usually referred to as super alloys

The primary uses of these alloys are in, (i) aircraft gas turbines disks, combustion chambers, bolts, castings, shaft exhaust systems, blades, vanes, etc , (ii) steam turbine power plants bolts, blades, stack gas reheaters, (iii) reciprocating engines turbo chargers, exhaust valves, hot plugs, etc , (iv) metal processing hot work tool and dies, casting dies, (v) medical applications dentistry uses, prosthetic devices, (vi) space vehicles, (vii) heat-treating equipment, (viii) nuclear power systems, (ix) chemical and petrochemical industries, (x) pollution control equipment, and (xi) coal gasification and liquefaction systems These super alloys (Ni, Fe-Ni, Co-base) are further subdivided into wrought, cast, and powder metallurgy alloys Figure 2 1 shows a classification of these alloys

Nickel base alloys contain at least 50% nickel whereas in nickel-iron base alloy, nickel is the major solute component In addition, deleterious elements such as silicon, phosphorus, sulphur, oxygen, and nitrogen must be controlled through

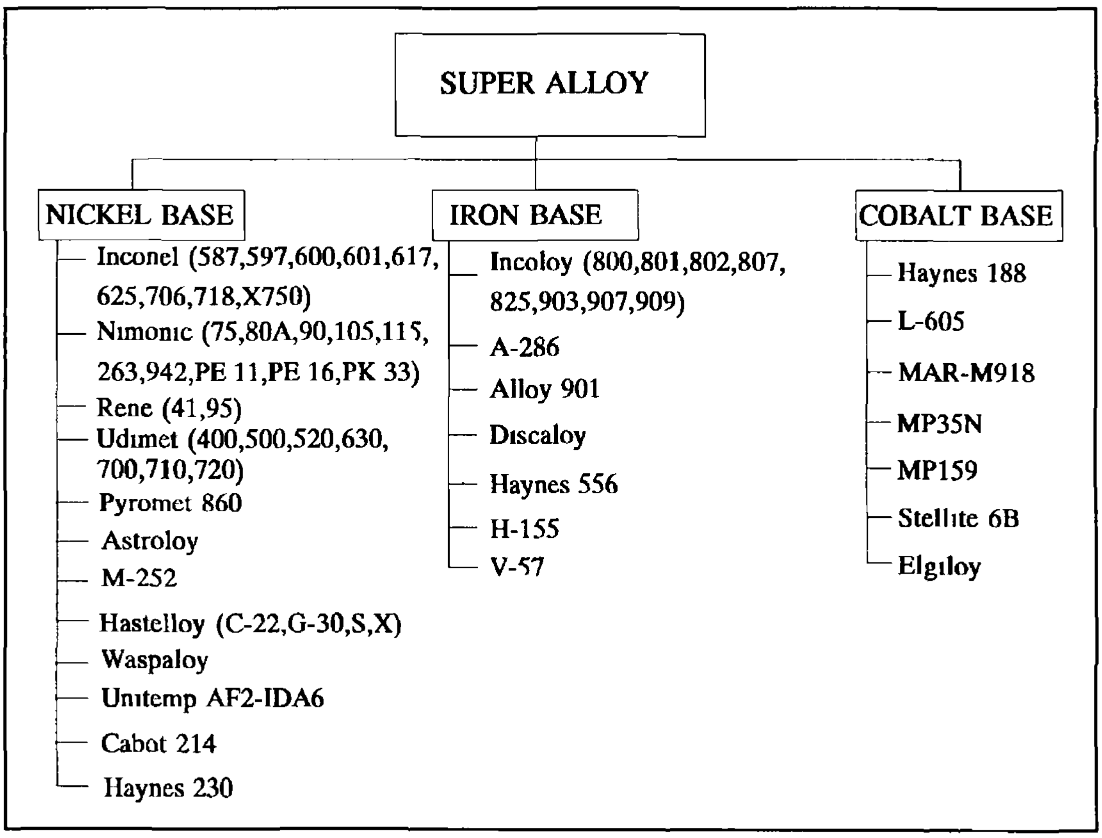


Figure 2.1 Classification of super alloys

appropriate melting practices Other trace elements such as selenium, bismuth and lead must be held to a very small (ppm) levels in critical parts Many wrought nickel base super alloys contain 10-20% chromium, up to about 8% aluminium and titanium combined, 5-15% cobalt, and small amount of boron, zirconium, magnesium and carbon Other additives are molybdenum, niobium, and tungsten Chromium and aluminium are also necessary to improve surface stability [2]

The super alloys are suitable for high temperature application Nickel base alloys, which are the most suitable against oxidation, may be used up to temperatures of 1010 ^{0}C The cobalt alloys exhibit the greatest strength at temperatures in the range of 980 ^{0}C The iron base alloys are not as effective as the nickel base and cobalt base alloys with respect to oxidation stability and high temperature strength The cobalt high temperature alloys have machining characteristics similar to the nickel base alloys Two types of heat treatment are usually recommended on bars, forgings, and flash welded rings of nickel base super alloys [3] These are i) solution heat treatment (annealed), and ii) precipitation heat treatment (aged)

In the solution heat treatment process, the specimen is heated to a temperature within the range 927°C-1010°C (1700°F-1850°F), holding at the selected temperature within $\pm$14°C ($\pm$25°F) for a time commensurate with the cross-sectional thickness

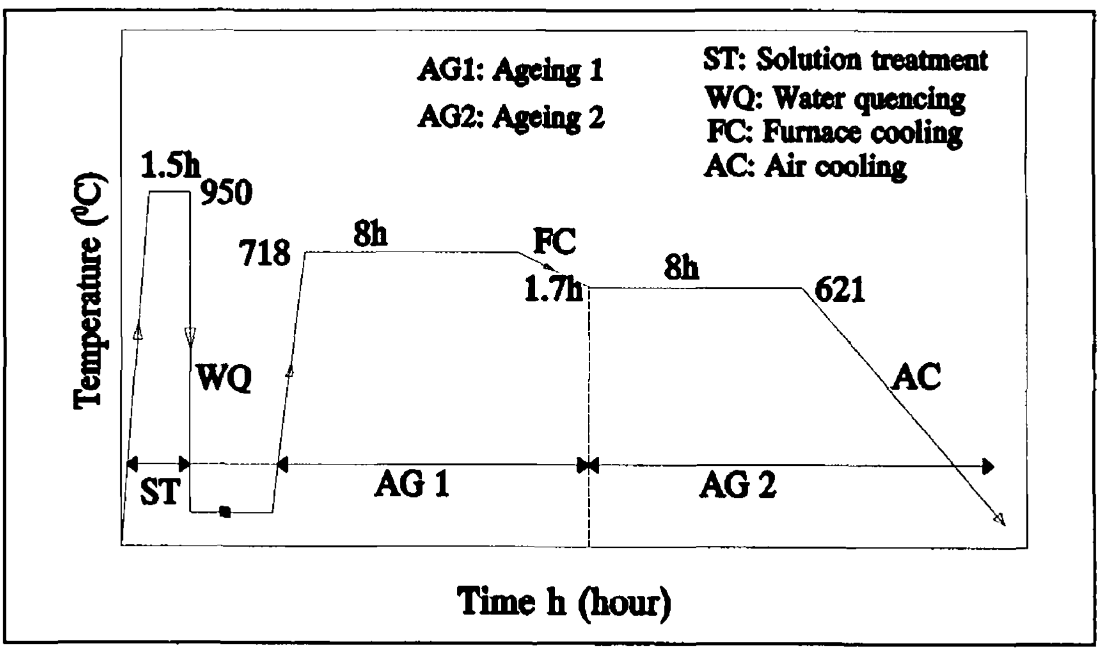


Figure 2.2 Heat treatment schedule of workpiece [47]

and cooling at a rate equivalent to air cool or faster This leads to hardness of $R_c \approx 12\text{-}15$

In the precipitation heat treatment (aged) process, the specimen is heated to a temperature within the range of 718°C-760°C (1325°C-1400°F), holding at the selected temperature within ±8°C (±15°F) for approximately 8 hours, cool at a rate of 55^0C ± 8°C (100°F ± 15°F) degrees per hour to a temperature within the range of 621°C-649°C (1150°F-1200°F), holding at the selected temperature within ±8°C (±15°F) for approximately 8 hours and air cool Instead of 55°C (100°F) degrees per hour cooling rate to 621°C-649°C (1150°F-1200°F), the product may be furnace cooled at any rate provided the time at 621°C-649°C (1150°F-1200°F) is adjusted to give a total precipitation heat treatment time of approximately 18 hours This usually leads to hardness of $R_c \approx 41\text{-}43$ The heat treatment phenomena is shown in Figure 2 2

Among the commercially available super alloys, 718 stands out as the most dominant alloy in production It accounts for as much as 45% of wrought nickel based alloy production and 25% of cast nickel based products [4]

2.3 Machinability Assessment: High Strength Materials

The following review is in relation to the tool life, surface finnish, and cutting forces obtained during turning of high strength temperature resistant materials with special emphasis on inconel 718

Shaw *et al* [5] observed from their experiments that super alloys strain harden during machining They noticed that a chip being cut from such a alloy had red hot edges while the centre of the chip was cooler They concluded that this high edge temperature is a consequence of a yield criterion which allows the edge to yield at a lower stress than the centre, the total effect therefore favouring a greater tendency to form large welds and heavy pullouts

Shaw and Nakyama [6] have discussed in detail the important aspects involved in machining difficult to machine materials They have recommended that for machining high strength temperature resistant materials, tool should be refractory to avoid plastic flow, have high wear resistant to avoid wear and have good brittle fracture resistance to avoid chipping

Taraman [7] developed mathematical models (1st and 2nd order) for cutting force, surface roughness, and tool life in terms of cutting speed, feed, and depth of cut He carried out the tests under dry cutting conditions using tungsten carbide disposable inserts having a nose radius of 0 8 mm The workpiece was SAE 1018 cold-rolled steel, 100 mm in diameter, and 600 mm in length He developed the following first order equations based on the experimental results

$$
\begin{aligned}
F_c &= 560\ V^{-0\,116}\, f^{0\,755}\, d^{0\,665} \\
R_a &= 4626\ V^{-0\,363}\, f^{1\,1371}\, d^{0\,1835} \\
T &= 24949\ V^{-1\,406}\, f^{-0\,248}\, d^{-0\,177}
\end{aligned}
\tag{2.1}
$$

These equations indicate that a reduction in all the investigated outputs (cutting force, surface roughness, and tool life) is achieved with the increase in the cutting speed However, as the feed increases, the surface roughness and cutting force increase while the tool life is reduced An increase in the depth of cut reduces tool life, however, it causes an increase in surface roughness and cutting force Also it should be noted that the feed effect is dominant on surface roughness and that the tool life is affected most by cutting speed, less affected by feed and least affected by depth of cut

Smart and Trent [8] investigated the temperature distribution in the tools used to machine nickel alloys They observed that while machining nickel base alloys, the tool temperatures were much higher than in conventional steels but the temperature gradient was lower An example of machining cast iron and Nimonic 75 at 10 m/min showed maximum temperature of 320 ^{0}C and 800 ^{0}C respectively Moreover, the tip of the cutting edge was the hottest location while machining nickel alloys

Lee *et al* [10] and Trent [11] have discussed the depth of cut notch wear mechanisms of ceramic cutting tools when machining super alloys They pointed out that as the chips become segmented with a typically ragged appearance, an interrupted seizure and breakage process cause a pull-out of the tool material For good resistance against this type of wear, toughness of the tool as well as a low reactivity against the work material is required

Kramer and Hartung [12] have determined the solution wear rates of five different carbide tools (coated and uncoated) in the turning of two different nickel base alloys A series of cutting tests carried out on inconel 718 (255 BHN) and inconel X (282 BHN) at a cutting speed of 135 m/min, feed of 0 127 mm/rev, and depth of cut of 1 27 mm using tools with 0 79 mm nose radius They observed that the test results were in good agreement with the relative wear rates predicted from the thermochemical data

The solution wear was the primary wear mechanism in the cratering of the carbides which limits its wear resistance However, they have suggested that unless more adherent coatings can be produced, coated tools may offer little benefit over the uncoated tools Titanium carbide and hafnium carbide proved to have substantially greater wear resistance than tungsten carbide

Wilson and El-Baradie [13] carried out a series of turning tests on vitallium, a cobalt base alloy, to investigate cutting forces, tool wear and surface finish Carbide and cubic boron nitride (CBN) inserts having three different rake angles (-6^0, 0^0, $+6^0$) were used They noticed very high cutting forces up to 1000 N at a feed rate of 0 08 mm/rev and a depth of cut of 0 25 mm Cutting tools with the positive rake angle resulted in the smallest cutting forces The wear of carbide tools with negative rake angle and low cutting speed ($<$20 m/min) was a combination of adhesive, abrasive, and diffusive wear In case of CBN inserts, flank wear curves did not show the three distinctive zones (initial rapid wear, steady wear, and final abrupt wear) The surface finish produced by the carbide tools improved when the cutting speed was in excess of 30 m/min The performance of CBN tools with regard to the surface finish was extremely good

Research was conducted by Huet and Kramer [14] and Wright and Chow [15] to find the relationship between the cutting speed and temperature of the cutting edge during machining of nickel alloys such as inconel 718 and nimonic 75. They noticed that at low speeds, the rate of increase of temperature of the cutting edge was very high. However, as the speed increased, the gradient was found to decrease.

Baker [16] reported that Kennametal Inc., USA has developed a new cutting tool material (Kyon 2000) that consisted of a sialon composition and was capable of machining nickel base alloys at higher cutting speeds and higher feed rates than those of ceramic tools. Moreover, its toughness was higher than the conventional ceramics.

Vigneua *et al.* [17, 21] and Bhattacharyya *et al.* [18] recommended ceramic or cubic boron nitride for machining inconel 718. However, they noticed that cubic boron nitride tools developed notch wear at the cutting edge because of its low toughness and low thermal diffusivity.

Komanduri *et al.* [19] mentioned that the nickel base alloys have properties that would cause a transition from a continuous chips to segmental chips as the cutting speed was increased. They thought that the segmental chips were encountered from the workpiece that has poor thermal properties, high hardness and/or hexagonal closed packed crystal structure.

Komanduri and Schroeder [20] noticed from their machining test of inconel 718 (400 BHN) that chips formed changed with the cutting speed. Al lower speed (<30 m/min), the chips are continuous and coiled while shear localization of the chip began at speeds between 30 to 90 m/min and the segments were joined together in long coils. At speeds above 150 m/min, isolated segments of chips were formed.

Sadat [22] examined surface characteristics of machined inconel 718 (38 Rc) using natural and controlled contact length at various cutting speeds under dry and lubricated conditions. Four levels of cutting speed (6.6, 18, 36, and 60 m/min) and a constant feed rate (0.01 mm/rev) were selected for the test. The machining tests were carried out with cemented carbide tools. He observed that for a given cutting speed, both the tangential and feed forces were lower under controlled contact length of 0 15 mm as compared to 0 39 mm natural contact length These tool forces decreased with an increase in cutting speed He also observed that the effect of lubricants on the tool forces was negligible at high cutting speed and the forces decreased with the increase of cutting speed

Bhattacharyya *et al* [23] investigated tool lives when machining inconel 718 (504 BHN) and 901 (407 BHN) with silicon carbide whisker reinforced Al_2O_3 composite ceramic tool at various speeds (150, 215, and 300 m/min) and compared the results with those obtained from sialon tools In the initial tests, feed and depth of cut were kept constant at 0 18 mm/rev and 2 5 mm respectively A second series of machining tests were carried out using a variable depth of cut (4 to 2 mm) Speeds of 215 and 300 m/min were used with a feed of 0 18 mm/rev All the cutting tests were carried out with flood coolant

They observed that whisker reinforced ceramic tools gave appreciably longer tool lives at all speeds when machining inconel 718 but this was not true with inconel 901 Sialon exhibited lower wear with 901 Flank wear rate increased and consequently the tool lives decreased as the cutting speed increased from 215 m/min to 300 m/min although the performance of sialon on inconel 718 was very poor giving an even worse performance than the whiskered ceramic on inconel 901 at this higher speeds At a constant depth of cut, notching was responsible for tool rejection but at variable depth of cut flank wear was the cause of tool failure

Zhonglin [24] has mentioned the development of a new ultra fine grain cemented carbide tool in a cemented carbide company in China The wear resistance of the tool, as he reported, has increased by 3 - 10 times the conventional cemented carbide tool when machining difficult to machine materials

Klaphaak [25] of Ovonic Synthetic Materials Company has outlined that the coating materials that prolong tool life are high hardness, smoothness, and a controlled tendency to diffusion with the work material The Company has developed an amorphous boron carbide coating which proved to be effective in machining of various super alloys

Mital and Mehta [26, 27] generated surface finish data for a wide variety of metals and alloys (aluminium alloy 390 (71 5 BHN), ductile cast iron (183 BHN), medium carbon leaded steel 10 L45 (197 BHN), medium carbon alloy steel 4130 (195 BHN), and inconel-718 (340 BHN)) for a wide range of machining conditions A randomised complete block factorial design was used with four levels of feed rates (0 0508, 1 27, 0 203, and 0 3048 mm/rev), and three levels of tool nose radii (0 794, 1 190, and 1 587 mm) Three levels of cutting speeds (22 9, 30 5, and 38 1 m/min) were used for machining test of inconel They developed predictive surface roughness model for inconel and was given by

$$R_a = -15\,11 - 5\,06(r) + 1\,57(V*f) + 19\,62(r*f) - 0\,95(V*r*f) - 7\,61\ \ln(f) + 1\,49\ \exp(r) - 0\,36\,f^{-1} \tag{2.2}$$

The equation was found to be non-linear and in addition to the main effects, the interactive effects on surface roughness were also highly significant

Dontamsetti and Fischer [28] investigated the factors affecting surface roughness in finish turning of grey cast iron (195 BHN) using uncoated tungsten carbide inserts Four levels of cutting speed and feed rate, two levels of nose radius and three levels of tool wear were used as independent variables They observed that the speed, feed and nose radius had a significant affect on surface roughness Also, interactions between tool wear and each of the other three variables were highly significant

Kitagawa *et al* [29] have investigated the flank wear characteristics of tungsten carbide tools in turning plain carbon steel without a built up edge by measuring temperature, normal stress, and wear rate on the flank wear land The characteristic equation for crater wear which was derived from an adhesive wear model was applicable to describe the flank wear as well The equation was given by

$$\frac{dW}{\sigma_t\, dL} = C\ \exp\left(-\frac{\lambda}{\theta_t}\right) \tag{2.3}$$

where W is the wear volume per unit area of the worn surface, L is the wear distance, σ_t is the normal stress on the worn surface, θ_t is the absolute temperature in Kelvin, and C and λ are the characteristic constants depending on the combination of the tool and work material

Ohtani and Yokogawa [30] have investigated the wear mechanism of the cubic boron nitride (CBN), ceramic and carbide tools and the cutting forces encountered when turning tool steel having several level of hardness ranging form 18 R_c - 60 R_c Three levels of cutting speeds (100, 150, and 200 m/min), a constant depth of cut of 0 2 mm, and a feed rate of 0 1 mm/rev were used under dry cutting condition They observed that the life span of carbide tools decreased as the workpiece hardness increased, while the life span of CBN and ceramic tools showed the opposite results The mode of tool failure for CBN and ceramic was abrasion wear by hard alloy carbide particles contained in the workpiece The increasing rates of cutting force components against flank wear were slower for carbide tools than for the other tool They concluded that the stress distributed on the worn flank face was lower in carbide tools

Focke *et al* [31], Tan [32], Oishi *et al* [33], Iijima *et al* [34], Masuda *et al* [35], and Takeyama [36] studied the wear of cutting tools when machining nickel base alloy They all have reported the formation of notch wear which was a problem for the tool failure

Enomoto *et al* [37] tested the effect of work material hardness on the life of CBN cutting tool in the turning of chromium-molybdenum steels They found that the CBN tool indicated the shortest tool life in the cutting of Cr-Mo steels when the hardness was low In the case of carbide tool, it exhibited shorter tool life with the increase of work material hardness

Focke *et al* [38] have reported excessive flank wear with time, when turning super alloys (Inconel 718, Rene 95) with cemented carbide tools at recommended cutting speed Also, they observed crater formation on the top rake with its maximum depth close to the cutting edge When attempting to machine with carbides at faster than the recommended speed on these super alloys, the rate of depth of crater was found to move toward the cutting edge

Richards and Aspinwall [39] have presented a comprehensive review of literature on the use of ceramic tools for the machining of nickel based alloys They have concluded that CBN, sialon, and whisker reinforced alumina have offered better overall performance than either conventional or mixed alumina compositions as a consequence of greater mechanical and thermal integrity Depth of cut notch wear was the main cause of tool failure irrespective of tool material composition However, reduced notching was observed with both CBN and sialon tools at high cutting speed These tools were reported to have been used at a cutting speed ten times greater than used with the cemented carbide toolings

Jang and Seireg [40] utilised dynamic simulation to develop a generalised equation for predicting surface roughness in turning operation covering the practical range of dynamic characteristics and cutting conditions They have given an equation describing the total roughness of the machined components as

$$R = R(f,r) + R(F_x(t)) \qquad (2.4)$$

where R = total predicted surface roughness, $R(F_x(t))$ = roughness generated by the dynamic cutting force The dynamic cutting force is given by

$$F_x(t) = K_s\, A_t(t) - F_d(t) \qquad (2.5)$$

where K_s = cutting resistance, a property of the work material, A_t = instantaneous uncut chip cross-sectional area, and $F_d(t)$ = damping force Using the test data reported in reference [9], they developed the following equation based on the simulation

$$R_{max} = 665\ V^{-0\,364}\ f^{0\,818}\ d^{0\,27}\ r^{-0\,364} \qquad (2.6)$$

This equation was compared with that of Hasegwa *et al* [10] which was based on experimental data and was given by

$$R_{max} = 624\ 24\ V^{-0\ 433}\ f^{0\ 813}\ d^{0\ 033}\ r^{-0\ 468} \tag{2.7}$$

Good correlation between the simulation results and the experimental results was observed

Komanduri [41] suggested sialon ceramics for rough machining of nickel-iron base super alloys These ceramic tools were much tougher than alumina ceramic and have low coefficient of thermal expansion (½ of that of cemented carbide and ⅓rd of that of alumina)

Hanasaki *et al* [42, 43] have investigated the tool wear of cemented carbide coated tools when machining high nickel alloy (Ni ~ 50%) under dry cutting conditions They used four kinds of coated tools with the thickness of the coating layer of 2 ~ 3 μm The coating layers were TiC and TiN which were single layer and TiN on TiC and Al_2O_3 on TiC which were double layers Three cutting speeds (60, 100, & 140 m/min) at a constant feed rate of 0 1 mm/rev and depth of cut of 0 5 mm have been used They observed less flank wear on the cemented carbide tools A TiC/Al_2O_3 coatings on the cemented carbide had the least wear among the coated tools

Szeszulski *et al* [44] carried out experiments on the wear of silicon carbide whisker reinforced aluminium oxide tools when machining inconel 718 Single point cutting tests were conducted with circular button type inserts Cutting speeds were of 456 m/min, 612 m/min and 762 m/min, feed rate was 0 25 mm/rev and depths of cut were 0 76 mm and 1 3 mm The work material was annealed and water quenched in the form of cylindrical bar stock of 152 mm diameter and the reported hardness was 201 BHN (centre) to 242 BHN (surface)
Three distinct wear types namely, flank wear, depth of cut notch wear and trailing edge wear were observed The magnitude of each was a function of the cutting conditions For both depths of cut, flank wear accelerated as the cutting speed was

increased from 456 m/min to 612 m/min, but did not increase when the speed was raised to 762 m/min Adhesion and abrasion were the likely wear mechanisms for the tool failure However, the flank wear behaviour did not show any significant change as the depth of cut was increased

Depth of cut notch wear was predominant and grew severe with increasing speed but tended to level off at 762 m/min for both depths of cut This suggested a change in wear mechanisms which was most likely due to substantial workpiece as well as tool softening Trailing edge wear was severe at the lowest cutting speed, and roughly independent of the depths of cut Otherwise, the wear pattern showed trends similar to those observed for both flank wear and depth of cut notch wear

Brandt *et al* [45] investigated wear mechanisms of ceramic cutting tools when machining inconel 718 (370 BHN) under lubricated condition The machining tests were performed as a continuous turning operation on a cylindrical bar of 180 mm length and 700 mm diameter using a depth of cut of 1 5 mm, feed rate of 0 15 mm/rev and 0 25 mm/rev, and speeds ranging from 150 m/min to 450 m/min Ceramic tool grades CC 620 (an alumina based material with additions of Zirconia), CC 670 (based on alumina and SiC whiskers), and CC 680 (Sialon) round inserts were used for the evaluation of tool life and wear mechanism
They found that tool life for the sialon grade was mainly dependent on flank wear whereas for the whisker grade, the tool life criterion was notch wear for most of the cutting conditions investigated They observed that wear area was concentrated mainly to the cutting edge Work piece material penetrated very long distance into the sialon tool material In the surface region, it was observed that Ni, Fe, and Cr diffused along the grain boundaries into the sialon tools Ti, Nb and Al were observed to form a coating on the tool surface In the case of SiC whisker reinforced alumina, flank worn zone showed that Fe, Cr and Ni diffused rather a long way into the tool material whereas Ti and Nb showed an enrichment at the tool surface The silicon content decreased as the SiC whiskers were dissolved but not the carbon content, which probably was a result of reaction of carbon with the carbide forming elements Cr, Ti, and Nb in the workpiece material

Bandyopadhyay and Teo [46] developed 1st and 2nd order surface roughness prediction models for high speed dry turning using coated carbide inserts Based on the factorial design of experiment, they evaluated the effects of cutting speed, feed, and depth of cut on the surface finish The workpiece material was SAE 1020, 250 mm long and 155 mm in diameter Five levels of speed (200, 285, 400, 560, and 800 m/min), feed (0 0584, 0 0737, 0 094, 0 1168, and 0 1488 mm/rev), and depth of cut (0 344, 0 50, 0 71, 1 0, and 1 454 mm) were used They concluded that the predicted roughness was significantly affected by the feed Cutting speed and depth of cut have a minor effect However, the surface finish improved with the increase of cutting speed They developed the following general equation relating surface roughness with the cutting parameters

$$R_a = 304\ 86\ V^{-0\ 322} f^{1\ 1284} d^{0\ 596} \tag{2.8}$$

Ezugwo *et al* [47] investigated the effects of high pressure coolant supply on tool wear and cutting forces when machining inconel 901 (407 BHN) A cylindrical bar of about 450 mm long and 205 mm diameter was used as the test specimen Carbide inserts of ISO designation (CNMP 12 04 12/08 and CNMA 12 04 12/08) and ceramic inserts (CNMG 12 04 12 and SNGN 12 04 16)) were used as the cutting tools The turning tests were carried out at speeds varying from 20 m/min to 55 m/min and at feed rate of 0 127 mm/rev and 0 18 mm/rev They observed that notching was the dominant cause of tool failure for both the inserts In case of carbide inserts, notching increased with increasing cutting speed and time
Flank wear was the main reason for insert rejection when cutting with sharp edged carbide inserts (CNMA 12 04 08, CNMP 12 04 08) using high pressure coolant supply The CNMA 12 04 12 and CNMP 12 04 12 inserts gave longer tool lives in relation to the CNMA 12 04 08 and CNMP 12 04 08 Tool lives achieved with SiC whisker reinforced alumina ceramic tools using high pressure coolant supply and using square inserts (SNGN 12 04 16) were low compared to cutting with the conventional coolant supply Longer tool lives were obtained at lower speeds when cutting with both inserts
The ceramic inserts failed mainly by a combination of notching at depth of cut region and severe fracture at the tool nose The conventional coolant supply produced longer tool lives as compared to high pressure coolant supply However

at higher speed (55 m/min) and depth of cut (2 5 mm), the high pressure coolant supply did suppress the premature fracture of the carbide inserts The cutting forces decreased with the increase of speed and increased with the increase of feed and depth of cut However, the difference in cutting forces for conventional and high pressure coolant supply was very small

Kazuhiro *et al* [48] investigated the performance of cutting tool (CBN) on turning inconel 718 According to his findings, tool life was affected significantly due to adhesion of work material to the tool tip during cutting operation He also examined the reaction between the tool material and workpiece and observed that due to metal diffusion between the binder phase of the cutting tool and the workpiece, tool wear was accelerated

El-Wardany *et al* [49] investigated the effect of cutting parameters (speed, feed, nose radius, and depth of cut) on the surface finish generated during turning of hardened steel AISI 1552 of 60 Rc hardness using ceramic tools Four levels of feed, nose radius, and depth of cut and two levels of cutting speed were used They developed a first-order mathematical model describing surface roughness as a function of the cutting parameters as

$$R_a = -3\,8906\ V^{0\,2551}\ f^{0\,2431}\ d^{-0\,0421}\ r^{-0\,2354} \qquad \textbf{(2.9)}$$

The positive exponent of velocity, however, does not agree with the general trend Usually, surface finish improves with the increase of speed

Sadat and Reddy [50, 51] examined the surface integrity of inconel 718 (27 Rc) nickel-base super alloy at various cutting speeds, depths of cut, and chip-tool contact lengths using orthogonal cutting conditions Silicon-nitride (Sialon) based ceramic insert tools were used with and without the application of a coolant Ring specimens of 65 mm o d and 54 mm i d was machined at five levels of speed ranging from 12 m/min to 96 6 m/min The various depths of cut were 0 028, 0 051, 0 074, and 0 99 mm and chip-tool contact lengths were 0 051 mm and 0 102 mm
In general, the cutting forces (tangential and feed components) decreased with an

increase in cutting speed and increased with the increase in depth of cut and chip-tool contact length The change in cutting force with the change in chip-tool contact length was almost insignificant They have explained that due to an increase in cutting speed, tool-rake face temperature is increased and consequently shear plane length is decreased and hence the cutting forces were decreased The increase in cutting forces with increasing depth of cut was due to the increase in the volume of the material removed with the increase in energy expended They found that the lubricant was effective at low cutting speed in reducing the tool forces that led to lower hardness and plastic strain in the surface region

Narutaki *et al* [52] and Yamane *et al* [53] carried out high speed machining tests for inconel 718 (420 BHN) with SiC whisker reinforced alumina (Al_2O_3/SiC), silicon nitride, and TiC added alumina ceramic tools (Al_2O_3/TiC) The SiC whisker tool showed good performance in respect of notch wear in the speed range of 100-300 m/min However, when the speed exceeded 400 m/min, the TiC added alumina tool showed the smallest wear compared to other tools Notch wear and flank wear of sialon and SiC whisker reinforced alumina became large when the cutting speed was high (400 m/min) or the feed rate was high (0 32 mm/rev) They have suggested that these tools have low wear resistance under high cutting temperature and the cause of tool failure was diffusion wear instead of abrasive wear

El-Baradie [54] has developed surface roughness prediction model (1st and 2nd order) for turning grey cast iron (154 BHN) using carbide inserts under dry conditions and a constant depth of cut The model was developed in terms of cutting speed, feed rate, and tool nose radius Based on the first order equation, the surface roughness as a function of the cutting variables were given by

$$R_a = 50\,44\ V^{-0\,317}\, f^{0\,484}\, r^{-0\,684} \qquad \textbf{(2.10)}$$

The equation indicates that an increase in either the cutting speed or the tool nose radius decreases the surface roughness, while an increase in the feed increases the surface roughness

Balazinski *et al* [55] investigated the effect of feed variation on tool wear when machining inconel 600 They observed experimentally a 33% decrease of tool wear by varying the cutting feed rate throughout the cutting process The comparison between constat feed and variable feed processes were based on the constant volume of metal removal rate in a given time span

Gatto and Iuliano [56] carried out high speed turning tests on inconel 718 using silicon carbide whisker reinforced ceramic tools in order to develop a wear model for the inserts They observed different wear patterns along the length of the flank On edge radius, considerable chipping and some welded material were present In the central section, wear was due to abrasive effect of chip that caused the cutting edge to move backward At the end of the cutting edge notch wear was present Furthermore, they noticed chip creeping at the face of the tool and this was even more pronounced when the cutting speed was more that 500 m/min

Table 2 1 gives a summary of the machinability assessment of inconel 718 carried out by different investigators

Table 2.1 Machinability assessment of inconel - 718

Investigators	Heat Treatment BHN	Machining Variables			Cutting Tool
		Speed (m/min)	Feed (mm/rev)	Doc (mm)	
S K Bhattacharyya et al ('87)	504 407	150, 215, 300 (Flood Coolant)	0 18	2 50, 4-2 (Taper)	Al_2O_3/SiC, Sialon, SNGN 120416
A B Sadat ('87)	38 Rc	6 6, 18, 36, 60 , Dry & Coolant	0 10		Cemented Carbide
A Mital & M Mehta ('88)	340	22 9, 30 5, 38 1	0 0508, 0 127, 0 2032, 0 30480	0 794, 1 19, 1 587 (NR)	Carbide (Coated & Uncoated)
G Brandt, et al ('90)	370	150, 300, 450 (Coolant)	0 15, 0 25	1 5	Al_2O_3/SiC, Sialon, Al_2O_3/ZrO_2
K J Szeszulski et al ('90)	Annealed & WQ, 201-242	378,456,534, 612,684,762	0 13,0 2,0 25, 0 31,0 38,0 51	0 76	Al_2O_3/SiC, RNGN
E O Ezugwu, et al ('91)	Inconel - 901, 407 Hv	20, 26, 32, 40, 47, 55, 150, 215, 300 Coolant (Normal & high pressure)	0 127, 0 18	0 5, 1 0, 1 25, 1 5, 2 5, 3 0	Carbide CNMP 120412/08 & CNMA 120412/08, Al_2O_3/SiC, CNMG 120412
A B Sadat & M Y Reddy ('92)	279 Hv	12, 21, 37 8, 8 75, 96 6, Coolant		0 028,0 051,0 074, 0 099	Si_3N_4 (Sialon)
K Shintani et al ('92)	Aged, 450	60 - 240			CBN
N Narutaki et al ('93)	Aged, 420	100 - 400	0 12 - 0 34	0 50	Al_2O_3/SiC, Si_3N_4, &, Al_2O_3/TiC, SNGN 120408 (Square), RNGN 120400 (Button)

2.4 Machinability Data Base Systems

Machinability data base systems are essential for the selection of optimum cutting conditions during process planning, and these form an important component in the implementation of Computer Integrated Manufacturing (CIM) systems Computerized machinability data systems can be classified into four general types such as

- i) Data storage and retrieval system,
- ii) Empirical equation system,
- iii) Mathematical model system, and
- iv) Machinability data selection expert system

The data storage and retrieval system is based on the collection and storage of large quantities of data in computer data storage files from laboratory experiments and shop experience and then simply retrieving the data (recommended cutting speeds, feed rates, and cost information) for any specific cutting operation

The empirical equation system generally uses the expanded Taylor's tool life equation to calculate the cutting parameters The data for a particular condition is translated to an empirical form and expressed as a generalised empirical equation [57]

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, power, etc , are used as the primary data for use in a machinability data base system The mathematical models of these machining responses are developed as a function of the machining variables using a model building module

With the advent of expert systems, some new concepts for the design of computerized machinability data selection systems have been developed Expert systems are computer based tools which are employed to solve problems that need a significant amount of expertise It consists of a knowledge base, and inference engine, and a working memory. The knowledge base is a repository of facts, hypothesis which are stored using an appropriate knowledge representation scheme. The inference engine searches through the knowledge base in order to find a suitable solution for the problem using working memory for that storage of data that is created or used in the process. The machinability data selection expert system provides cutting parameters from its data base depending on the user's inputs such as tool material, work material, hardness of the work material etc. The use of computers to assist people in generating machining parameters has become a critical area both in research/academic institutes and industry [58-61].

Rasch and Rolstadås [62] have carried out a series of finish turning tests in order to establish a functional relationship among the response (surface roughness) and the machining independent variables (speed, feed, tool nose radius, cutting time, tool quality, and material quality). They developed a mathematical equation based on the regression analysis. The equation based on 99.9% confidence interval was given by

$$R_a = 2.95\, f^{0.7}\, r^{-0.4}\, T^{0.3} \tag{2.11}$$

where f is the feed in mm/rev, r is the tool nose radius in mm, and T is the tool life in minutes. With this equation as a basis, they developed an automatic system for calculation of optimal cutting data. The system provided optimal feed, speed, and tool nose radius as output for a given surface roughness, diameter and cutting length.

Friedman *et al.* [63] presented a concepts and design of computerized numerical machining data bank suitable for implementation in manufacturing. The systems of the data bank consisted of three modules namely; machinability data file module, model building module, and optimization module. The machining data file consisted of a basic file containing numerical data on machining material and machining operation. The machining data file could be updated depending on various feed back information. The model building module is used to estimate a mathematical relationship between the response and the cutting parameters. The output of model building module served as input for the optimization module. The optimization module optimizes a target function (cost, production or profit) under different constraints (surface finish, power etc)

Eversheim *et al* [64, 65] developed programmes on turning, milling, and drilling for selection of cutting data These programme systems generate production documents like tables for cutting data, manufacturing instructions etc depending on input information of machine tool, tool data, workpiece/tool material, and lot size

Zdeblic [66] proposed a machinability data base structure consisting of three modules These are (i) manufacturing data, (ii) model building, and (iii) manufacturing analysis and optimization The input to the data base structure comes from process plans and the output of the data base structure are recommended cutting tools and machining conditions The manufacturing data modules consists of four data files (machining data, machinability models, supporting data, and part/operation data) The model building module consisting of three elements (model form selection, parameter estimation, and risk analysis), develops a mathematical model between the machinability responses and machinability variables The manufacturing analysis/optimization module contains the specific algorithms which recommends the correct cutting tool, cutting speed, and feed rate

Balakrisnan and DeVries [67, 68] attempted to present a comprehensive survey of the work which has been done in the area of computerized machinability data base systems They have analyzed the techniques used by various systems to obtain recommended or optimum cutting conditions

Balakrisnan & DeVries [69] have proposed sequential maximum a posteriori as a mathematical tool for use in the mathematical model type machinability data base systems According to their investigation, this technique was a better alternative to the commonly available regression analysis methods

Wang and Wysk [70] have developed an expert system for machining data selection The structure of the system had four modules, User Interface module (UIM), Knowledge Base Module (KBM), Empirical Equation Module (EEM), and Data Base Module (DBM) Written in FORTRAN 77, the system was designed to generate and display machining data on a computer screen based on the input data for material, tool, and operation The system included almost all of the common machine shop operations like turning, milling, etc

Chapman [71] has described one machinability software package called *The Gte Valentine Network* This programme incorporates exhaustive data files that include information on virtually all common part materials, cutting grades, tool geometries, as well as application results obtained over a wide range of operating parameters and machining conditions in field tests and production operation Typical information provided by the programme are machinability rating of parts materials, grade of the cutting material, optimum cutting speed, optimum feed rate, chip control information, tool life, power consumption, and cost of operation

Badiru [72] has outlined a guideline on how industrial engineers can successfully take the lead in beneficial implementations of the emerging technology of expert systems One of the potential application areas include computer aided manufacturing

Yeo *et al* [73] have developed an expert system based on COMMON LISP (Artificial Intelligent Language) for machinability data selection in turning The essential feature of the system was that, a knowledge base contained all facts in a codified form and a working memory stores the description of work material, cutting tool etc The inference engine where the reasoning takes place used forward chaining which started with a set of assertions (data) provided as input This involved pattern matching until a recommendation was made or no more rules could be satisfied An user interface allowed interaction with the users The programme provided speed, feed, depth of cut, and power requirement depending on the input of work material type, hardness and tool geometry

Yeo *et al* [74] investigated various multiple regression model building techniques on machinability data (tool life and surface roughness) in order to study the suitability of the empirical equations They have made a comparative analysis of the first-order and second order regression model using the various stepwise regression selection methods The output of the regression model building module could be ıncorporated ınto an expert system for achıevıng an ıntegrated manufacturıng system

Gopalakrıshnan [75] has descrıbed the dıfferent methods that could be used to make expert systems suıtable for applıcatıon ın the field of machınıng parameter selectıon He has analyzed the desıgn of expert systems wıth respect to the dıfferent technıques that helps the expert system shells ın the areas of data acquısıtıon, ınference path modıficatıon and user ınput to make them functıon effectıvely ın the domaın of machınıng parameter selectıon Some expert systems that are ın use ın the domaın of manufacturıng has been outlıned *Cuttech* ıs such a system that recommends cuttıng tool, speeds, feeds for machınıng

Sıngh and Raman [76] provıded a comprehensıve survey of lıterature on machınabılıty parameter selectıon systems followed by a lıterature based analysıs of the anomalıes of machınıng and the process and materıal effects ın machınıng They developed a prototype expert system called *Metex* for machınıng parameter selectıon It consısted of three modules, ı) a rule-orıented data base contaınıng nomınal feeds and depths of cut compıled from Machınıng Data Handbook [77], ıı) a rule base for sımulatıng the metal cuttıng process, and ııı) a user frıendly ınterface to collect ınputs from the user and provıde the outputs The system was lımıted to four combınatıons of tools and work materıals However, the rule base could be expanded to accommodate other tool and work materıal combınatıons

CHAPTER 3

MACHINABILITY ASSESSMENT

3.1 Introduction

This chapter presents an overall description about machinability assessment and the different factors affecting the machinability A brief discussions about the different cutting tool materials have been presented The different parameters usually investigated for a machinability test have been presented

3.2 Machinability

The term machinability is used to refer to the ease with which a work material is machined under a given set of cutting conditions A prior knowledge of a work material is important to the production engineer so that he can plan its processing efficiently If a material *A* is more machinable than material *B*, it can mean that less power is required to machine material *A*, or a higher tool life is achievable with material *A*, or a better surface finish can be obtained with material *A* Moreover, ease of chip disposal, cutting temperature, operator safety, etc are other criteria of machinability as well

It is important to mention that the machinability is only applicable to a particular set of circumstances under which the observations are made Machinability of a material *A* may be better than that of *B* with respect to surface finish under a set of cutting conditions while machinability of material *B* may be better than that of *A* with respect to tool life under a different set of cutting conditions

According to Ernst [78], the term machinability means a complex physical property of a metal which involves true machinability, finishability or ease of obtaining a good surface finish and abrasiveness or abrasion undergone by the tool during cutting

Boulger [79] has defined machinability as the removal of chips with satisfactory tool life and surface finish Boston [80] has defined machinability as the response of a metal to machining which gives long tool life under otherwise equal conditions when compared with other materials, provides good surface finish, produces well broken chips, gives uniform dimensional accuracy of successive parts, produces each part at the lowest overall cost, and requires lower power consumption in removing a given quantity of chips

Reen [81] has pointed out that for accurate rating of machinability, three factors namely, tool life, surface finish, and power consumed during cutting must be considered Similar views are expressed by Shaw [1] Trent [12] has outlined that tool life, cutting force, chip shape, surface finish/integrity are all important parameters for machinability assessment of a material According to Sandvik [82], machinability of a material is the ability of the work material to be machined

In general machinability of a material can be considered as a combination of small cutting force, high metal removal rate, longer tool life, better surface finish/integrity, well broken chips, and uniform dimensional accuracy The different factors influencing machinability of a material are (i) machining operations, (ii) cutting conditions, (iii) workpiece properties, (iv) tool properties, and (v) machine tool-tool-workpiece dynamics

The machining operation may be a continuous cutting operation (turning) or an intermittent cutting operation (milling) The cutting conditions which influence the machinability parameter are cutting speed, feed, depth of cut, and cutting fluid Higher the cutting speed is, lower is the tool life This is true for feed as well Moreover, as the feed increases, the power consumed during cutting also increases Higher the depth of cut is, the greater is the power requirements

The workpiece properties which have a pronounced affect on machinability are it's microstructure, chemical composition, and physical properties A small change in the microstructure of a material can greatly affect its machinability [83] The chemical composition of a material also influence its machinability The presence of sulphur, lead, and phosphorus improve machinability of a material while chromium, vanadium, nickel, and molybdenum retard machinability The presence of hard abrasive carbides in the microstructure can have a detrimental effect on machinability [84] The physical properties of a material affecting machinability are it's hardness and work hardening properties [85]

The tool material and it's geometry also have an influence on the machinability of a material The requirements of a good cutting tool is it's high hardness and toughness, good wear resistance, mechanical and thermal shock resistance and the ability to maintain these properties at very high temperatures encountered during metal cutting operation Rake angle of a cutting tool has an affect on the cutting force As the rake angle becomes positive, the cutting force decreases [86]

Tool material and geometry must carefully be chosen in relation to the workpiece material to be machined, the kinematics and stability of the machine tool to be employed The main cutting tool materials in use are (i) high speed steel, (ii) cast alloys, (iii) cemented tungsten carbides, (iv) coated cemented carbides, (v) TiC-TiN based cermets, (vi) ceramics, (vii) polycrystalline diamond and cubic boron nitride, and (viii) single crystal diamond

Tungsten based cemented carbide are the oldest among the hard cutting tool materials in use The present tungsten carbides for cutting applications are classified into P, M, and K codes The P group is for cutting materials with long chips such as carbon steels, alloy steels, and ferritic steels The M group is used for cutting materials with long to medium chips such as steel castings, austenitic steels, and ductile cast iron The K group is used for cutting materials such as grey cast irons, non ferrous alloys, non metals Coated carbides have the advantage of wear resistance of ceramics and the strength of cemented carbides The coating materials are TiC, TiN, and Al_2O_3 and the coating layers may be single, or multiple with coating thickness varying from 3 - 10 μm The main factors affecting the cutting performance of coated tools are the kind of coatings, the thickness of the coating, the coating method, and the substrate

Ceramics and cubic boron nitride (CBN) have excellent hot hardness, good wear resistance and chemical stability properties which make them suitable for machining many difficult to machine material Two basic ceramic materials are used for cutting tools These are aluminium oxide (Al_2O_3) and silicon nitride (Si_3N_4) Aluminium oxide ceramics are further divided into (i) pure ceramic (Al_2O_3 + ZrO_2), (ii) mixed alumina (Al_2O_3 + TiC), and (iii) reinforced alumina (Al_2O_3 + SiC_w) The whisker reinforced alumina ceramics give superior cutting performance in the case of machining super alloys Sialon (Si_3N_4) cutting tools have been in use since 1980 The main advantage of this ceramic is it's higher toughness values The feed rate can be doubled compared to the conventional Al_2O_3 based ceramics

Heat resistant super alloys possess some characteristics which deter their machinability The metallurgical characteristics responsible for the good strength and creep resistance of nickel base super alloys at high temperatures are liable for their being difficult to machine These materials work harden rapidly during machining Other factors such as low thermal diffusivity, presence of carbide particles are also responsible for their poor machinability

3.3 Machinability Tests

A range of machinability tests have been developed, often to assess specific cutting conditions, whilst others are used for more general machining assessment Sometimes machinability data is expressed in the form of a single index such as a "standard" material being ranked as 100% with others having values relative to it The ratings can be dependent on the type of test as well such as the Volvo "flycutting" milling test [87] Here the tests have index values on a "100 scale" In general a machinability test assess the speeds and feeds which are varied by trial and error and with specified constraints [88]

Nevertheless, the three main parameters of machinability assessment are i) cutting force, ii) tool life, and iii) surface finish Figure 3 1 shows different machinability

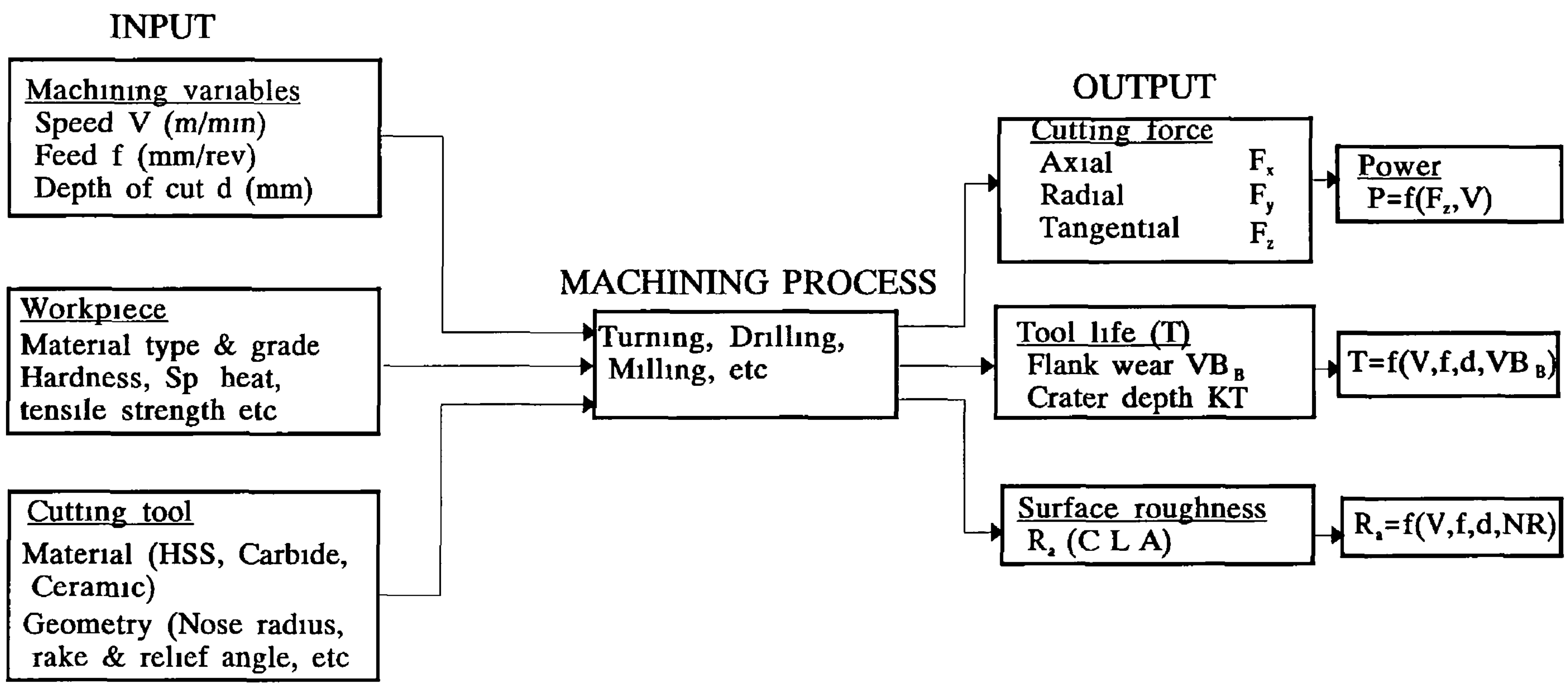


Figure 3.1 Various machinability parameters in a machining process.

parameters in the form of input/output model of turning operation These three parameters have been measured/recorded in our machinability tests of EN24T steel and inconel 718 A brief discussion of these parameters follows

3.3.1 Cutting Force

The metal cutting process is a result of two relative movements between the cutting tool and the work material which has to be machined The relative movements between the cutting edge and the work piece 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

An understanding of the forces and velocities which occur during the various cutting processes is the essential basis for determining the size and material of the load transmitting elements together with the required driving power 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-force situation where the cutting edge is inclined to the cutting velocity The details of these cutting processes with regard to chip formation are described in different books and papers [89-99] A short outline of the different forces involved in the oblique cutting is explained

In the turning operation, the primary cutting motion is rotational with the tool feeding parallel to the axis of rotation The resultant cutting force F which acts upon the cutting tool is resolved into three components in the three directions as shown in Figure 3 2 The tangential force F_z acts along the direction of the cutting speed i e, it is tangential to the turned surface This is the main component of cutting force, which together with the cutting speed determines the net power required for the main spindle drive The tangential force accounts for almost 99% of the power required by the process The feed force F_x acts along the direction of the tool feed This force is usually about 15%-50% of the tangential force F_z but accounts for only a small percentage of the power required The power required for the feed drive is determined by the feed force together with the feed velocity The radial or thrust force F_y acts perpendicular to the turned surface This force is about 30%-50% of the feed force F_x and contributes very little to power requirements because the velocity in the radial direction is negligible The net resultant force F becomes

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

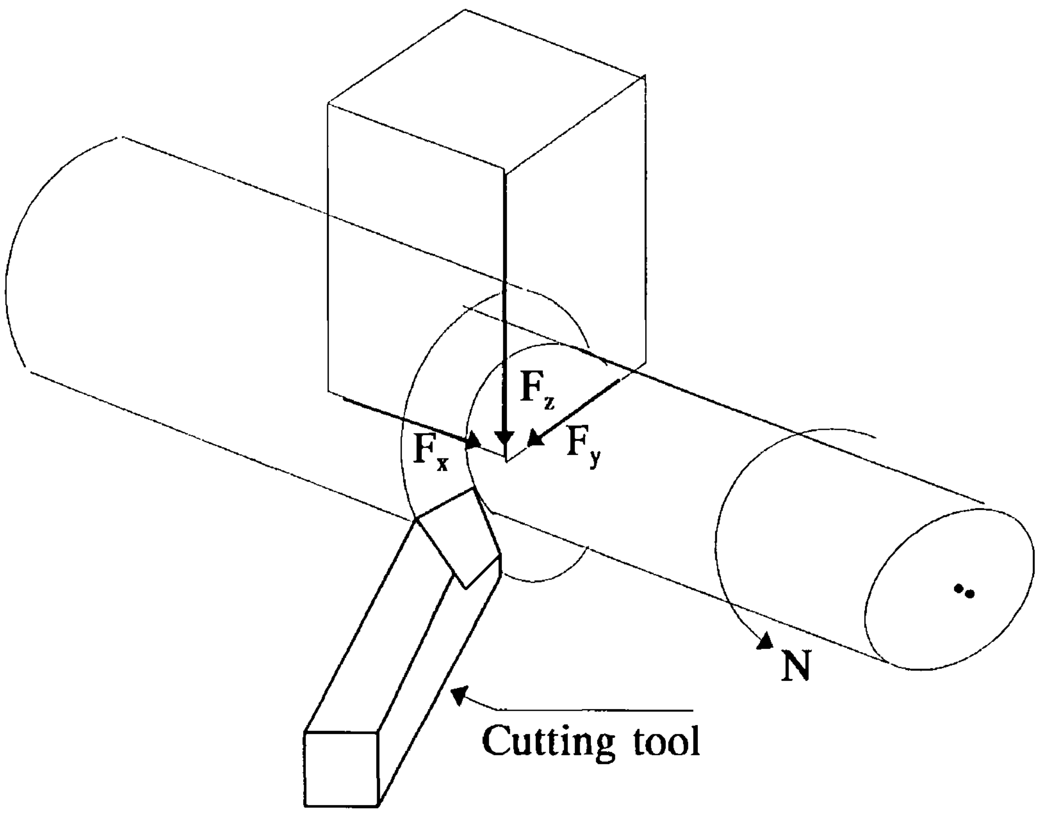


Figure 3.2 Three components of measurable cutting forces acting on a single-point turning tool in oblique machining

3.3.2 Tool Life

In metal cutting operations, the tool life is one of the most important economic considerations Any tool or work material improvements that increase tool life is desirable Cutting tools are in metal to metal contact with the chip and workpiece under conditions of very high stress at high temperature The existence of extreme stress and temperature gradients near the surface of the tool further aggravates the situation

The term tool wear refers to the degradation of the cutting and/or clearance surface of the tool, fracture, and a reduction of the tool mechanical properties due to high temperature [100] Tool wear is a product of a combination of four load-factors which continually attempt to change the geometry of the cutting edge [101] These four factors are mechanical, thermal, chemical, and abrasive which result in five basic wear mechanisms such as (i) adhesive wear, (ii) abrasive wear, (iii) diffusion wear, (iv) fatigue wear, and (v) oxidation wear Acting in isolation or in combination, these mechanisms cause two distinct wear modes [100]

The first type known as irregular wear, includes cracking, breakage, chipping, and plastic deformation of the insert The second type defined as regular wear consists of flank wear on the nose and the primary cutting edge, and the crater wear across the rake face of the tool insert Flank wear is generally the normal type of tool wear and is responsible for increasing the cutting force and the interfacial temperature Crater wear, on the other hand, is usually observed when machining steel and other high melting point metals at a relatively high cutting speeds The crater is formed some distance away from the cutting edge in the region where the tool is hottest

The simple mechanism of adhesive wear [102] is based on the concept of the formation of welded joints and the subsequent destruction of these joints when two mating surface come close enough together During metal cutting, when these junctions formed between the chip and tool materials are fractured, small fragment of tool material can be torn out and carried away on the underside of the chip or on the new workpiece surface

Abrasive wear involves the removal of tool material by mechanical action when hard particles on the underside of the chip pass over the tool face The abrasion process depends on the hardness, the elastic properties and the geometry of the two mating surfaces Usually, the larger the amount of elastic deformation a surface can sustain, the greater will be its resistance to abrasion wear [103]

In the diffusion type wear, solid state diffusion plays an important role when surface temperatures become very high and surface velocities are low Bowden and Tabor [104] suggested that some diffusion must occur in the adhesion of contacting asperities During metal cutting operation, when the temperature at the interface of the tool and work material is very high, diffusion can take place where atoms move from the tool material to the work material This leads to the weakening of the tool

When two surfaces slide in contact with each other under pressure, asperity on each contacting surface is associated with a wave of deformation At some distance ahead of the asperity the underlying material is compressed, while behind the asperity, tensile stresses elongate the material This change in sign of the stress as an asperity passes a given point can cause fatigue failure of the material below the surface In theory, wear particles are created by cracks, formed underneath the surface, spreading and moving up to the surface [105]

The main manifestations of tool wear are flank wear and/or crater wear Wear on the flank face of a cutting tool is caused by friction between the newly machined work material surface and the contact area on the tool flank This results in a loss of relief angle on the clearance face of the tool The width of the wear land gives an indication of the amount of wear and can be readily measured by means of a toolmaker's microscope The crater wear occurs on the rake face of the tool in the form of a pit known as crater The crater formed on the tool face conforms to the shape of the chip underside and is restricted to the chip-tool contact area

A tool life criterion is defined as a predetermined threshold value of a tool wear measure which indicates that a tool is to be rejected after the threshold value is reached In metal cutting operation, unfortunately the wear of the face and flank of the cutting tool is not uniform along the main cutting edge It is therefore necessary to specify the locations and degree of wear when deciding on the amount of wear permissible before replacing the tool

Figure 3 3 shows wear pattern of a single point tool As shown in the figure, 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 chip at the tool corner region of the cutting edge, the conditions are more severe at the corners The width of the flank wear land at the tool corner *C* is designated by VB_C while that at the opposite end is designated by VB_N known as notch or groove wear

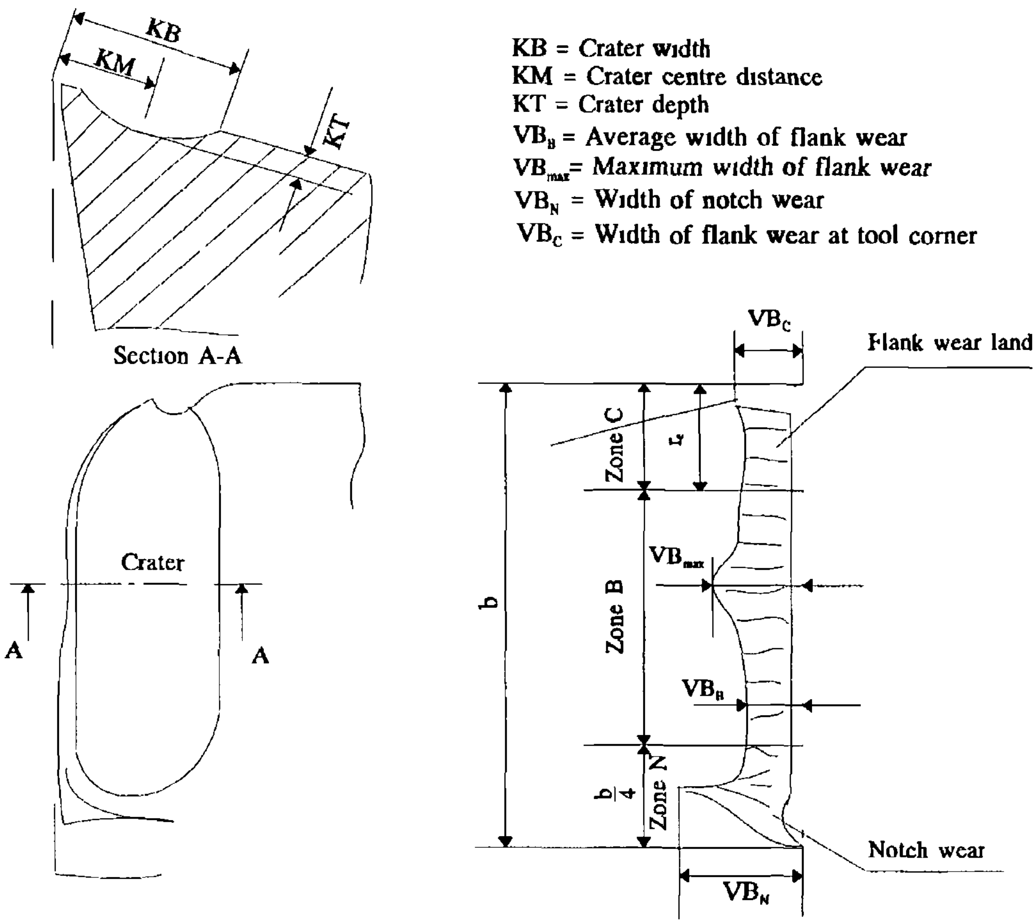


Figure 3 3 Features of single-point-tool wear in turning operations

In the central part of the active cutting edge, the wear land is fairly uniform and is designated as zone *B* The average wear land in this region is VB_B and maximum wear land width is designated as VB_{max} The criteria recommended in the ISO 3685 [106] standard dealing with tool life testing are as follows

3.3.2 1 *Common criteria for high-speed steel tools*

a) catastrophic failure,

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

c) the maximum width of the flank wear land VB_B max $= 0\ 6$ mm if the flank wear is irregularly worn, scratched, chipped or badly grooved on zone *B*

3.3 2 2 *Common criteria for sintered carbide tools*

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

b) the maximum width of the flank wear land VB_B max $= 0\ 6$ mm if the flank wear is not regularly worn on zone *B*

c) the depth of the crater *KT* (mm) is given by the formula

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

where f is the feed in mm per revolution

3 3 2 3 *Common criteria for ceramic tools*

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

b) the maximum width of the flank wear land VB_B max $= 0\ 6$ mm if the flank wear is not regularly worn on zone *B*

c) catastrophic failure

3.3.3 Surface Roughness

In any machined surface, the term used to describe its geometrical quality is known as surface roughness Roughness of a surface refers to a property of a machined surface Surface roughness is that part of surface finish (surface texture) which can be defined as the marks left by the action of the production process used, such as turning operation

Surface roughness consists of relatively closed-spaced or fine surface irregularities usually in the form of feed marks left by the cutting tool on the machined surface It is measured by the heights of the irregularities with respect to a reference line The surface texture of a machined surface consists of primary texture (roughness) and secondary texture The primary texture can be measured by various indices such as average arithmetic roughness height R_a, smoothening depth R_p, maximum roughness R_t, and root-mean-square *RMS* height [107]

With the exception of *RMS*, these various indices (R_a, R_p, R_t) are common in use The index most commonly used is the arithmetic roughness height R_a The secondary texture is that part of the surface texture which underlies the roughness All types of machine vibrations, occurrence of built-up-edge, inaccuracies in the machine tool movement may contribute to secondary texture Figure 3 4 shows the various components and parameters of a machined surface

The average arithmetic roughness R_a is also known as centre line average *CLA* (British) and arithmetic average *AA* (American) R_a is quoted in microns representing a mean value of roughness The *CLA* or *AA* roughness R_a is obtained by measuring the mean deviations of the peaks from the centre line of a trace, the centre line being established as the line above and below which there is an equal area between the centre line and the surface trace The theoretical relationship between the surface roughness value and the feed f is given by the following equation [108]

$$R_a = \frac{0.0321 f^2}{r_\epsilon}$$

where r_ϵ is the corner radius of the cutting tool

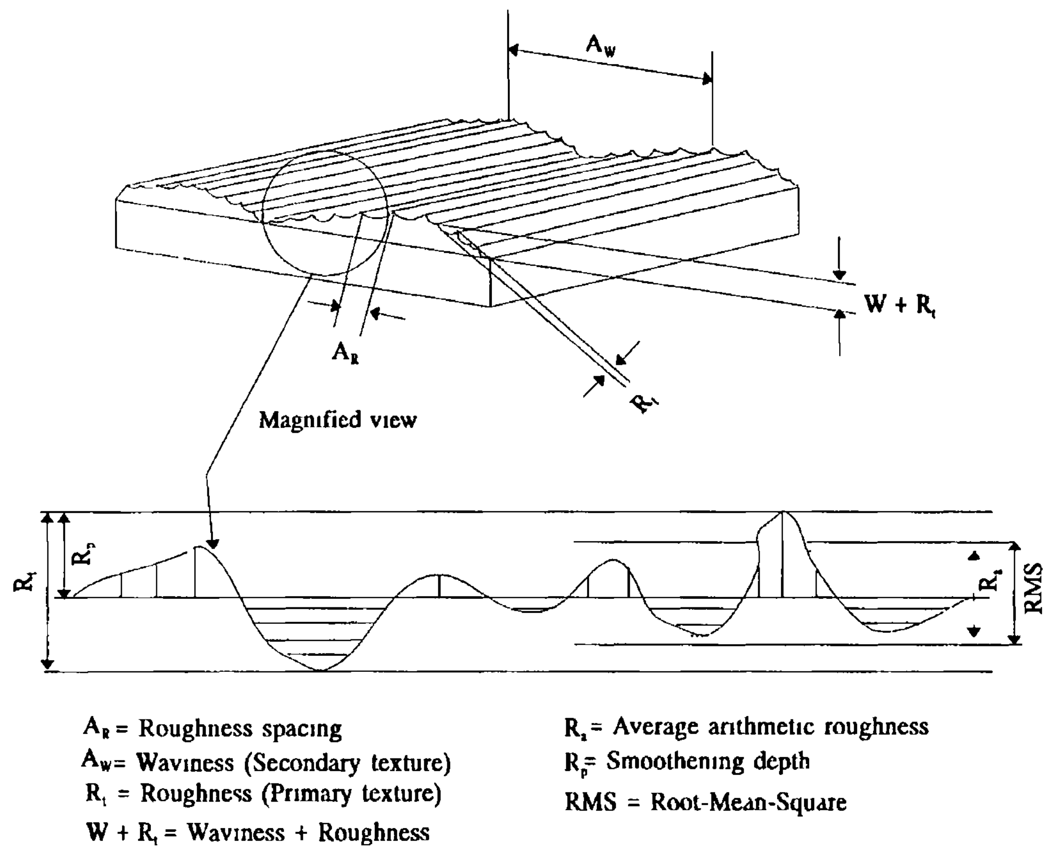


Figure 3.4 Various components and parameters of a machined surface

The smoothening depth R_p is the distance between the highest point and the mean line R_p usually results from the condition of the cutting tool The maximum peak to valley height within the tracing stroke of a surface profile is known as R_t The *RMS* is average geometric roughness and was an American standard Its numerical value is some 11% higher than that of R_a

CHAPTER 4

DEVELOPMENT OF MACHINABILITY MODELS

4.1 Introduction

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 (Figure 3 1) 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 used

In developing a data base system, these machining response data (tool life, surface finish, cutting force) are used as the primary data and mathematical model of these responses are developed as a function of the cutting variables using a model building module

The response surface methodology and the designs for fitting a first-order and second-order model have been described in this chapter Also, the different statistical regression model building techniques for developing mathematical models have been discussed A relatively new approach known as sequential estimation technique which might be useful for model building in the development of machinability data base systems has also been described in this chapter

4.2 Response Surface Methodology

Response surface methodology (RSM) is a combination of experimental and regression analysis and statistical inferences The concept of a response surface involves a dependent variable y called the response variable and several independent variables x_1, x_2, , x_k [109] The RSM was initially developed and described by Box [110-112] in the study of optimization problems in chemical processing engineering Mead and Pike [113] and Hill and Hunter [114] reviewed the earlier work on RSM This has been used in tool life modelling, surface roughness modelling, and in other machining processes [7,54, and 115 -119]

If all of these variables are assumed to be measurable, the response surface can be expressed as

$$y = f\,(x_1, x_2, \quad , x_k) \tag{4.1}$$

The goal is to optimize the response variable y It is assumed that the independent variables are continuous and controllable by the experimenter with negligible error The response or the dependent variable is assumed to be a random variable

Say in a turning operation, it is necessary to find a suitable combination of speed (x_1), feed (x_2), and depth of cut (x_3) that optimize tool life (y) The observed response y as a function of the speed, feed, and depth of cut could be written as

$$y = f\,(x_1, x_2, x_3) + \epsilon \tag{4.2}$$

where ϵ is a random error If the expected response is denoted by E(y) = η, then the surface represented by η = f(x_1, x_2, x_3) is called a response surface It is required to find a suitable approximation for the true functional relationship between y and the set of independent variables x_i's Usually a low order polynomial (first-order and second-order) in some regions of the independent variables is employed

The first-order model

$$y = \beta_o + \sum_{i=1}^{k}\beta_i x_i + \epsilon \tag{4.3}$$

and the second-order model

$$y = \beta_o + \sum_{i=1}^{k}\beta_i x_i + \sum_{i=1}^{k}\beta_{ii} x_i^2 + \sum_{i}\sum_{j}\beta_{ij} x_i x_j + \epsilon \qquad for\ i<j \tag{4.4}$$

are generally utilized in RSM problems The β parameters of the polynomials are estimated by the method of least squares

The matrix approach of solving equation (4 3) or (4 4) has been adopted in our analysis We define **y** to be an *(n x 1)* vector of observations on *y*, **x** to be an *(n* x *p)* matrix of independent variables, β to be a *(p x 1)* vector of parameters to be estimated, ϵ to be an *(n x 1)* vector of errors Equation (4 3) or (4 4) can be written in the matrix form as

$$y = \beta x + \epsilon \tag{4.5}$$

The least squares estimate of β is the value *b* which, when substituted in equation (4 3) or (4 4), minimizes $\epsilon'\epsilon$ The normal equations can be expressed as

$$(x^T x)b = x^T y \tag{4 6}$$

where β is replaced by **b** matrix If $(x^T x)$ is non-singular, the solution of the normal equations can be written as

$$b = (x^T x)^{-1} x^T y \tag{4.7}$$

where x^T is transpose of the matrix x and $(x^Tx)^{-1}$ is the inverse of the matrix (x^Tx) The details of the solution by this matrix approach is explained in reference [120, 121] The response surface analysis is done in terms of the fitted surface Designs for fitting response surfaces are known as the response surface design The main purpose of RSM is to ascertain the optimum operating regions for the system involving the independent variables

In developing the response surface designs, Box and others [122,123] have found that the calculations can be simplified if the designs can be rotated A rotatable design is one that has equal predictability in all directions from the centre and the points are at constant distance from the centre In a rotatable design, the variance of the predicted response $\hat{y}$ at some point x is a function only of the distance of the point from the design centre, and not a function of direction An experimental design with this property will leave the variance of $\hat{y}$ unchanged when the design is rotated about the centre (0, 0, ,0)

4.2.1 Designs for fitting the first-order model

Say it is necessary to fit the first-order model in k variables

$$y = \beta_o + \sum_{i=1}^{k}\beta_i x_i + \epsilon \tag{4.8}$$

An orthogonal first-order design may be employed which minimize the variance of the regression co-efficients (β_i) A first order design is said to be orthogonal if the off-diagonal elements of (x^Tx) matrix are all zero This leads to the cross products of the columns of the x matrix sum to zero The orthogonal first-order design is of two types such as (i) 2^k factorial design, and (ii) simplex design

(i) 2^k factorial design

A factorial design of experiment is one in which all levels of a given factor are combined with all levels of every other factor in the experiment For example, if there are a levels of factor A and b levels of factor B, then each replicate contains all ab treatment combinations Factorial designs are more efficient than one-factor-at-a-time experiments A factorial design is necessary when interactions between the variables are to be investigated Furthermore, factorial designs allow effects of a factor to be estimated at several levels of the other factors, giving conclusions that are valid over a range of experimental conditions This is explained more in detail by Hicks [109] and Montgomery [121] In using 2^k factorial designs, it is assumed that the k factors are coded to the standardized levels ± 1 Let us suppose that we use 2^3 design to fit the first-order model

$$y = \beta_o + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \epsilon \tag{4.9}$$

The x matrix for fitting the model is

$$\boldsymbol{x} = \begin{array}{c} \begin{array}{cccc} \beta_0 & \beta_1 & \beta_2 & \beta_3 \end{array} \\ \begin{bmatrix} 1 & -1 & -1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & 1 & -1 \\ 1 & -1 & -1 & 1 \\ 1 & 1 & -1 & 1 \\ 1 & -1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix} \end{array}$$

The first column of the **x** matrix of independent variables contain only 1's This is the general convention for any regression model containing a constant term β_0, by imagining the β_0 terms to be of the form $\beta_0 x_0$ where x_0 is a dummy variable always taking the value 1 The off-diagonal elements of $(\mathbf{x}^T\mathbf{x})$ matrix are zero for this design It is interesting to note that the 2^k design does not take into account the estimate of the experimental error unless some runs are repeated The common method of including replication in the 2^k design is to augment the design with several observations at the centre ($x_i = 0$, $i = 1,2, \ldots, k$). The inclusion of centre points to the 2^k design does not affect the regression co-efficients (β_i) for $i \geq 1$, but the estimate of β_0 becomes the grand average of all observations. Moreover, the centre points do not influence or change the orthogonal property of the design.

(ii) Simplex method

The simplex method of the design is a regularly sided figure with $k + 1$ vertices in k dimensions. A simplex design is an equilateral triangle for $k = 2$, a tetrahedron for $k = 3$. A more detailed description can be found in reference [121].

4.2.2 Designs for fitting the second-order model

The most commonly used design for fitting a second-order model is the central composite design. An experimental design for the second-order model must have at least three levels of each factor so that the model parameters can be estimated. These designs consist of a 2^k factorial (coded as ±1 notation) augmented by $2k$ axial points ($\pm\alpha$, 0, 0, ..., 0), (0, $\pm\alpha$, 0, ..., 0), (0, 0, $\pm\alpha$, ..., 0), ..., (0, 0, 0, ..., $\pm\alpha$) and n_0 centre points (0, 0, ..., 0). Figure 4(a) and 4(b) represent a central composite first-order and second-order designs respectively for $k = 3$.

The choice of α helps make a central composite design rotatable. The value of α for rotatability depends on the number of points in the factorial portion of the design. A value of $\alpha = F^{1/4}$ yields a rotatable central composite design where F is the number of points used in the factorial portion of the design. For $k = 2$, $\alpha = 1.414$ and for $k = 3$, $\alpha = 1.682$. The central composite design may be built-up from the first-order design (2^k) by adding the axial points and several central points.

The selection of the number of central points n_0 control the properties of the central composite design. With proper choice of n_0, the central composite design sign may be made orthogonal or it can be made a uniform-precision design. In a uniform-precision design the variance of $\hat{y}$ at the origin is equal to the variance of $\hat{y}$ at unit distance from the origin. There are other forms of rotatable designs which are useful as well for problems involving two or three variables. These are known as equiradial designs [121].

The first-order central composite design involving three variables as shown in Figure 4 1(a) consists of twelve experimental runs comprising of two blocks Eight experiments constitute 2^3 factorial design with an added centre point repeated four times (9,10,11,12) *Block 1* (1,4,6,7,9,10) and *block 2* (2,3,5,8,11,12) together provide a precise estimate of the β parameters of equation (4 9)

A second-order model is developed by adding six augment points to the factorial design The augment points consists of three levels for each of the independent variables denoted by $-\sqrt{2}$, 0, $\sqrt{2}$ These six experimental run of *block 3* shown in Figure 4 1(b) is repeated twice to develop the second-order model *Block 4* (19,20,21,22,23,24) is a repetition of *Block 3*

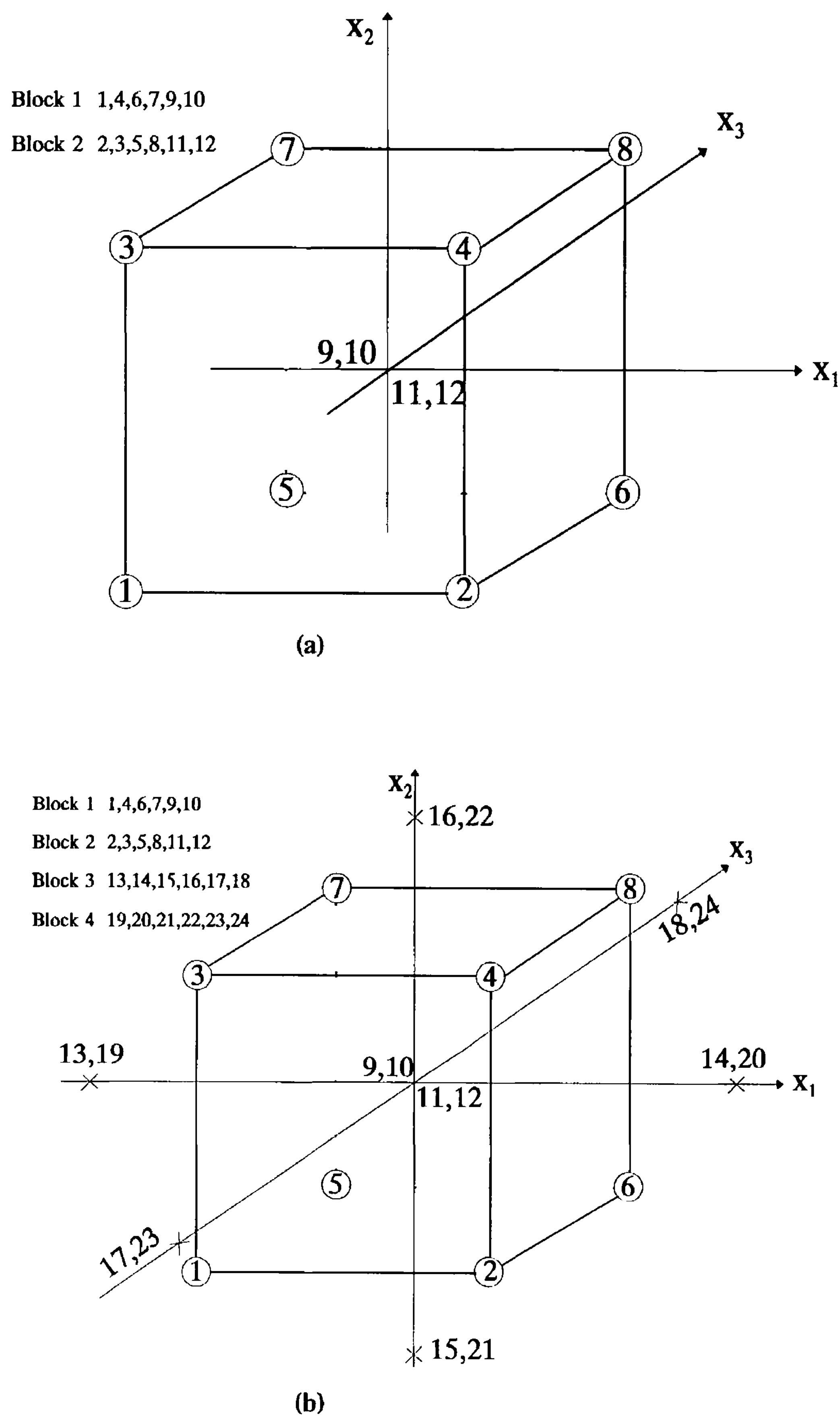


Figure 4.1 Central composite design for K = 3; (a) First-order Design, (b) Second-order design

4.3 Statistical Regression Model Building Techniques

A wide range of regression model building techniques available in commercial statistical packages can be used to derive the functional relationship between the response and the machining independent variables. Given a single response variable **y** and k independent variables $\mathbf{x}_i$ (i = 1 to k), the objective is to determine the subset of the k independent variables and the regression model which taken together best describe the relationship between **y** and the $\mathbf{x}_i$'s. In selecting the best regression equation, the following steps are to be specified. These are (a) the largest model with all the independent variables to be considered, (b) a criterion to be specified for selecting a model, (c) a strategy to be specified for applying the criterion, and (d) the specified analysis to be conducted.

The reason for choosing a large maximum model is to include the basic variables, the higher order and interaction terms of the basic variables. The next step is to specify a selection criterion for selecting the best model. The selection criterion is an index that can be computed for each model and used to compare the models. Many selection criteria for choosing the best model have been suggested [124]. In our analysis, four selection criteria namely RMS_p (Residual mean square), R square, *Adjusted* R square, and Mallows C_p have been considered. These are described in Appendix A. The next step is to specify a technique for selecting the variables. Such a technique determines how many variables and also which particular variable should be in the final model.

Computer programs based on different techniques are available in commercial statistical packages. These are (i) backward elimination, (ii) forward selection, (iii) stepwise regression, and (iv) all possible subsets regression. The various regression model building techniques are briefly described below.

4.3.1 Backward elimination

The backward elimination method computes a regression equation with all the independent variables. A partial F statistic is calculated for every variable treated as though it were the last variable to enter the regression equation. The lowest observed partial F-test value is compared with a preselected F value known as F_{out} If the lowest F-test value is greater than F_{out}, the regression equation as calculated, is the final model If on the other hand, the lowest F-test value is less than F_{out}, the corresponding variable is removed, and the regression equation is recomputed with the remaining variables The lowest F-test value is compared again with F_{out} and the procedure is repeated in this way until all the F-test values are greater than F_{out} [120] The regression equation obtained at this stage is the final model

4.3.2 Forward selection

In this method, the variable having the highest correlation with the dependent variable is selected as the first variable to enter into the model Then a regression equation is computed The significance of the variable entered, is checked by applying partial F-test If F statistic is not significant, the procedure stops and concludes that no independent variables are important predictors On the contrary, if F value is significant, the procedure continues with the inclusion of the next variable Among the remaining variables, the one, having the highest partial correlation with the dependent variable is selected as the second variable and a second regression equation is computed Again, F statistic is checked for significance A preselected value of F, known as F_{in}, determines whether a variable is significant or not The procedure continues until no variables qualify for F_{in} value or all the independent variables are entered and the final model is obtained

4.3.3 Stepwise regression

This method is a modified version of forward selection that allows re-examination, at each step, of the variables incorporated in the model in previous steps The first variable is selected as in forward selection A variable that entered at an early stage may become superfluous at a later stage because of its relationship with other variables now in the model To check on this, at each stage a partial F-test for each variable presently in the model is evaluated and compared with a preselected F_{out} as though it were the most recent variable entered, irrespective of its actual entry point into the model The variable with the lowest insignificant partial F value is removed, the model is refitted with the remaining variables, the partial F values are calculated and similarly examined, and so on The entire procedure continues until no more variables can be entered or removed [125] and the final model is reached To prevent the same variable from cycling in and out, F_{in} must be larger than F_{out}

The forward selection, backward elimination, and stepwise regression algorithms are available in SPSS [126], BMDP [127], and Minitab [128] programme packages For our analysis, SPSS package has been used

4.3.4 All possible subset regression

The procedure for this regression requires to fit each possible regression equation associated with each possible combination of the k independent variables For k independent variables, the number of models to be fitted would be $2^k - 1$ Once $2^k - 1$ models have been fitted, the models are assembled into sets involving 1 to k variables and arranged according to C_p (Appendix A) criterion

A computer algorithm for this regression given by G M Furnival and R W Wilson [129] is available in the BMDP [127] package and this algorithm has been used in the analysis On the basis of C_p and user defined k, the program produces the 'best K' subsets out of all possible regressions In addition, the program also gives the 'best K' subset with one variable, the 'best K' subset with two variables and so on up to the subset with all the variables depending on the number K Finally, the program provides the 'best K' out of all the 'best Ks' with all the statistics and residuals for the subset and that becomes the final model

4.4 Sequential Estimation Procedure

This is another suitable model building procedure to estimate model parameters of a machinability model which we have proposed as a means for efficient parameter estimation The use of this technique is common in the area of on-line system identification [130,131] without any apparent application in the machinability model parameter estimation

A sequential maximum a posteriori (MAP) estimation technique is capable of utilizing prior information regarding the parameters in addition to information regarding the measurement of errors. Inclusion of prior parameter information can have the beneficial effect of reduction of variances of parameter estimators. Assuming a response model of the form given in Equation (4.9), the equation for MAP estimation of the model parameters b_{MAP} are given as [132]

$$b_{MAP} = \mu_\beta + P_{MAP}\, x^T \psi^{-1} (y - x\mu_\beta) \tag{4.10}$$

$$P_{MAP} = (x^T \psi^{-1} x + V_\beta^{-1})^{-1} \tag{4.11}$$

Where

b	= Parameter vector $[p \times 1]$ to be estimated
μ_β	= Parameter vector $[p \times 1]$ known from prior information
P	= Covariance matrix of estimates $[p \times p]$
x	= Matrix $[n \times p]$ of independent variables
y	= Dependent (Response) variable vector $[n \times 1]$
ψ	= Covariance matrix of the errors $[n \times n]$
$\mathbf{V}_\beta$	= Covariance matrix of μ_β $[p \times p]$

Equations (4.10) & (4.11) can be transformed into sequential form by letting

$$b \to b_{i+1},\ \mu_\beta \to b_i,\ y \to y_{i+1},\ P \to P_{i+1},\ V_\beta \to P_i,\ x \to x_{i+1},\ \psi \to \phi_{i+1} \tag{4.12}$$

where ϕ is $m \times m$ diagonal covariance matrix of errors where m is the number of observations taken at each time. The subscript i refers to the sequence number. Substituting Equation (4.12) to Equations (4.10) & (4.11) gives

$$b_{i+1} = b_i + P_{i+1}\, x_{i+1}^T\, \phi_{i+1}^{-1} (y_{i+1} - x_{i+1} b_i) \tag{4.13}$$

$$P_{i+1} = (x_{i+1}^T\, \phi_{i+1}^{-1}\, x_{i+1} + P_i^{-1})^{-1} \tag{4.14}$$

Here $\mathbf{b}_{i+1}$ is an estimator for all p parameters based on $\mathbf{y}_1$, $\mathbf{y}_2$, $\mathbf{y}_3$, $\ldots$, $\mathbf{y}_{i+1}$ as well as on prior information, if any. In order to use the above formulation, it is necessary to invert $p \times p$ matrix $\mathbf{P}_{i+1}$ and the $m \times m$ matrix ϕ_{i+1} at each time. If $m\langle p$, inverses of the matrices in Equation (4.14) can be found by using the matrix inversion lema. The matrix inversion lema is described in Appendix B. Using the equation of the Appendix B, Equation (4.14) yields

$$P_{i+1} = P_i - P_i\, x_{i+1}^T\, (x_{i+1}\, P_i\, x_{i+1}^T + \Phi_{i+1})^{-1}\, x_{i+1}\, P_i \tag{4.15}$$

$$P_{i+1}\, x_{i+1}^T\, \Phi_{i+1}^{-1} = P_i\, x_{i+1}^T\, (x_{i+1}\, P_i\, x_{i+1}^T + \Phi_{i+1})^{-1} \tag{4.16}$$

Even though $\mathbf{P}_{i+1}$ is a $p \times p$ matrix, the matrices on the right hand sides of Equations (4.15) & (4.16) have become $m \times m$. These $m \times m$ matrices are to be inverted in order to calculate $\mathbf{P}_{i+1}$. Substituting Equations (4.15) & (4.16) into Equations (4.13) & (4.14), we obtain

$$A_{i+1} = P_i\, x_{i+1}^T \tag{4.17}$$

$$\Delta_{i+1} = \Phi_{i+1} + x_{i+1}\, A_{i+1} \tag{4.18}$$

$$K_{i+1} = A_{i+1}\, \Delta_{i+1}^{-1} \tag{4.19}$$

$$e_{i+1} = (y_{i+1} - x_{i+1}\, b_i) \tag{4.20}$$

$$b_{i+1} = b_i + K_{i+1}\, e_{i+1} \tag{4.21}$$

$$P_{i+1} = P_i - K_{i+1}\, A_{i+1}^T \tag{4.22}$$

where $\mathbf{A}$, $\mathbf{\Delta}$, $\mathbf{K}$, and $\mathbf{e}$ are the intermediate values required for updating the values of $\mathbf{b}$ and $\mathbf{P}$. Equations (4.17-4.22) give a general sequential procedure that can be used for Ordinary Least Squares (OLS), Weighted Least Squares (WLS), Gauss-Markov, Maximum Likelihood (ML), and MAP estimation.

Equations (4 17-4 22) can be simplified further when there is a single observation at each time i e , $m = 1$ This is because Δ_{i+1} is a scalar and thus its inverse is a scalar The sequential estimation for $m = 1$ implied by Equations (4 17-4 22) is

$$A_{u,i+1} = \sum_{k=1}^{p} x_{i+1,k} P_{uk,i} \tag{4.23}$$

$$\Delta_{i+1} = \sigma_{i+1}^{2} + \sum_{k=1}^{p} x_{i+1,k} A_{k,i+1} \tag{4.24}$$

$$K_{u,i+1} = \frac{A_{u,i+1}}{\Delta_{i+1}} \tag{4.25}$$

$$e_{i+1} = y_{i+1} - \sum_{k=1}^{p} x_{i+1,k} b_{k,i} \tag{4.26}$$

$$b_{u,i+1} = b_{u,i} + K_{u,i+1} e_{i+1} \tag{4.27}$$

$$P_{uv,i+1} = P_{uv,i} - K_{u,i+1} A_{v,i+1}, \qquad v=1, 2, 3, \quad , p \tag{4.28}$$

where $u = 1, 2, 3, \quad , p$ and σ^2_{i+1} is the variance of y_{i+1} It may be noted that there are no simultaneous equations to solve or non scalar matrices to invert A computer programme written in Fortran can estimate the model parameters sequentially using Equations (4 23-4 28) The sequential estimation procedure can be utilized to estimate the model parameters with/without prior information The prior information provides data for initial model parameters, the covariance matrix $\mathbf{P}_{uv\,0}$ and the standard error of estimate σ_i Details of the analysis on the basis of this method are described in references [69,133]

CHAPTER 5

EXPERIMENTAL FACILITY

5.1 Introduction

In this chapter the experimental facilities used for assessing the machinability have been discussed The details of the machines/equipment, work materials, and cutting tool inserts used have been described

5.2 Experimental Set-up

A three component dynamometer in conjunction with the charge amplifiers, a UV recorder, and a computer were used to measure and record the cutting forces Surface finish was measured by a Surftest detector while the tool wear was measured under a Toolmakers microscope A schematic diagram of the set-up used for force measurement is shown in Figure 5 1 The following machine, equipments, work materials and cutting tool inserts comprised the experimental set-up

5.2.1 Machine and equipments

(a) A Colchester M1600, 10HP engine lathe with maximum spindle speed 1600 rpm, feed range of 0 06 - 1 0 mm/rev,

(b) Kistler three component dynamometer (type 92625A1, calibrated range F_x = 0-15000 N, F_y = 0-15000 N, and F_z = 0-3000 N) with three Kistler charge amplifiers (type 5011), and a UV recorder (type M12-150A),

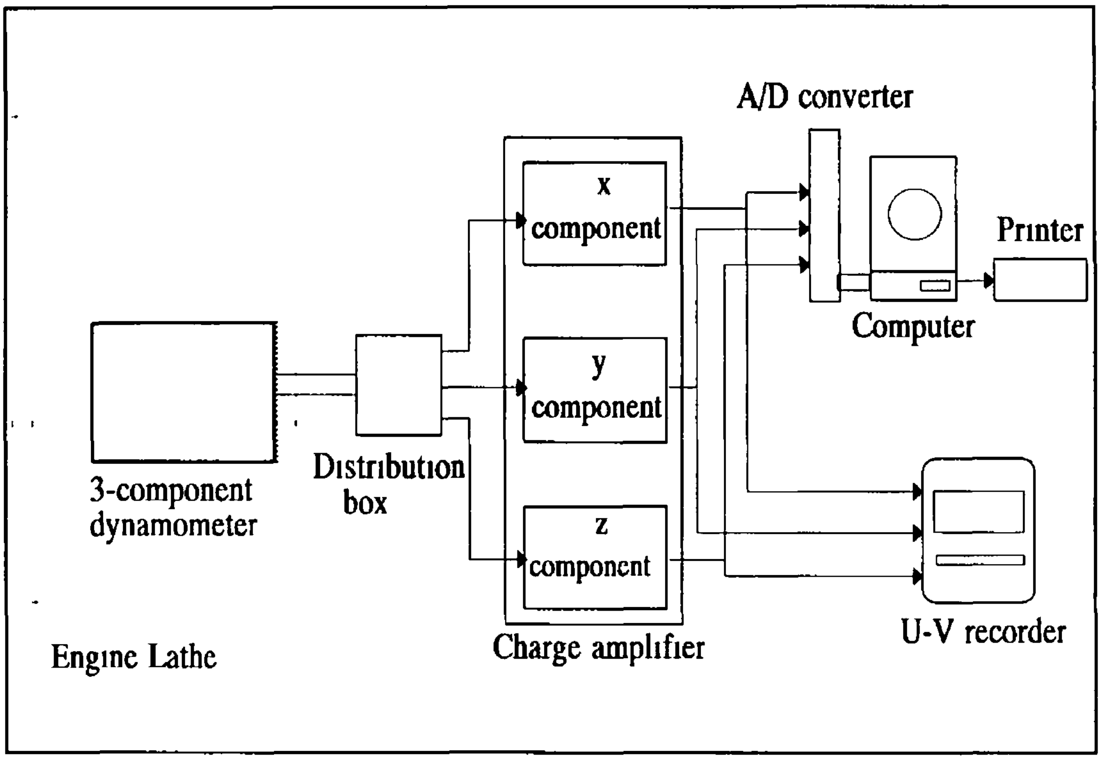


Figure 5.1 A schematic diagram of force measuring set-up

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

(d) Tool wear measuring microscope (Mitutoyo TM300 toolmakers microscope)

The force measuring system consists of a 3-component dynamometer, a distribution box, three charge amplifiers, an analog to digital (A/D) converter, a computer with printer facility and a light beam oscillograph recorder Surface finish were recorded by a Surftest detector and flank wear were measured by a Toolmaker's microscope

5 2 1 1 Three-component dynamometer

It is a piezo-electric transducer that measures the three orthogonal components of a cutting force and consists of a basic unit and a fixture for lathe This is procured from Kistler piezo-instrumentation, type 9265A1 for turning The basic unit is the main component and consists of a stainless steel base plate, a mounting plate with a cooling system, and transducers The base plate has mounting flanges and on one side, it has a 9-pin Fischer flanged socket

The four 3-components transducers are held under high preload in between the baseplate and the mounting plate They are shielded thermally and mechanically The preload is necessary in order to enable tensile forces in the z-direction and cutting forces to be transmitted by frictional contact The fixture consists of a base plate and a yoke and opening of the yoke takes up the cutting tool holder

A detailed technical data of the dynamometer is given in the Kistler manual [134] The calibrated range of F_x and F_y are from 0 to 1 5 kN and that of F_y is from 0 to 3 0 kN The sensitivities are -7 87 pC/N for F_x, -7 91 pC/N for F_y, and -3 58 pC/N for F_z An isometric view of the dynamometer is shown in Figure 5 2 The unit is mounted on a smooth ground flat surface which in turn is fixed to the cross-slide of a lathe The position of the tool holder is such that the point of application of the cutting force was within 50 mm in front of the front plate and 115 mm above the base plate of the dynamometer

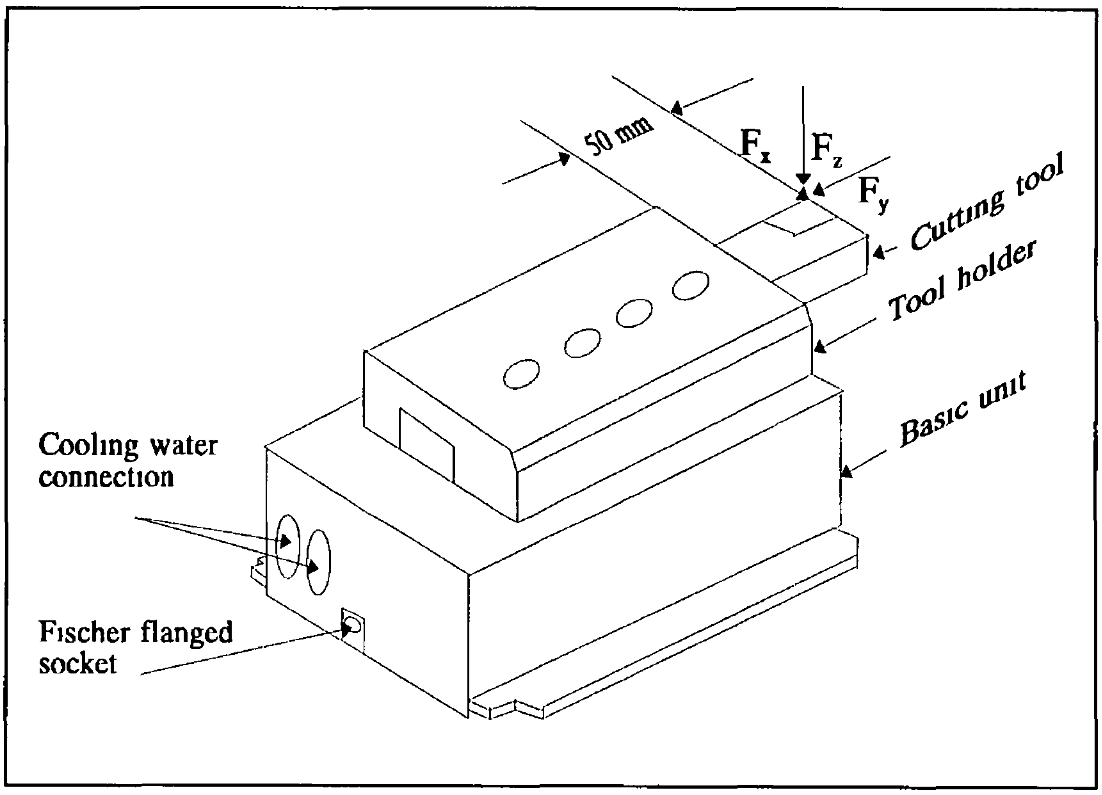


Figure 5.2 Kistler three-component dynamometer

The force to be measured is introduced via the tool holder and the mounting plate, and distributed between four 3-component transducers These force transducers are arranged in a rectangle between the mounting plate and base plate Resolution of the force applied into its three components takes place in the transducers A proportional electric charge corresponding to each of three force components is generated in the dynamometer and converted by the charge amplifiers into proportional voltages

5 2 1 2 Distribution box

The distribution box acts as a connecting link between the dynamometer and amplifiers The F_x and F_y outputs of the transducers are led in pairs and the F_z output singly to the Fischer flanged socket From the socket, the signals for the individual components are added to the distribution box From the box, the three force components are connected to three charge amplifiers by means of special low noise BNC cables

5.2.1.3 Charge amplifier

This is a mains-operated microprocessor controlled one-channel amplifier, type 5011 Three of these types were used for 3-component forces It converts the electric charge yielded by the piezo-electric transducers into a proportional voltage signal The continuous range setting as well as the microprocessor controlled electronics allow for a simple and clearly arranged manipulation The technical details are given in Kistler charge amplifier manual [135] Depending on the magnitude of the cutting forces, the measuring range could be set up in the amplifier through a combination of transducer sensitivity T and scale S Every channel was adjusted to the number of kN per volt output corresponding to the range From the charge amplifiers, the output is parallely connected to a computer and an UV recorder

5 2 1.4 A/D converter

The analog to digital converter receives signals from the transducer via the charge amplifiers It is an 8-channel 12 bit successive approximation high speed converter, full scale input for each channel is ± 5 volts with a resolution of 2 44 millivolts, and the conversion time being typically 25 microseconds

5.2.1.5 Computer

This is a 640 Kbyte RAM with 42 Mbyte disc space with IBM compatible VDU. It digitizes the signal through a programme written in BASIC language and displays the magnitude of the component forces through a printer output.

5.2.1.6 Lightbeam oscillograph recorder

This is a M12-150A [136] direct writing recorder. It uses a low power light source with a high performance optical system together with a servo controlled chart drive system. The performance of the lamp is optimised by operating it from a regulated supply to eliminate the damage caused by short term overloads and supply fluctuations. In the stand-by mode, the lamp is run below full power and is instantly brought up to full power at the commencement of recording. Up to 12 channels of information can be recorded on a 150 mm wide roll of direct print out paper.

The principle of operation follows from the ability to reimage a tiny light source as a spot of light for each channel, which can be deflected across the full width of light sensitive paper, by the mirror of a miniature galvanometer. The resulting record becomes visible shortly after emergence from the recorder, by the action of the ambient light on the recorded image.

5.2.1.7 Surface roughness tester

Surface roughness can be expressed numerically in a number of ways, but the most widely used is the arithmetical mean deviation designated as R_a. The different parameters used to express surface roughness are R_z, R_p, and *RMS* values [107]. In our experimental work, R_a values have been used to express surface roughness. It is defined as the arithmetical average value of the departure of the profile above and below the reference line (centre line) throughout the prescribed sampling length. Surftest detector from Mitutoyo has been used for this purpose. The detector is made up of (a) driving/display unit, (b) a slider, (c) a skid, (c) a detector, and (d) a nosepiece.

Figure 5.3 shows a schematic diagram of the instrument. A cut-off value was set before measuring the roughness. Cut-off is a filtering operation which is performed by a frequency dependent electronic filter. Its function is to suppress waviness (secondary texture) to whatever degree is required within the limitation of the cut-off unit It may be noted here that a misleading roughness height value could be obtained for the surface if proper value of cut-off is not selected Three sample measurements over the diameter were taken at each observation point to ensure that the values obtained are representative of the whole surface area The average of the three readings were taken as the roughness value

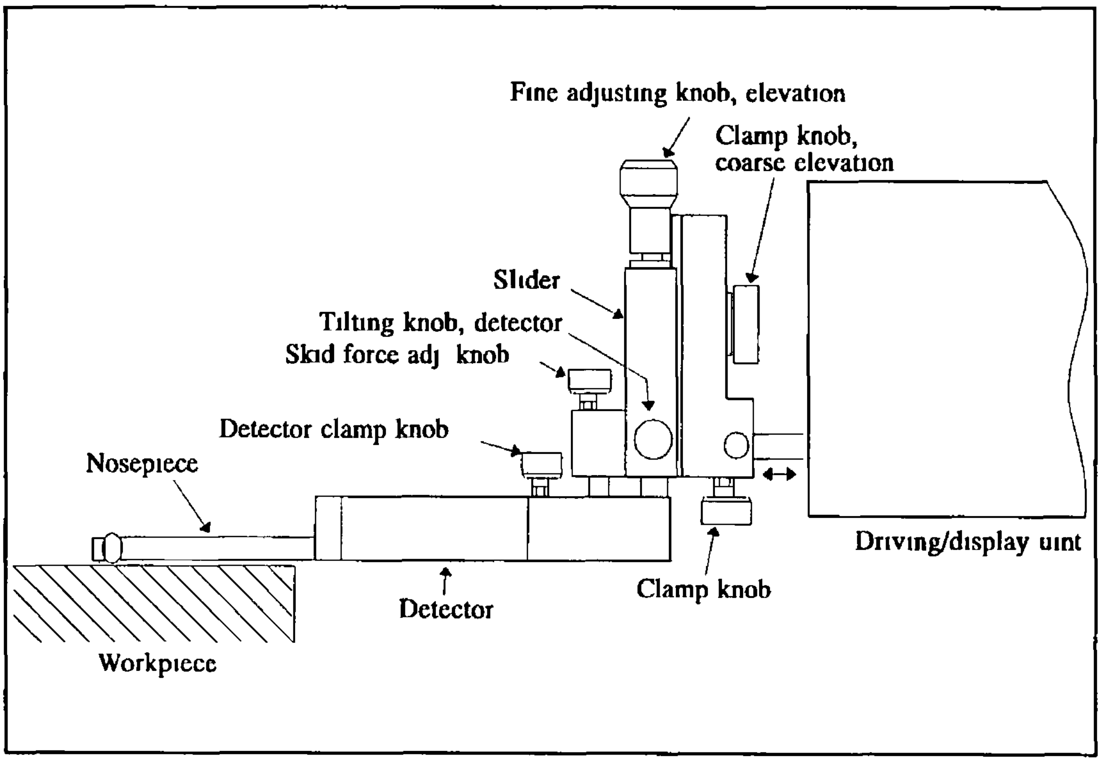


Figure 5.3 A schematic of surface roughness measurement with the Surftest

The specifications of the Mitutoyo Surftest - 402 [137] are as follows

Driving/Display unit:

Displayable parameters	R_a, R_q (RMS), R_z, and R_{max}
Displayable range (μm)	$(R_a, R_q) \Rightarrow$ 0 01 - 2 0, 0 1 - 10 0, 0 2 - 50
	$(R_z, R_{max}) \Rightarrow$ 0 1 - 10 0, 0 2 - 50 0, 1 - 250
Cut-off value (mm)	0 25, 0 8, and 2 5
Driving speed	0 5 mm/s during measurement and approximately 1 mm/s during return

Elevation range of	
the detector	Coarse range is 40 mm, fine range is 10 mm
Display	Liquid crystal display
Power supply	Nickel cadmium storage batteries/ AC adapter 9V-800 mA

Detector:

Detecting method	Differential inductance type
Stroke	0 3 mm
Stylus tip	Of diamond
Tip shape	Conical of 90^0
Tip radius	5 μm
Curvature of radius of skid	30 mm

5 2 1 8 Toolmakers microscope

The Tool maker's microscope used for flank wear measurement was a precision optical measuring instrument with the following specifications [138]

Type:	Column supported erect type, TM301
Microscope:	Eyepiece optical tube Vertical tilt angle 30 degrees, monocular type
	Objective Magnification 3x,
	Working distance 72 5 mm
	Eyepiece Magnification 10x
	Image Erect image
Maximum height of workpiece:	150 mm
Column optical distance:	148 mm
Contour illuminator:	Adjustable telecentric aperture stop
	Light source Halogen lamp 6V, 20W
Control panel:	Power switch with pilot lamp
Power supply:	100,110,120,220,240 VAC, 50/60 Hz

A schematic of the microscope is shown in Figure 5 4

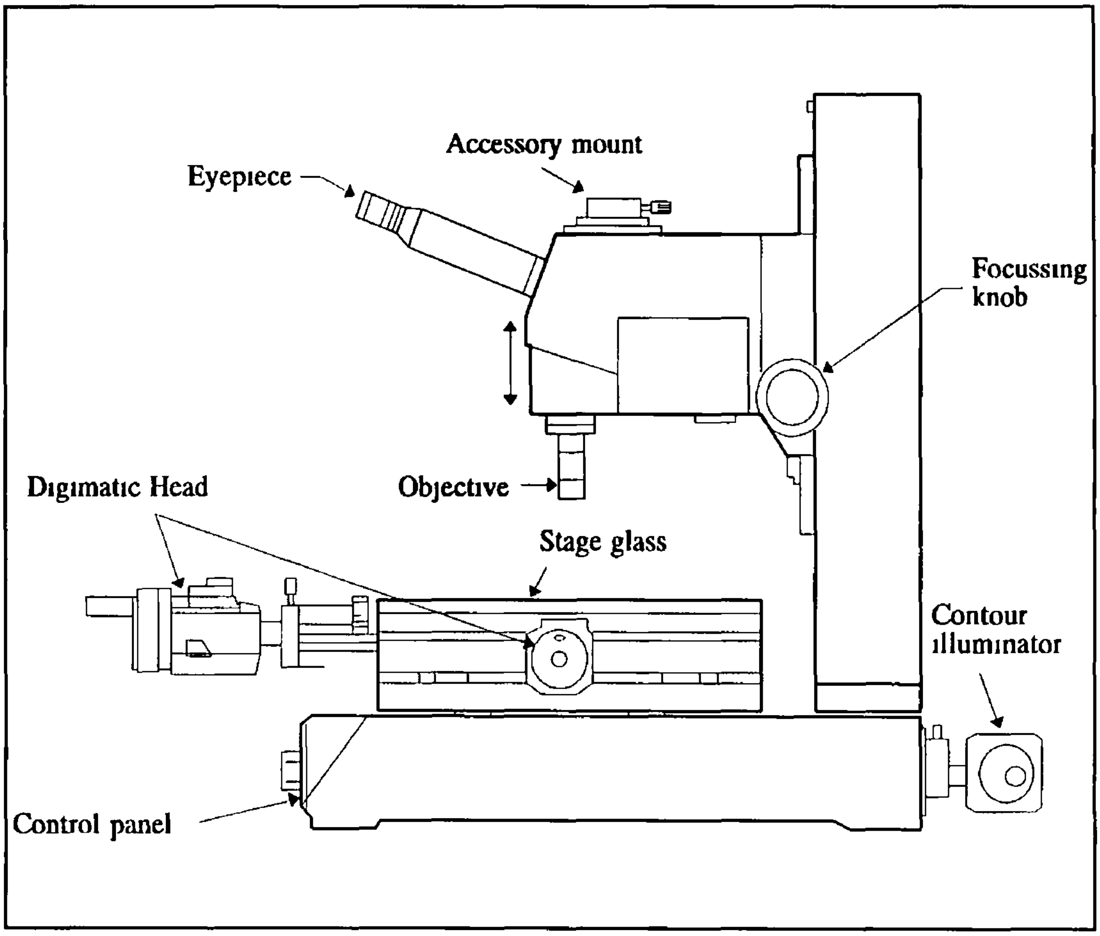


Figure 5.4 Mitutoyo toolmakers microscope

5.2.2 Work-piece material

The work materials used as the test specimen were i) high strength steel specified as EN24T (2 metre long and 76.2 mm diameter) and ii) inconel 718. Two cylindrical bars of inconel (1 metre long and 55 mm diameter) were used for the tests. The details of material properties are given in Table 5.1, Table 5.2, and Table 5.3.

The nickel alloy 718 round bar to AMS 5663G specification was purchased from Devtec Ltd, Ireland at fully heat treated condition. By fully heat treated condition, it means that the specimen is solution treated (980 ^{0}C for 2 hours, oil quenched) and

Table 5.1 Chemical composition of inconel-718

AMS 5663G	C	Si	Mn	P	S	Cr	Fe	Mo	Bi
1	0.034	0.07	0.08	0.01	0.0017	18.43	BAL	2.98	<0.25 ppm
2	0.036	0.08	0.03	0.001	<0.001	17.20	BAL	2.98	<0.00003
AMS 5663G	**Ni**	**Al**	**Ti**	**Co**	**Cu**	**B**	**Pb**	**Cb/Nb+Ta**	**Se**
1	52.67	0.56	1.01	0.11	0.04	0.0041	<0.5 ppm	5.10	<3 ppm
2	51.17	0.65	1.03	0.11	0.02	0.0045	0.0001	5.241	0.0001

Table 5.2 Mechanical properties of inconel-718

AMS 5663G	Yield 0.2%PS (MPa)	Tensile Stress (MPa)	Reduction of Area %	Elongation %	Condition	Hardness HB
1	1248	1419	49	20	Room Temp	415
	1027	1140	48	19	649 ^{0}C	
2	1176	1422	43	22	Room Temp	444
	951	1154	44	26	649 ^{0}C	

Table 5.3 Composition and properties of EN24T

Chemical composition %							
C	Si	Mn	P	S	Cr	Ni	Mo
0 40	0 27	0 47	0 01	009	1 01	1 34	0 21
Ultimate tensile strength							925 MPa
Yield strength							820 MPa
Hardness							290 BHN

aged (720 ^{0}C for 8 hours, furnace cooled to 620 ^{0}C and held for 8 hours, air cooled) The details of heat treatment phenomena is discussed in chapter 2 1 and in reference [139]

5.2.3 Tool material

Cemented tungsten carbide (both uncoated and coated) cutting tool inserts were used for turning These inserts are manufactured by Sandvik

Cemented tungsten carbide inserts specification CNMA 12 04 04, uncoated carbide H13A, and coated carbide GC3015 (approach angle K_r = 95°, rake angle = -6°, angle of inclination = -6°) and tool holder (PCLNR25 M12) GC3015 has a thick layer of Al_2O_3 on top of a layer of titanium carbide The total thickness of the coatings is 10μm [140] A view of the coated insert is shown in Figure 5 5

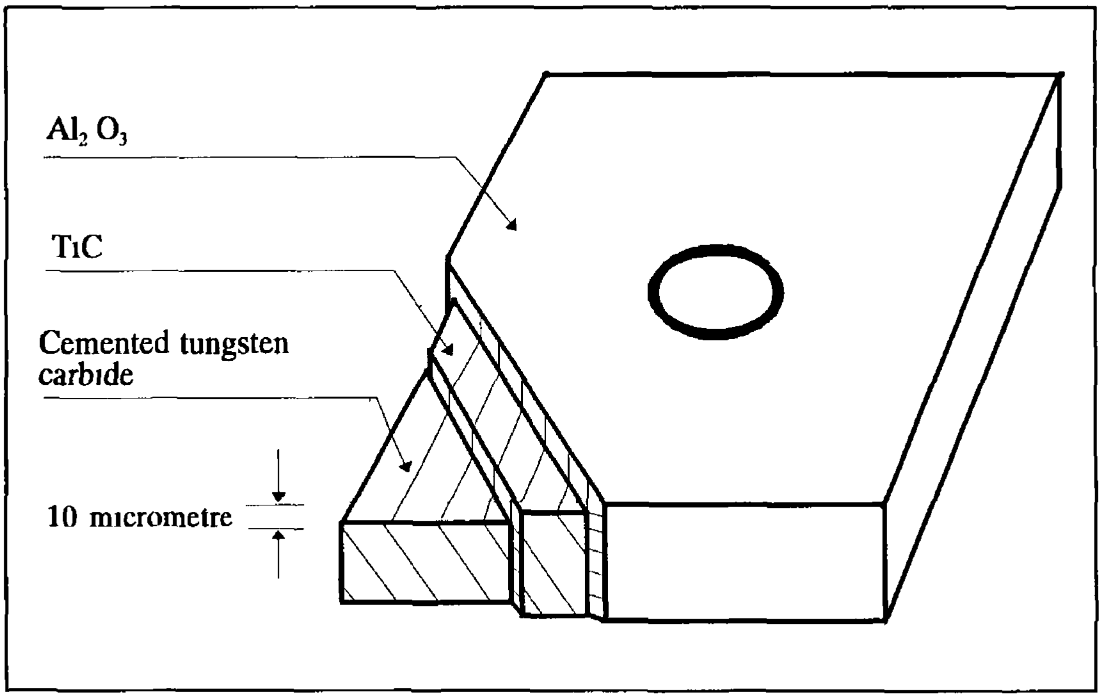


Figure 5.5 A coated carbide (GC3015) cutting tool insert

CHAPTER 6

EXPERIMENTAL RESULTS AND DISCUSSIONS: ONE-VARIABLE-AT-A-TIME

6.1 Introduction

In this chapter, the cutting force and tool life test results (for EN24T Steel and Inconel 718) are presented and analyzed The main analysis include

1 Cutting forces The effect of the machining independent variables, i e cutting speed, feed rate, and depth of cut
2 Tool life The effect of the cutting speed, feed rate, and depth of cut when using uncoated and coated carbide cutting tools

6.2 EN24T Steel

In carrying out the experiments of one-variable-at-a time, two machining independent variables out of the three (speed, feed, and depth of cut) were kept constant and the machining response (cutting force, tool life) was measured/recorded by varying the third variable The turning tests were performed on a high strength material (290 BHN) The objectives of these tests were

(i) to estimate the cutting forces and derive optimum cutting conditions
(ii) to find the tool life values and relationships.
(iii) to determine the exponents of the cutting variables

6.2.1 Cuttıng force

A senes of oblıque cuttıng tests was carned out on a Colchester lathe to ınvestıgate the effect of cuttıng forces on speed, feed and depth of cut All the tests were run dry and Sandvık uncoated carbıde ınserts desıgnated as H13A were used as the cuttıng tools The specıficatıon of the ınsert have been descnbed ın sectıon 5 2 A hıgh strength steel specıfied as EN24T steel (290 BHN) was used as the workpıece matenal

In order to measure the dıfferent cuttıng force components F_z, F_x, and F_y (tangentıal, axıal, and radıal), the tool holder was mounted on the Kıstler dynamometer connected to a PC based data acquısıtıon system through the charge amplıfiers The Kıstler pıezoelectnc dynamometer was mounted on the lathe A UV chart recorder was also ıncorporated ın the data acquısıtıon system to measure the force components and compare the values wıth those obtaıned through the computer Chapter 5 descnbes the detaıls of these ınstrumentatıons and equıpments used

In the force-speed tests, a constant feed rate (0 25 mm/rev) and depth of cut (0 25 mm) were maıntaıned whıle the speed was varıed from 5 to 280 m/mın In ınvestıgatıng the effect of feed on the cuttıng force, feed rate was varıed from 0 08 to 0 60 mm/rev at a constant cuttıng speed (124 and 90 3 m/mın) and depth of cut (0 25 and 1 0 mm)

The cuttıng forces at varıous depth of cuts (0 25 to 1 5 mm) were measured at a constant cuttıng speed (90 3 m/mın) and dıfferent feed rates (0 10, 0 15, 0 25, 0 40, and 0 50 mm/rev) A new cuttıng edge was used at each expenmental condıtıon Three data poınts were taken at each condıtıon and average values are shown on the dıfferent plots

Fıgure 6 1 ıllustrates varıatıon of the tangentıal F_z, feed F_x, and radıal F_y forces wıth the cuttıng speed at a constant feed rate (0 25 mm/rev) and depth of cut (0 25 mm) At low speed (5-70 m/mın), F_z whıch ıs the maın power component of the cuttıng forces was found to be hıgh and then decreased as the speed ıncreased to about 60 - 70 m/mın It ıncreased agaın wıth the ıncrease of speed and thıs continued until the speed reached about 130 m/min. Beyond this speed, F_z decreased gradually with the increase of speed.

As the speed increased from 60 m/min, F_y remained almost constant. The feed force F_x, increased until 130 m/min and gradually became constant as the speed was increased. The tangential force which accounts for the power consumption was the highest among the three components. The feed force was about one half of the tangential force.

The built up edge (BUE) had a major influence on the cutting forces encountered during machining. As the cutting speed increased, the friction between the chip and tool increased and when this became large enough to cause a shear fracture in the region of the tool face, a BUE forms. At very low speed, there was no BUE because the temperature on the face of the chip was not high enough to cause the chip surface to behave in a ductile manner. So the force was high at the low speed since no BUE was present to alter the rake angle.

With the increase of speed, BUE started growing and became maximum in size when the speed was around 60 - 70 m/min. As the size of the BUE grew large, it changed the effective rake angle of the tool and the forces became low. This phenomena was observed when the cutting speed was around 60 - 70 m/min. When the speed was increased from 70 - 130 m/min, the BUE size decreased and disappeared at 130 m/min where the cutting forces were high again. Beyond this cutting speed, the material on the tool face began to soften due to high cutting temperature and the tool face friction was reduced. The chip tool temperature increased and shear resistance of the chip contact layer dropped. This resulted in lower forces [141].

Figure 6.2 and Figure 6.3 depict the force-feed trend at two different constant speeds and depth of cuts. Figure 6.2 is for a cutting speed of 124 m/min and depth of cut of 0.25 mm while Figure 6.3 is for a cutting speed of 90.3 m/min and depth of cut of 1 mm. In both cases, the cutting forces increased with the increase of feed. The rate of increment is almost linear which suggests that the cutting force is directly proportional to the feed rate.

The feed force was smaller than the radial force when the depth of cut was 0 25 mm It may be because at low depth of cut, the chip flow approaches radial direction and the force increases as a result With the increase of speed, chip flow changed its direction until it became longitudinal and thereby increasing the axial component [141]

Figure 6 4 shows the variations of cutting forces with depth of cut at constant speed and feed rate The tangential and the feed forces were observed to increase linearly and have the similar trend but the radial component increased slowly with the depth of cut As the depth of cut was increased from 0 5 mm to 1 0 mm, tangential force was almost doubled

Figure 6 5 through Figure 6 7 shows the individual component of the cutting forces with depth of cut at various feed rates

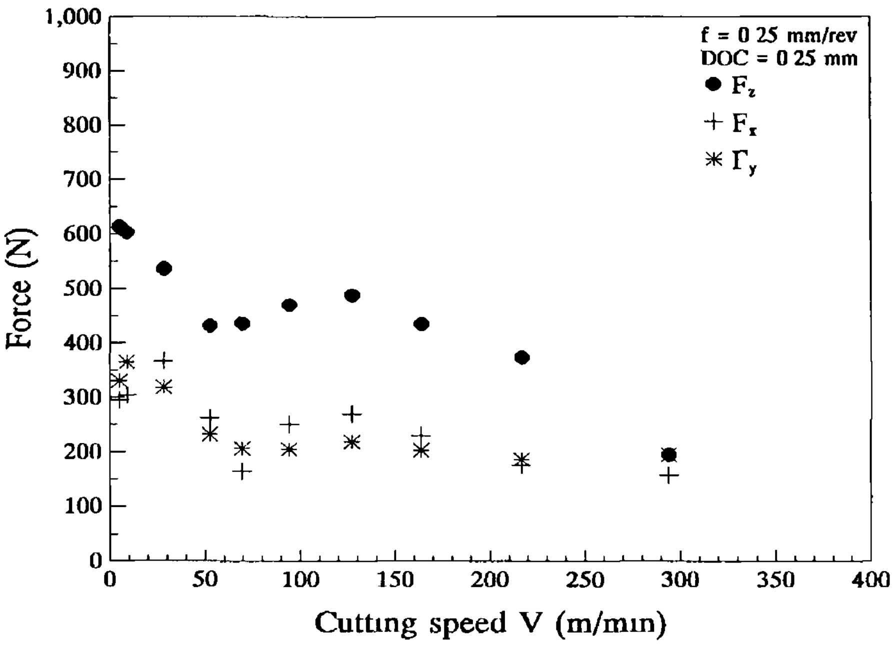


Figure 6.1 Variation of cutting forces with speed

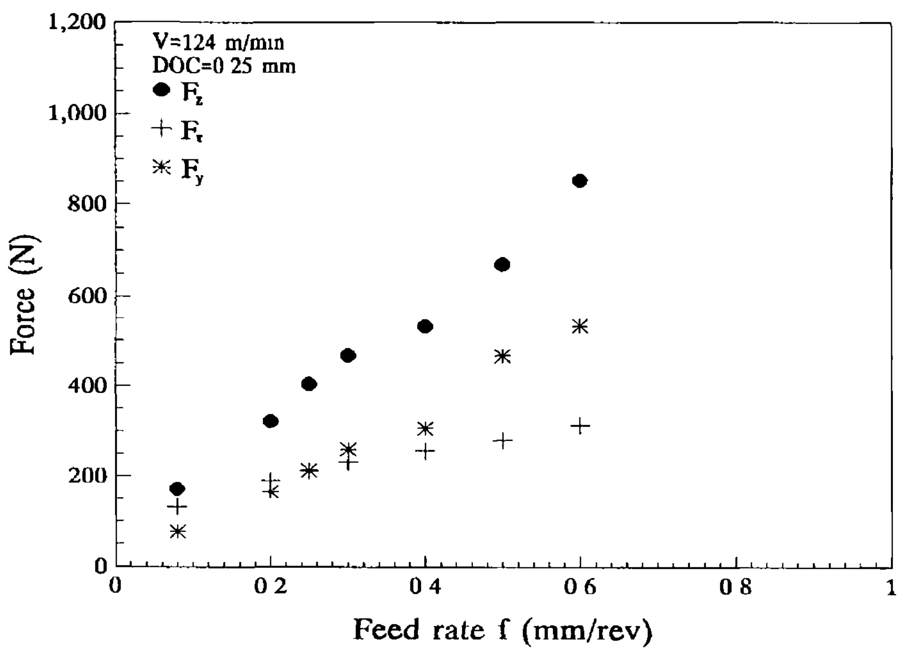


Figure 6.2 Variation of cutting forces with feed rate

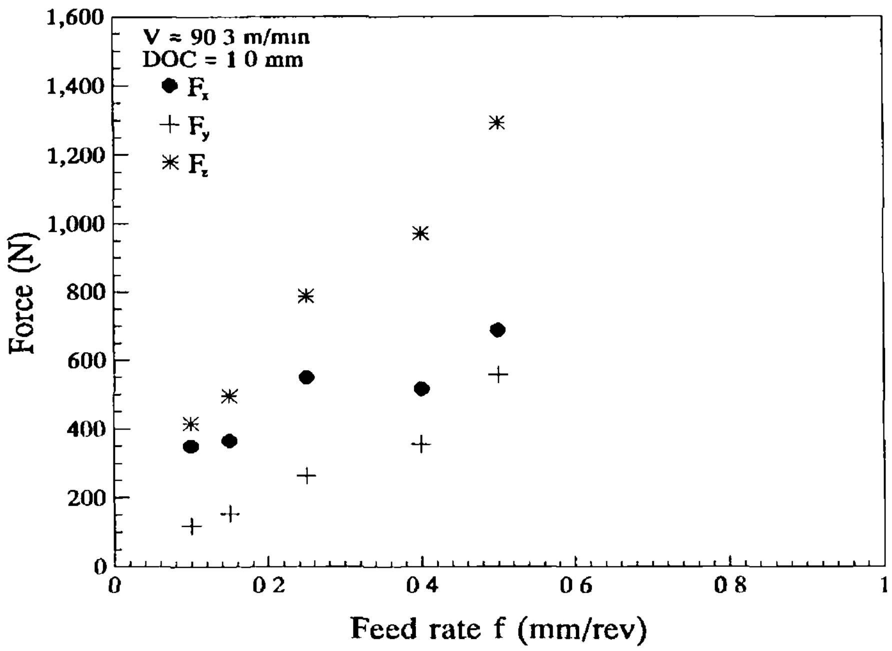


Figure 6.3 Variation of cutting forces with feed at different cutting condition

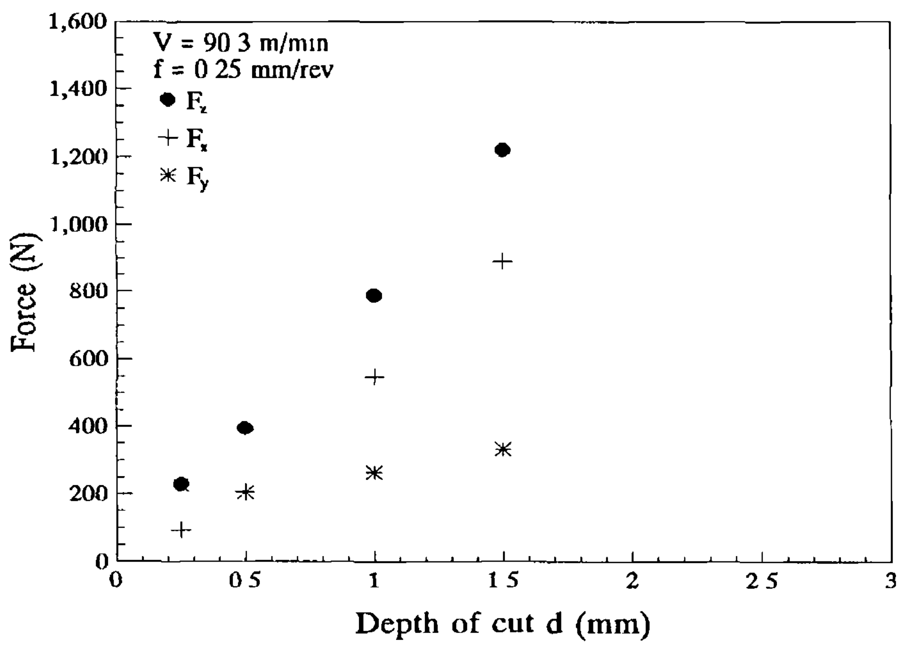


Figure 6.4 Variation of cutting forces with depth of cut

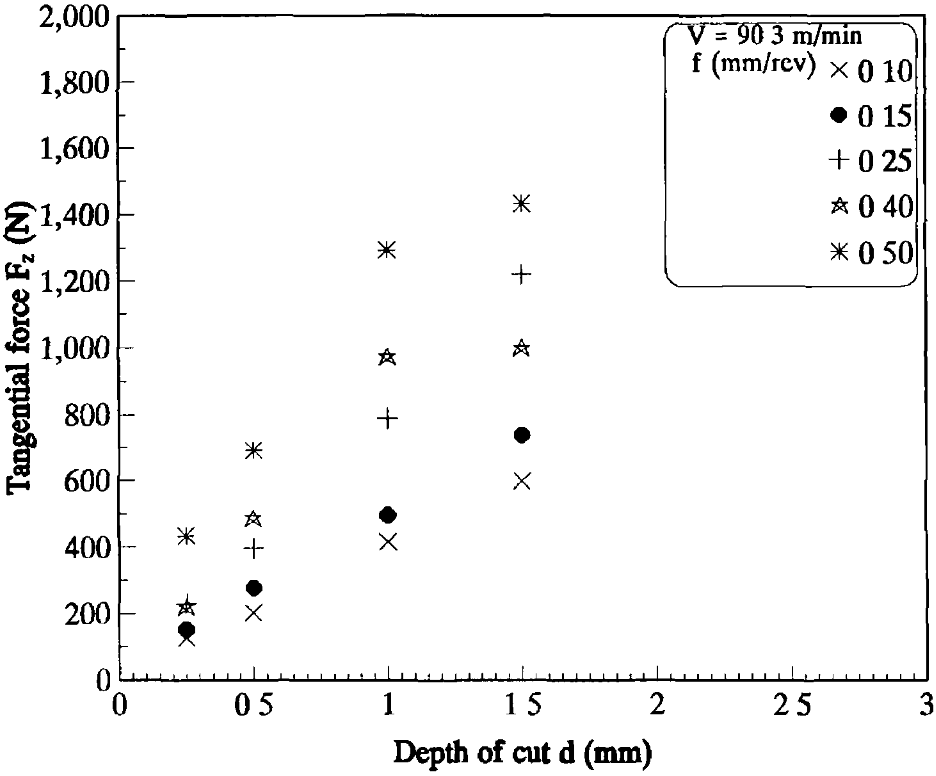


Figure 6.5 Variation of tangential force with depth of cut at different feed rates

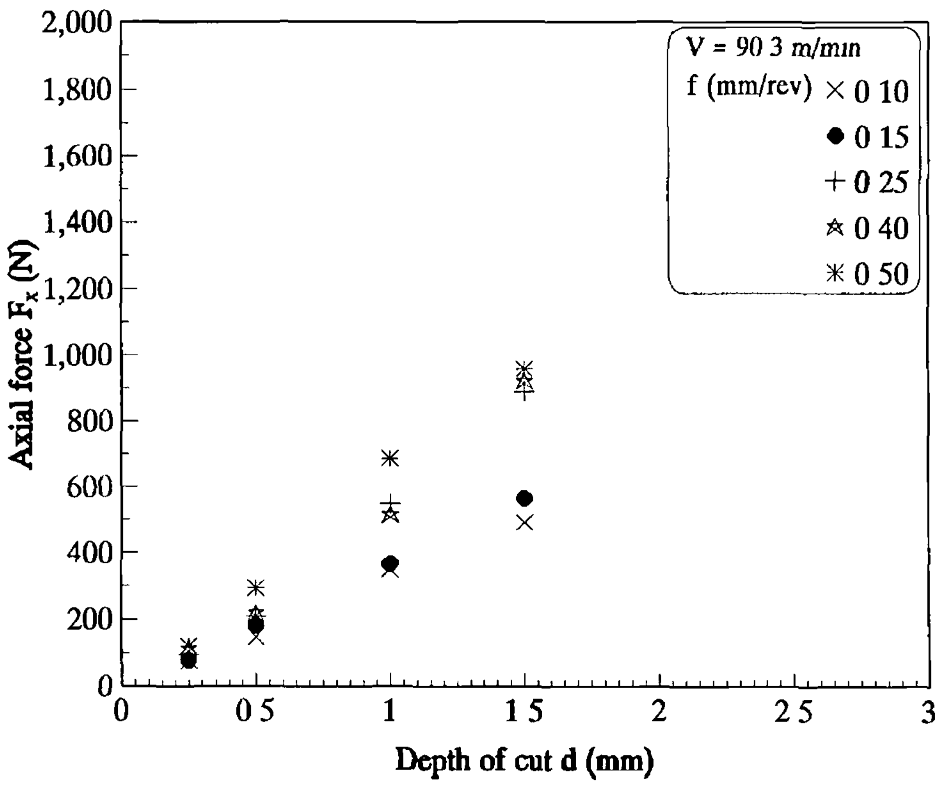


Figure 6.6 Variation of axial force with depth of cut at different feed rates

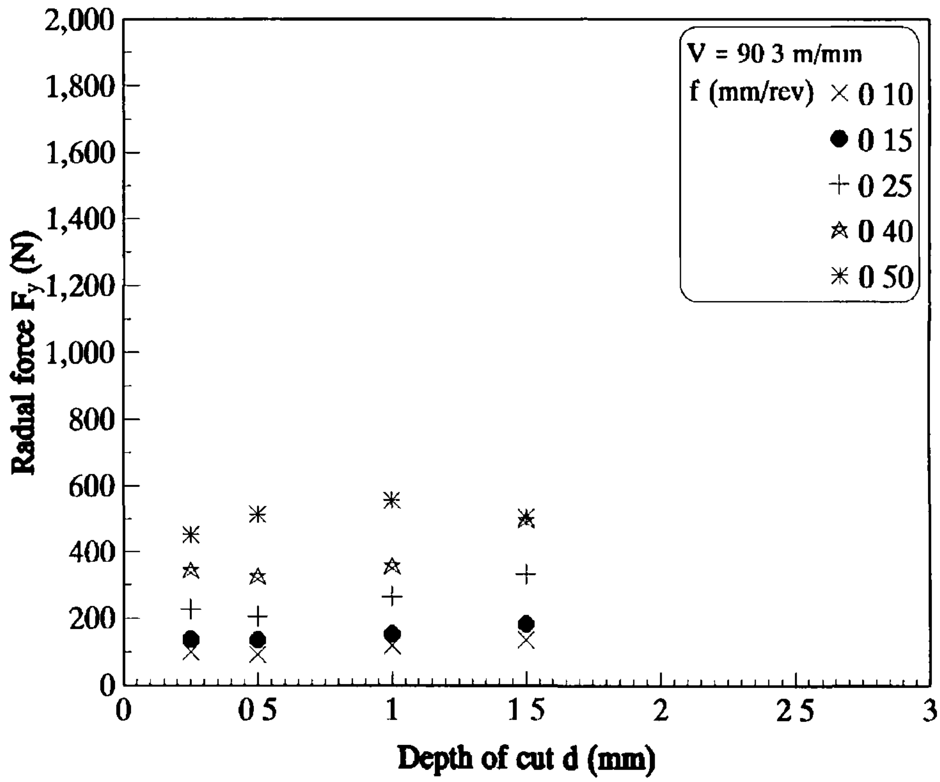


Figure 6.7 Variation of the radial force with depth of cut at different feed rates

6.2.2 Tool life

To investigate the tool life relationship, a series of cutting tests was run under different cutting conditions In these experiments, feed and depth of cut had three levels each and cutting speed had four levels The levels chosen for the variables are given in Table 6 1

Table 6.1 Levels of different cutting variables

Velocity (m/min)	Feed (mm/rev)	Depth of cut (mm)
33	0 15	0 5
65	0 30	1 0
94	0 40	1 5
125		

Round bar of high strength steel specified as EN24T was turned with uncoated carbide cutting tool inserts manufactured by Sandvik Each test was started with a new insert edge and all the tests were run under dry condition Depending on the cutting conditions and wear rate, machining was stopped at various intervals of time varying from 1/2 minute to 1 minute to record wear on the insert The wear was then measured using a Mitutoyo TM300 Toolmakers microscope Further testing was stopped and an insert was rejected when average flank wear equal to or greater than 0 30 mm was reached

ISO 3685 [106] was used as a guide in determining the wear criterion For each set of cutting conditions, one cutting edge was used Average flank wear values have been plotted against cutting time for different experimental conditions from Figures 6 8 to 6 10

Figure 6 8 is a plot of tool wear for various cutting speeds while feed rate and depth of cut were kept constant Clearly three wear zones were observed at low speeds These were (i) primary or initial wear zone with an abrupt increase in flank wear, (ii) secondary wear zone (or steady state region) for a longer period of tool life time, and (iii) tertiary or accelerated wear zone leading to tool failure The extent of these zones is greatly dependent on the cutting speed [96] At higher speed (125 m/min), wear rate was very rapid and three zones were not clearly defined Flank wear increased almost linearly with cutting time until failure occurred

In Figure 6 9, the three characteristic tool wear curves are shown for three different feed rates at constant speed and depth of cut It is obvious that as the feed rate increased tool life decreased But the effect of feed compared to speed on tool life was less pronounced As the feed rate was doubled from 0 15 to 0 30 mm/rev, tool life was changed from 6 22 minute to 5 3 minute whereas it was almost halved when the cutting speed was changed from 33 to 65 m/min

Flank wear at different depth of cuts under constant speed and feed rate is shown in Figure 6 10 The depth of cut had very little effect on tool life Although depth of cut was changed from 0 5 to 1 5 mm, tool life reduced from 5 75 to 4 5 minutes only Comparing the three figures, it can be concluded that cutting speed has the greatest influence on tool life followed by feed rate and depth of cut

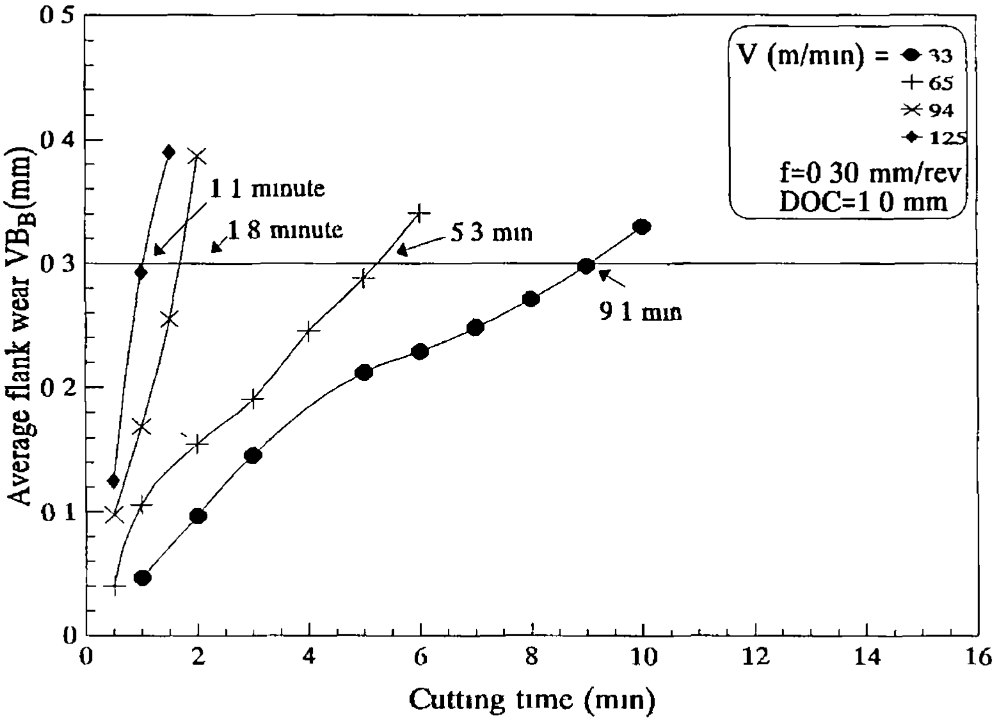


Figure 6.8 Tool wear at different cutting velocities

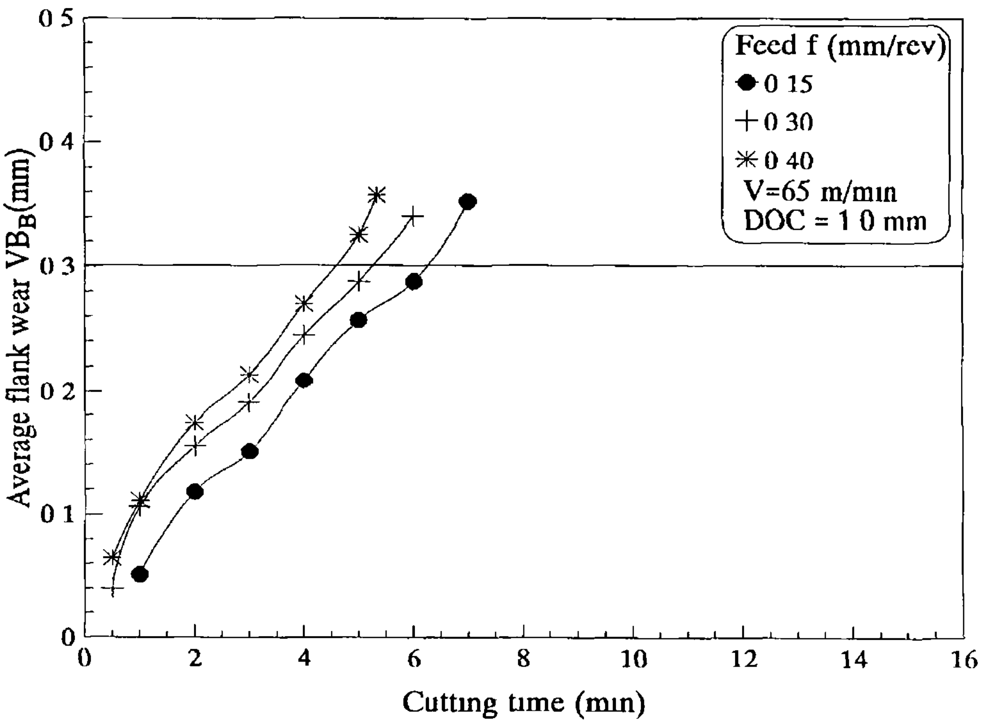


Figure 6.9 Tool wear at different feed rates

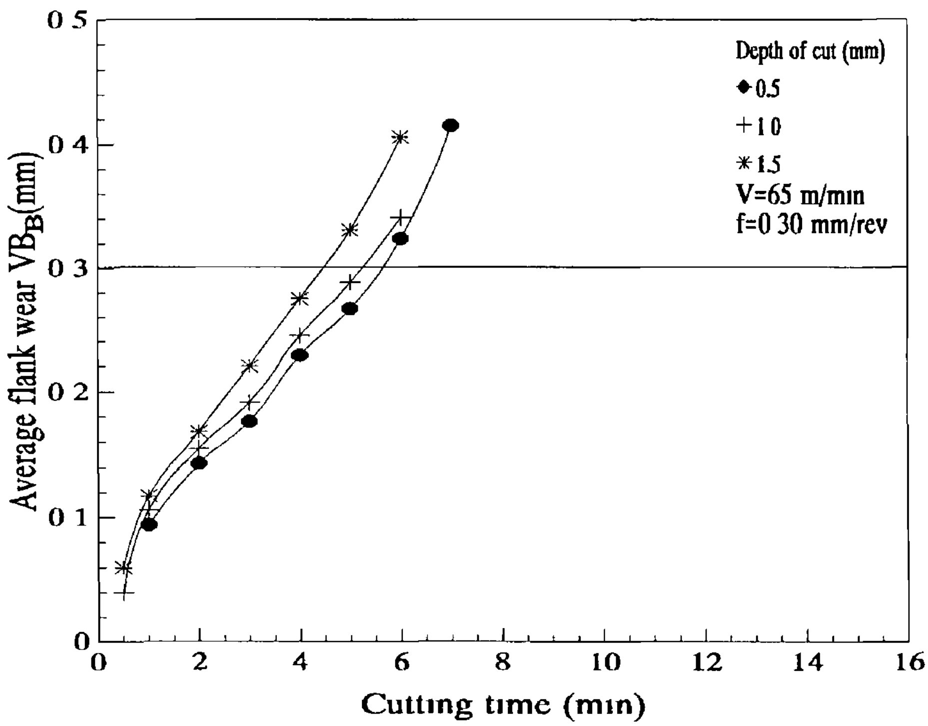


Figure 6.10 Tool wear at various depth of cuts

In order to determine the three exponents of the cutting variables (speed, feed, and depth of cut), the tool life data are plotted on logarithmic coordinates shown in Figure 6 11(a) - 6 11(c) Tool life values for different velocities, feed rates, and depth of cuts are obtained from Figure 6 8, 6 9, and 6 10 respectively

The best fit line obtained by regression analysis [106] has been drawn in each case represented by the solid line in Figure 6 11(a) through Figure 6 11(c) The slope of these lines are the exponents ($1/n_1$), ($1/n_3$), and ($1/n_2$) corresponding to velocity, depth of cut, and feed respectively These exponents describe the effect of the cutting variables (speed, depth of cut, and feed) on tool life The larger the value $1/n_1$, the steeper the V-T slope and greater the change in tool life for a given change in cutting speed The values of the various exponents calculated from figures 6 11(a) - 6 11(c) are shown in Table 6 2

Table 6.2 Values of exponents for various cutting variables

Tool material	Exponent		
	n_1 (speed)	n_2 (feed)	n_3 (DOC)
Uncoated carbide	0 50	2 25	3 9

The largest value of $1/n_1$ compared to $1/n_2$ or $1/n_3$ suggests that speed has the greatest influence on tool life followed by the feed rate and depth of cut

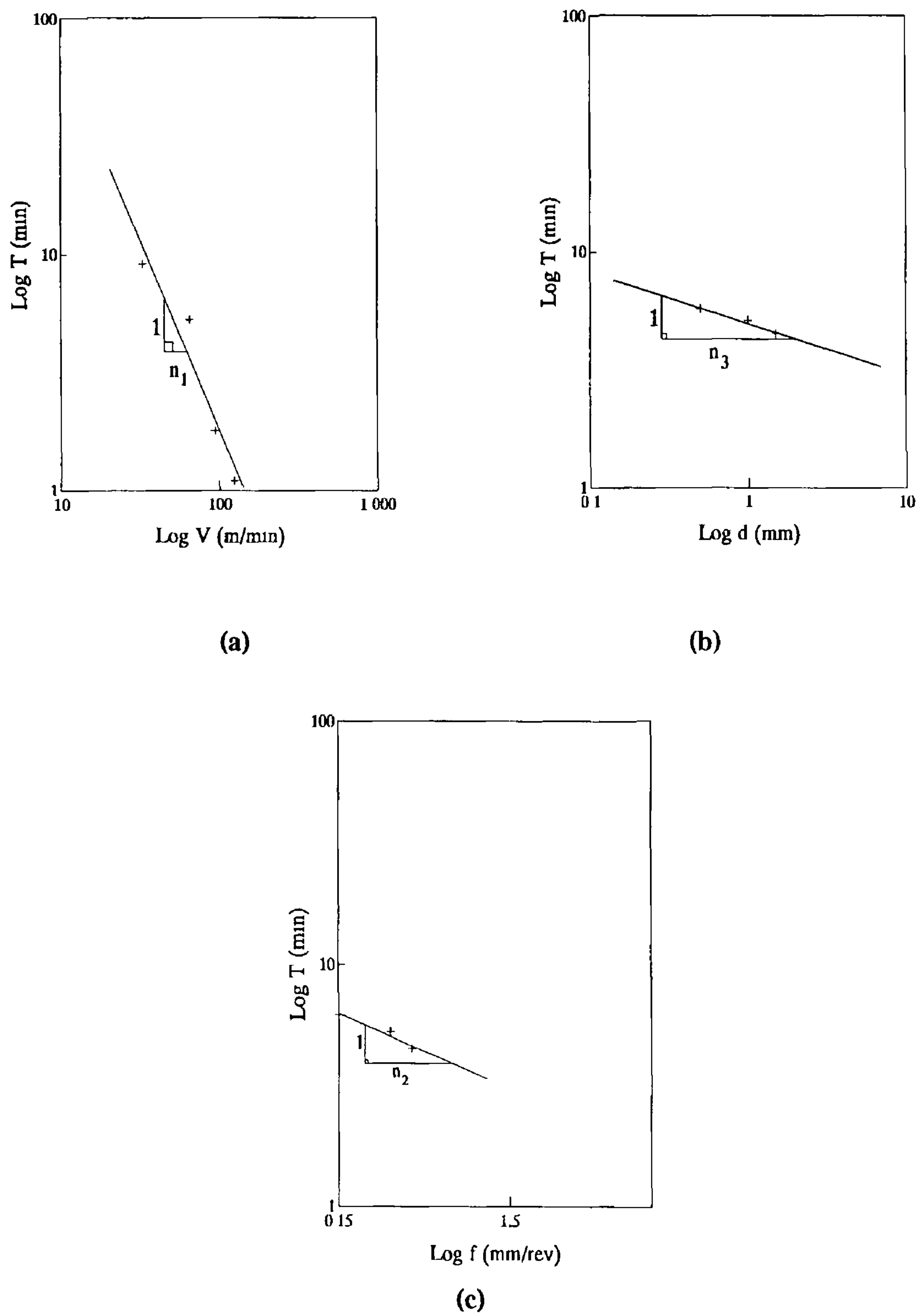


Figure 6.11 Graphical calculation of tool life exponents (a) speed, (b) depth of cut, (c) feed

With the outcome of the test results of turning EN24T steel, the following conclusions could be made

1 The feed force may not vary in the same manner as the tangential force because the latter acts in the direction of cutting which is considerably larger than the force along the direction of feed

2 Higher cutting speeds increase tool temperature and accelerate all types of tool wear Cutting forces decrease with increase in speed since the shear strength of the workpiece decreases

3 With the increase of feed, cutting force increases and the likelihood of chipping of the cutting edge through mechanical shock also increases

4 The higher the depth of cut, the greater is the chip-tool contact area and higher is the tool temperature This accelerates the abrasive, adhesive, and diffusion wear processes

5 The range of speed exponent n_1 for the carbide tool material is reported to be 0 2 - 0 49 [96] which compares well with the one obtained in Table 6 2

6 It is usually found that $1/n_1 \rangle 1/n_2 \rangle 1/n_3$ so that the cutting speed has the greatest influence on tool life followed by feed and depth of cut

6.3 Inconel-718

Round solid bars (length 1 metre, diameter 55 mm) of inconel 718 (415 - 444 BHN) were turned with Sandvik carbide (uncoated and coated) tools in order to assess the cutting forces and tool lives under various cutting conditions All the turning tests were run dry The cutting tool materials used were in the form of tips (80^0 rhomboid shaped) without any chip breaker which were attached to a tool holder The composition and properties of carbide tools have been described in Chapter 5

6.3.1 Cutting force

The force measuring set up described in section 6 1 1 had been adopted to record the three components of the cutting force in turning inconel 718 In the force measurement, only uncoated carbide tools have been used to machine inconel 718 The machining operation involved continuous turning at three different feed rates (0 12, 0 20, 0 30 mm/rev) and three different depth of cuts (0 5, 1 0, 1 5 mm) with the cutting velocity varying from 8 m/min to 69 m/min

Figures 6 12 - 6 14 show the variation of tangential, axial (feed force), and radial forces with cutting speed at a feed rate of 0 12 mm/rev, and depth of cuts of 0 5, 1 0, and 1 5 mm respectively Similar plots of force speed variation at different feed rates of 0 20 mm/rev and 0 30 mm/rev have been presented in Figures 6 15 - 6 17 and Figures 6 18 - 6 20 respectively

All these figures depict that the tangential component of the cutting force F_z is the highest in magnitude followed by the axial F_x and radial F_y components Generally as the speed increased, the forces decreased and became constant At very low speed, the force was relatively higher The axial force was higher than the radial force at higher depth of cuts (1 0 and 1 5 mm)

When the depth of cut was low (0 5 mm) and feed was high (0 30 mm/rev), the radial force was higher than the axial force (Figure 6 19) This suggested that the chip flow direction was radial instead of axial at lower depth of cut With the increase in depth of cut, the direction of chip flow changed from radial to axial with an increase in the axial force

Figure 6 21 and 6 22 show the variation of the resultant cutting force *F* with cutting speed for various feed rate at depth of cut of 1 0 and 1 5 mm respectively In all cases, *F* increased as the feed increased

Figure 6 23 presents the variation of resultant cutting force with feed rate at three different cutting velocities at a constant depth of 1 0 mm The cutting force was observed to increase linearly with the feed rate A similar trend was observed when the forces were plotted against different depth of cuts as shown in Figure 6 24 The forces were found to increase linearly with the depth of cut

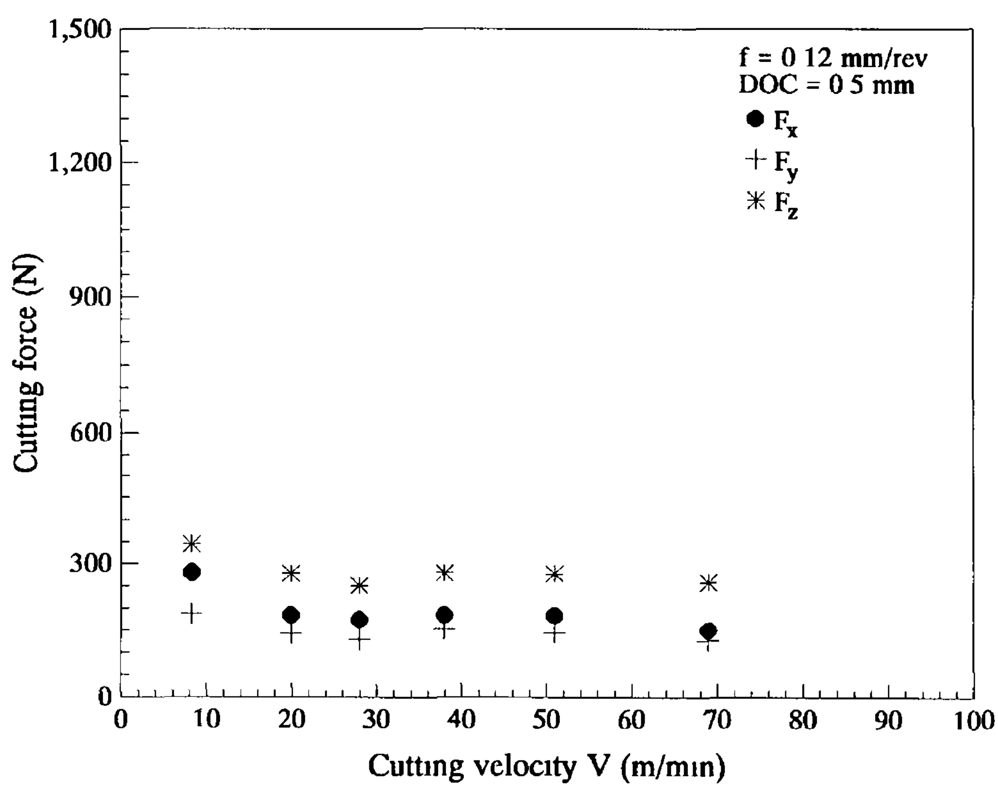


Figure 6.12 Variation of cutting forces with cutting velocity at feed = 0.12 mm/rev and depth of cut = 0.5 mm

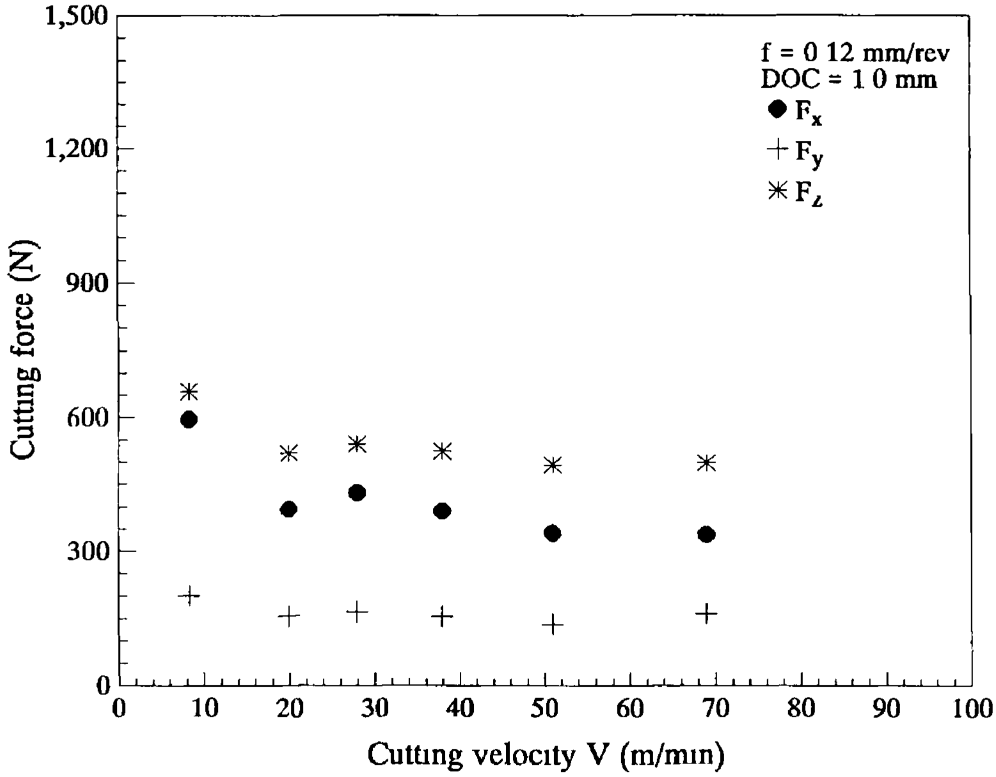


Figure 6.13 Variation of cutting forces with cutting velocity at feed = 0.12 mm/rev and depth of cut = 1.0 mm

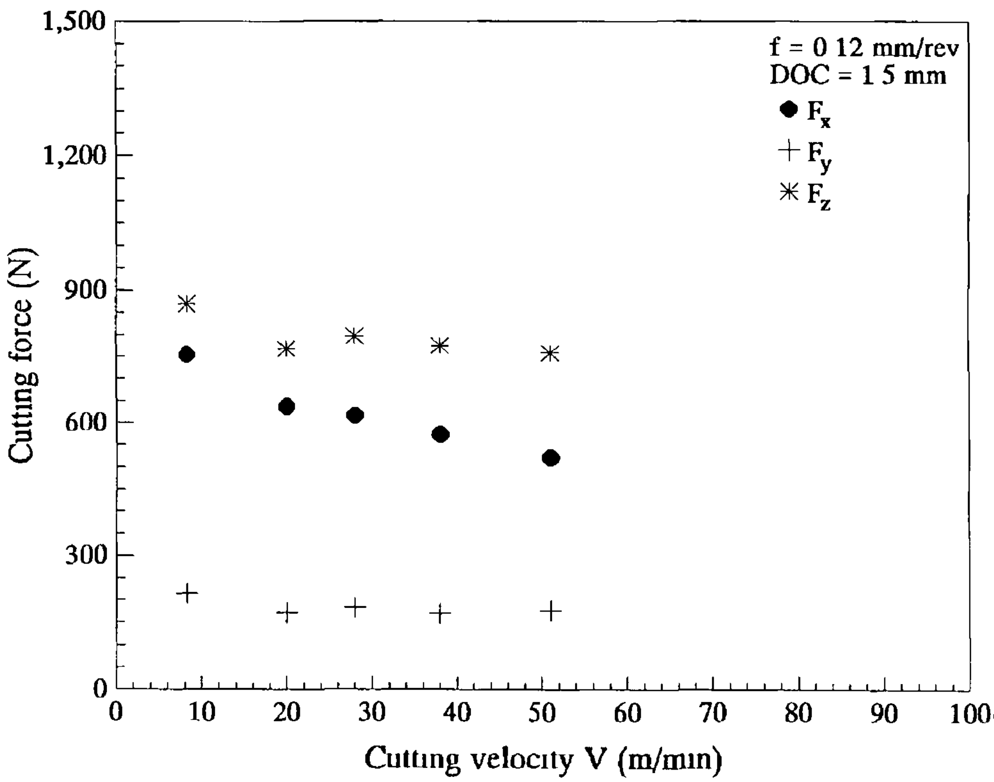


Figure 6.14 Variation of cutting forces with cutting velocity at feed = 0.12 mm/rev and depth of cut = 1.5 mm

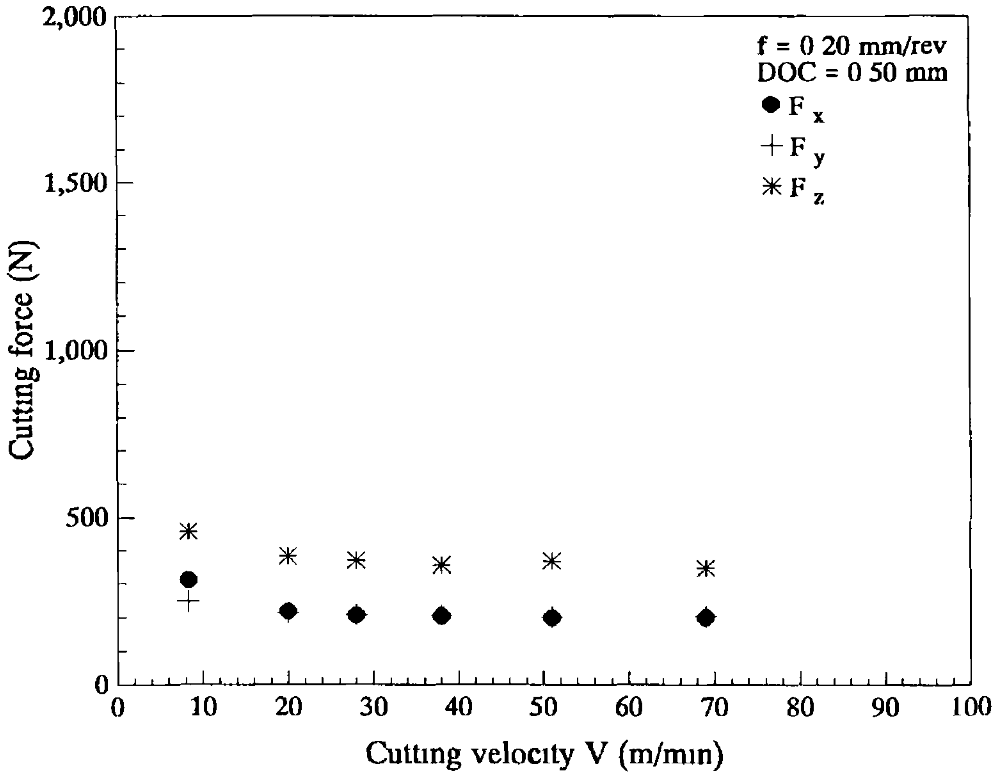


Figure 6.15 Variation of cutting forces with cutting velocity at feed = 0.20 mm/rev and depth of cut = 0.5 mm

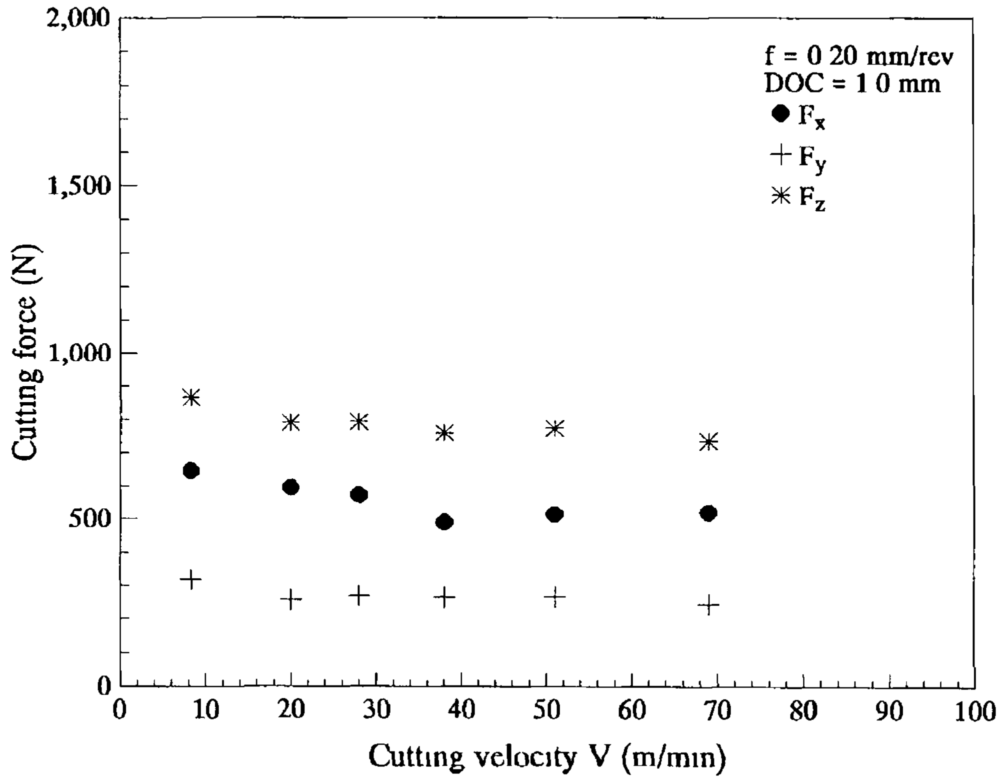


Figure 6.16 Variation of cutting force with cutting velocity at feed = 0.20 mm/rev and depth of cut = 1 0 mm

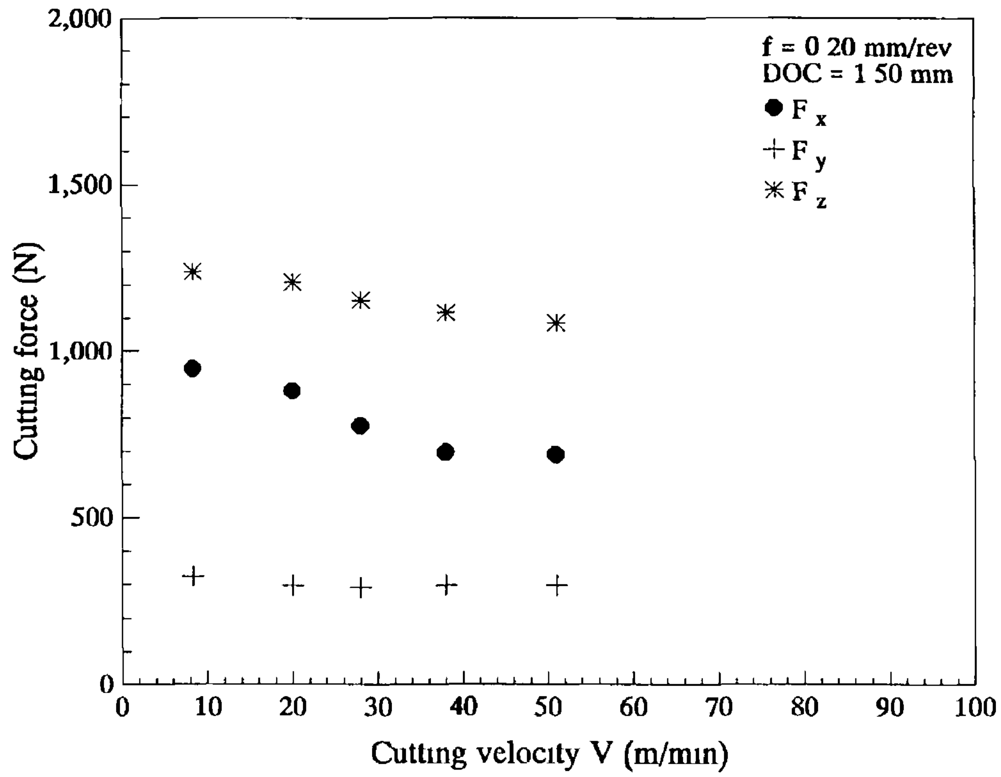


Figure 6.17 Variation of cutting forces with cutting velocity at feed = 0 20 mm/rev and depth of cut = 1.50 mm

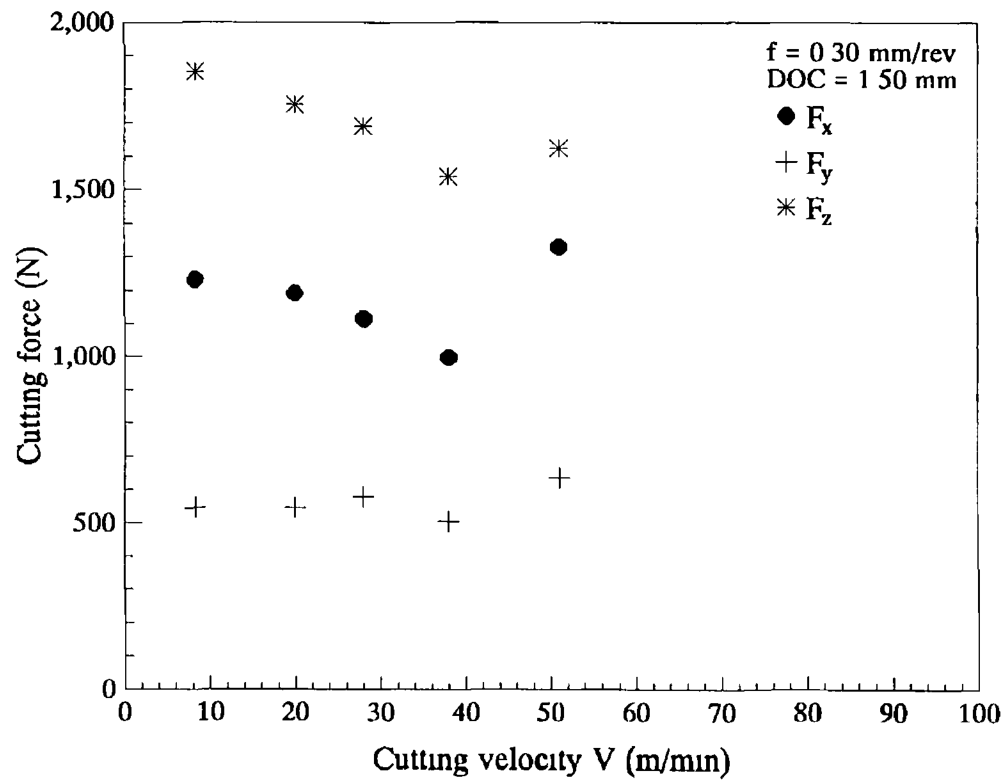


Figure 6.18 Variation of cutting forces with cutting speed at feed = 0.30 mm/rev and depth of cut = 1 5 mm

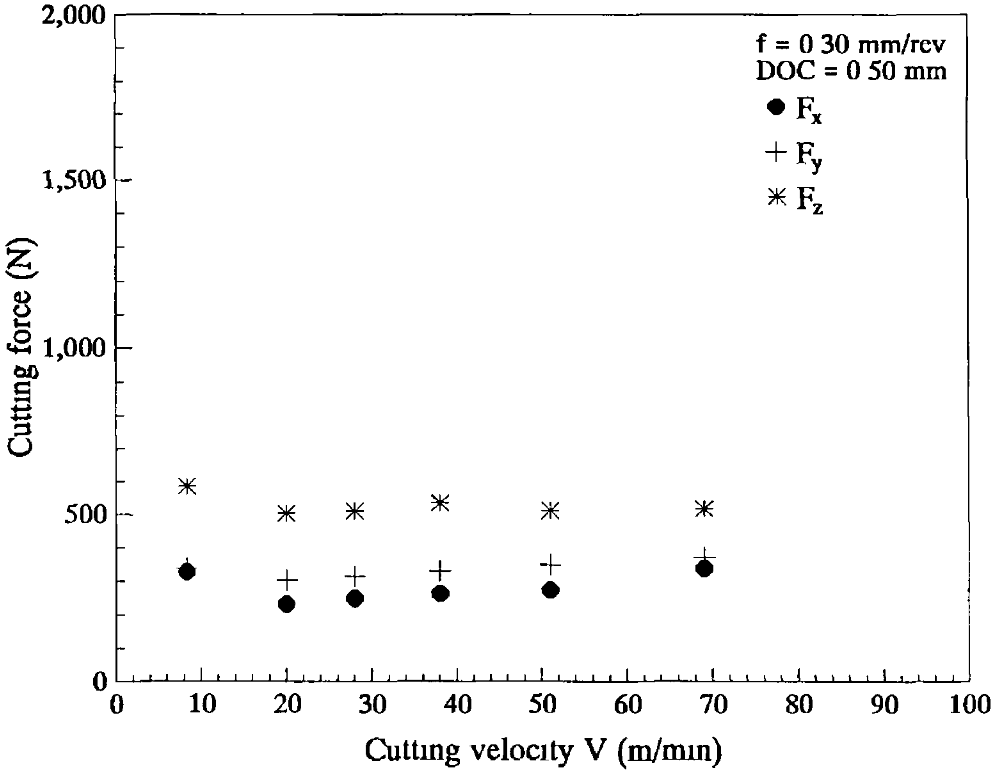


Fıgure 6.19 Varıatıon of cuttıng forces wıth speed at feed = 0.30 mm/rev and depth of cut = 0.5 mm

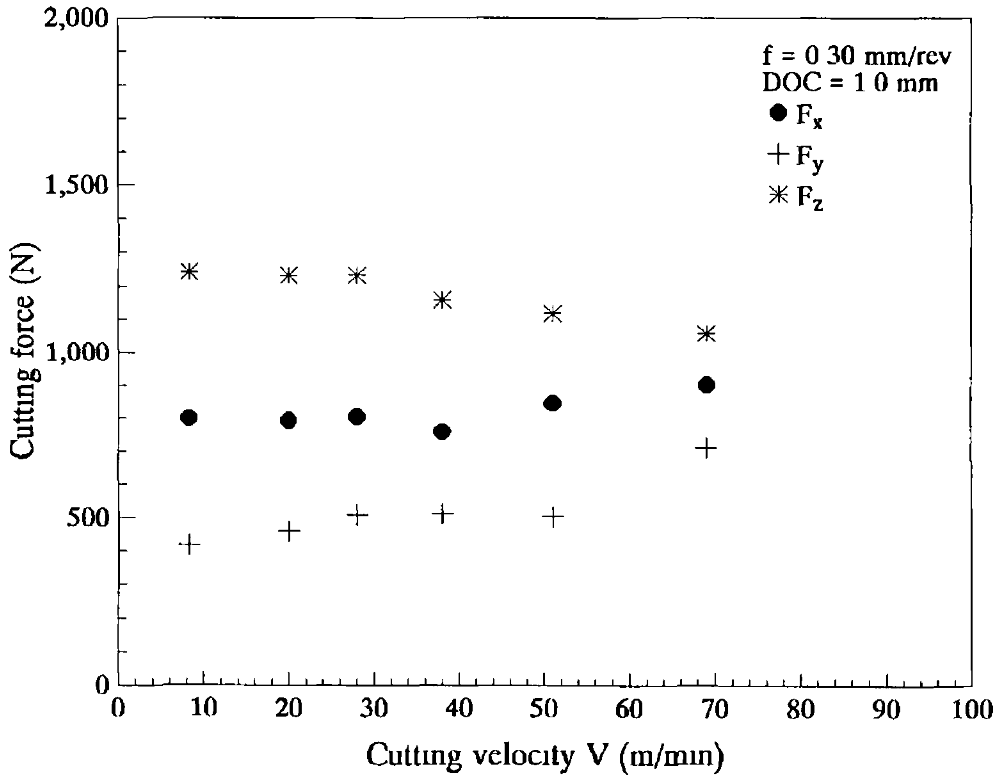


Fıgure 6.20 Varıatıon of cutting forces wıth speed at feed = 0.30 mm/rev and depth of cut = 1.0 mm

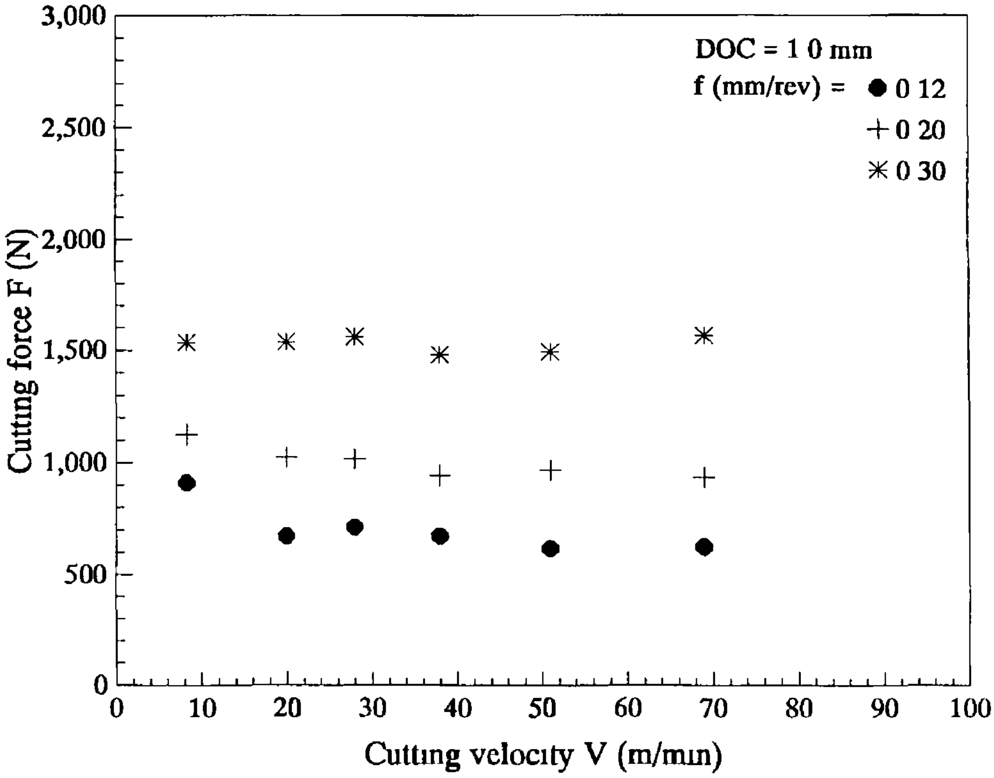


Fıgure 6 21 Varıatıon of resultant cuttıng force at various feed rate and depth of cut = 1.0 mm

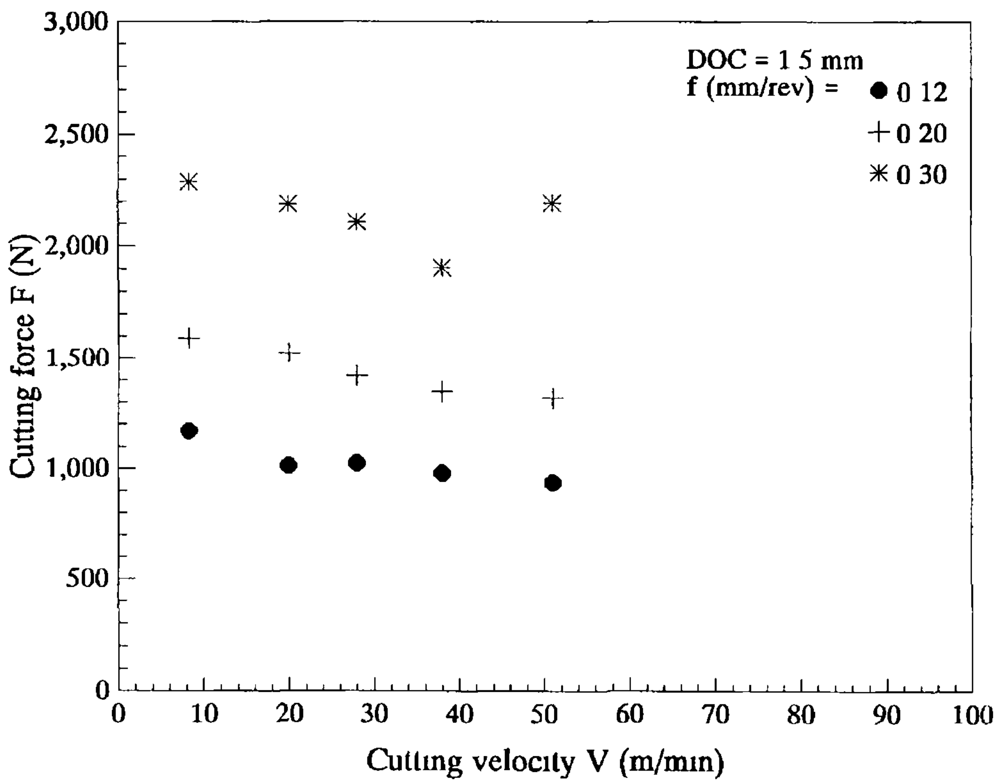


Fıgure 6 22 Varıatıon of resultant cuttıng force at dıfferent feed rate and depth of cut = 1.5 mm

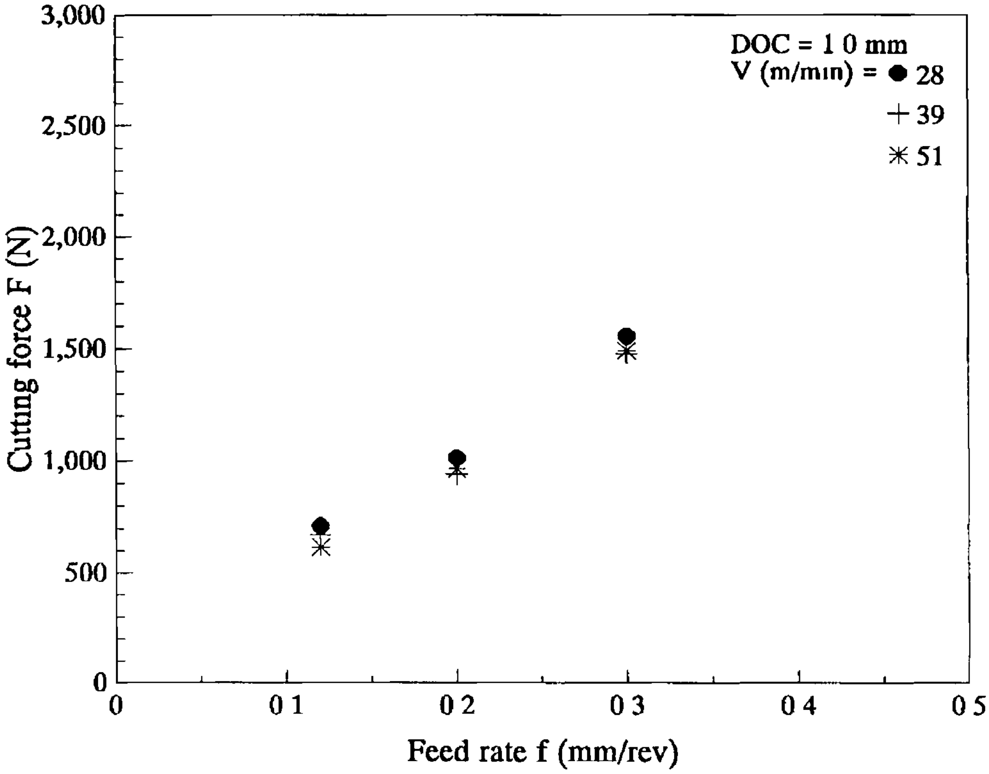


Figure 6 23 Variation of resultant cutting force with feed rate

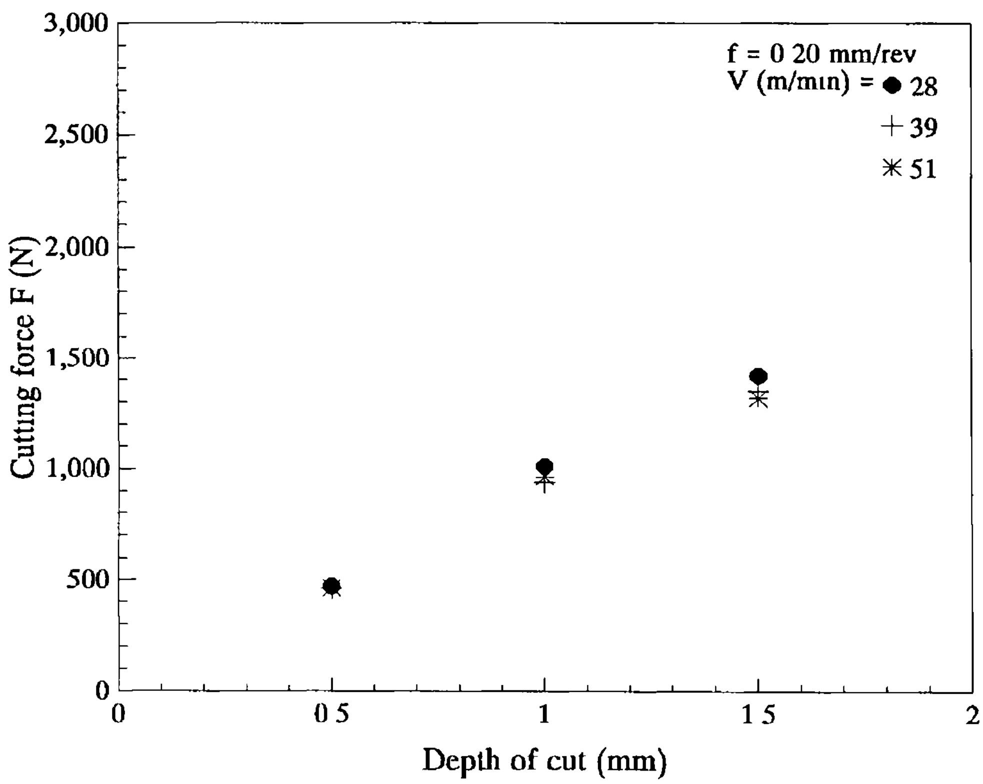


Figure 6.24 Variation of resultant cutting force with depth of cut

6.3.2 Tool life

The tool lıfe experıments were carrıed out ın three set of test runs The first set of experıments was conducted by varyıng the cuttıng velocıtıes at constant feed rate (0 20 mm/rev) and depth of cut (1 0 mm) Durıng the second set of experımental runs, feed was varıed whıle the cuttıng velocıty and depth of cut were kept constant The depth of cut was varıed durıng the thırd set of experıments whıle the cuttıng velocıty and feed rate were kept constant

Tool wear values were recorded usıng a Mıtutoyo TM300 Toolmakers mıcroscope ISO 3685 [106] was used as a guıde ın establıshıng the wear crıterıon Each test was started wıth a new cuttıng edge and machınıng was stopped and the ınsert was removed to measure ıts wear at dıfferent ınterval of tıme rangıng from one to two mınutes Further machınıng was stopped and an ınsert was rejected when the average flank wear exceeded 0 30 mm Three test runs were carrıed out for each cuttıng condıtıon and the average wear values were consıdered to determıne the tool lıfe The experımental condıtıons are shown ın Table 6 3

Table 6.3 Experımental cuttıng condıtıons

Velocıty V (m/mın)	Feed f (mm/rev)	Depth of cut d (mm)
20		
26	0 20	1 0
36		
48		
	0 12	
20	0 20	1 0
	0 30	
		1 0
20	0 20	1 5
		2 1

Both coated and uncoated carbide inserts were investigated in these tool life tests The details of these tools have been described in section 5 2 The flank wear values of uncoated carbide inserts for different cutting conditions have been presented in Figure 6 25 through 6 28

Figure 6 25 shows the progression of the width of the flank wear land against cutting time when the test has been repeated three times at the same cutting conditions The wear progression in all cases were very similar and the tool life values ranged form 18 - 20 minutes

In all tool life cutting experiments, the tests were repeated three times and the average value is plotted Figure 6 26 depicts tool wear obtained from four different speeds at constant feed rate and constant depth of cut At the cutting speeds of 36 and 48 m/min, wear progression was almost linear and very rapid and the tool life was short During machining at these cutting conditions, chips were observed to be red hot and broken When the cutting speed was changed to 20 m/min, initial wear was rapid, followed by a gradual steady wear, and then an abrupt wear until failure occurred

Figure 6 27 and 6 28 represent tool wear values for various feed rates and depth of cuts respectively With the increase of feed rate, tool wear increased At high feed rate, broken and fragmented chips were observed during machining The rate of tool wear with respect to the depth of cut (Figure 6 28) was very similar with those of feed rates

With the identical set of experimental conditions, tool life of the coated carbides was also investigated Figure 6 29 through Figure 6 31 represent such plots for different cutting velocities, feed rates, and depth of cuts respectively In general, the tool life of coated carbide was observed to be shorter when compared with that of the uncoated carbide for identical experimental condition

The tool life dependence on the tool material at various cutting speeds, feed rates, and depth of cuts are shown in Figure 6 32 to 6 34 These tool life values have been obtained from Figures 6 26 to 6 31 From Figure 6 32, it is observed that at a cutting velocity of 20 m/min, the performance of uncoated carbide tools was much better than that of the coated carbide As the velocity was increased, both coated and uncoated carbides tool lives were the same

When the tool life was investigated at various feed rates, the life of uncoated carbide tools was better (Figure 6 33) Coated carbide tools proved to be better only when the depth of cut was higher (1 5 and 2 1 mm) as shown in Figure 6 34

The reason for accelerated tool wear of the coated tools at 20 m/min may be due to the fact that the deposition process (Chemical Vapour Deposition) used for coatings might reduce the tool toughness Konig [142] pointed out that CVD coatings usually reduce the toughness of the carbide substrate The toughness of the tool may have a dominant role in resisting the wear mechanism when the speed is low [43]

However, the toughness of the coated tool improves with the temperature [142] and these were observed when the depth cut was higher (1 5 and 2 1 mm) The increased tool lives in the case of coated carbide tools with higher depth of cuts proves that coatings improved its toughness at high temperatures The temperatures in the cutting zone is usually higher when the depth of cut is higher

The advantage of using a coated carbide tool rather than an uncoated tool for machining inconel 718 was not clear, but the coated tools appeared to have performed better when the depth of cut exceeded 1 0 mm These observations agree with the recommendations made by Shaw [1] that in general coated carbides are not useful for machining high temperature alloys (either nickel- or cobalt base)

The GC3015 tool has a thick layer of Al_2O_3 on top of a layer of TiC The total thickness of the coating is 10 μm The thick layer of Al_2O_3 increases its wear resistance property at higher speeds However, the coating can reduce the toughness of the carbide substrate The toughness strength of tungsten carbides is higher than that of the coated carbide while the chemical stability and resistance of diffusion to oxidation of coated carbides are better

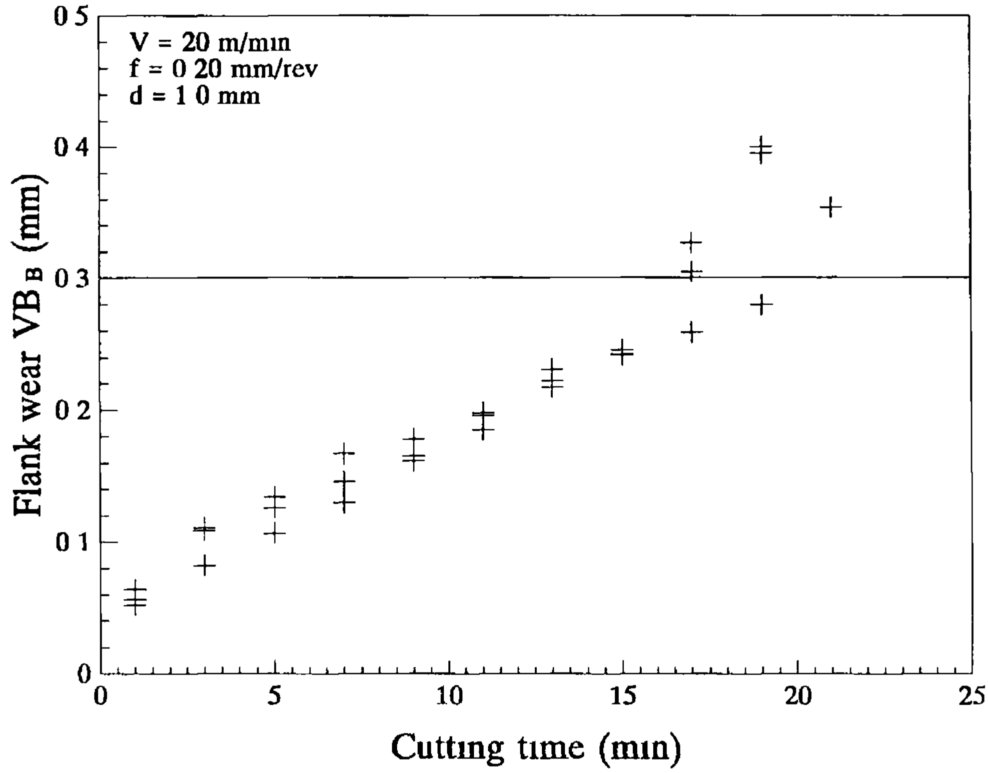


Fıgure 6.25 Tool wear plot of uncoated carbide ınserts for three cuttıng test runs

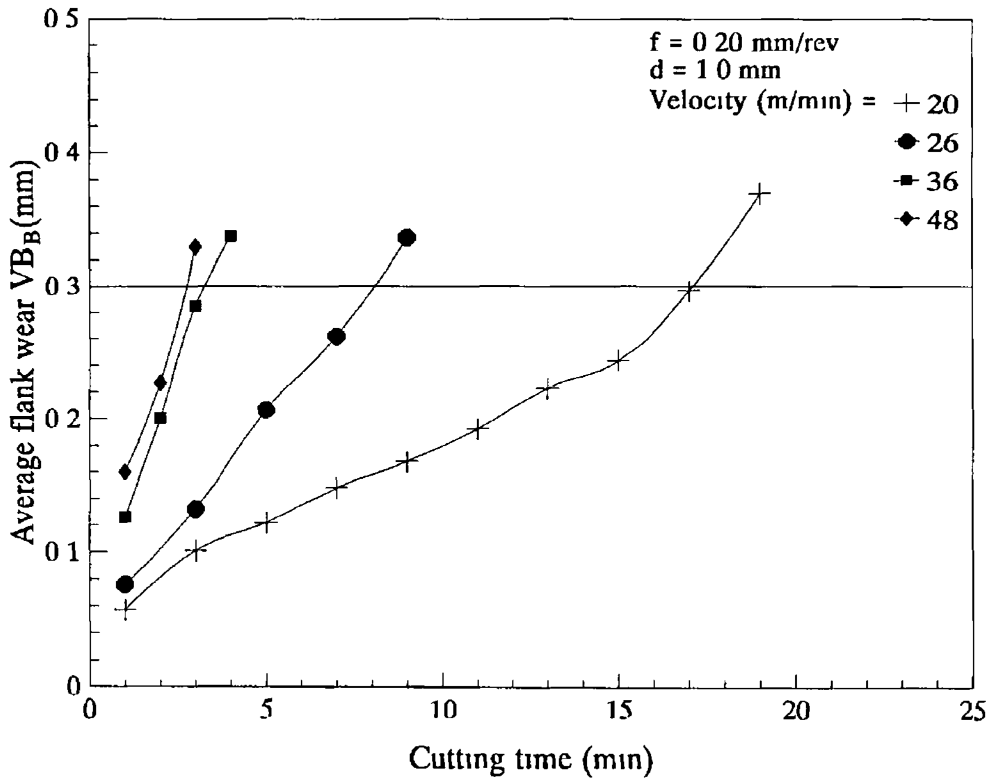


Fıgure 6.26 Tool wear of uncoated carbıde ınserts at dıfferent cuttıng speeds

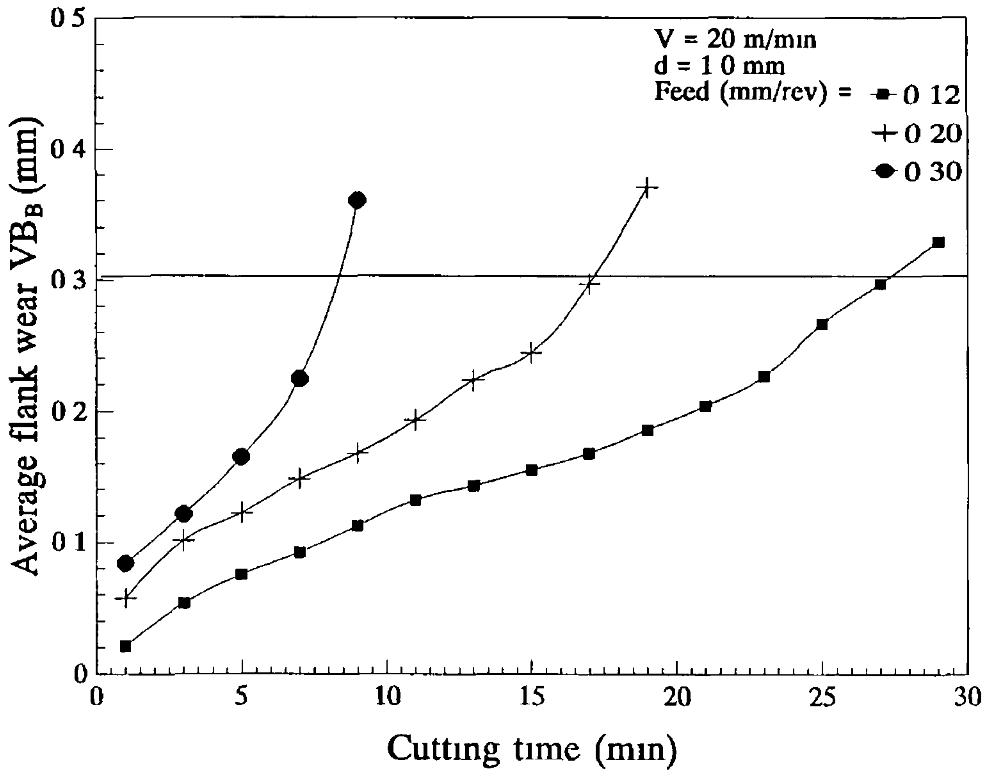


Figure 6.27 Tool wear of uncoated carbide at different feed rates

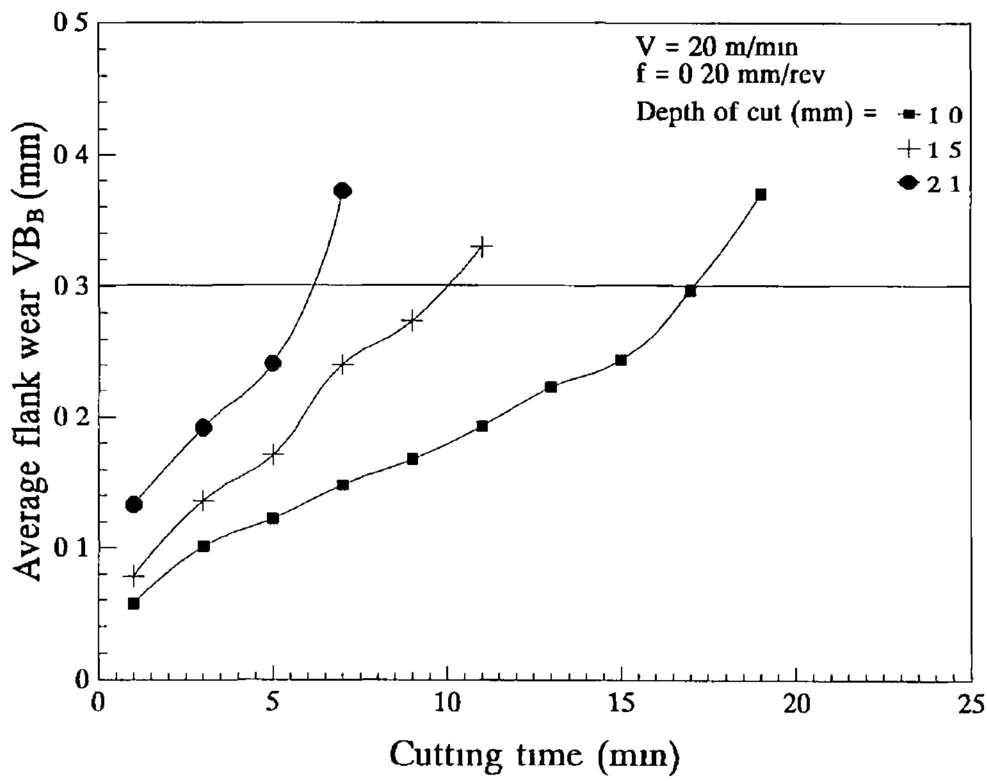


Figure 6.28 Tool wear of uncoated carbide at different depth of cuts

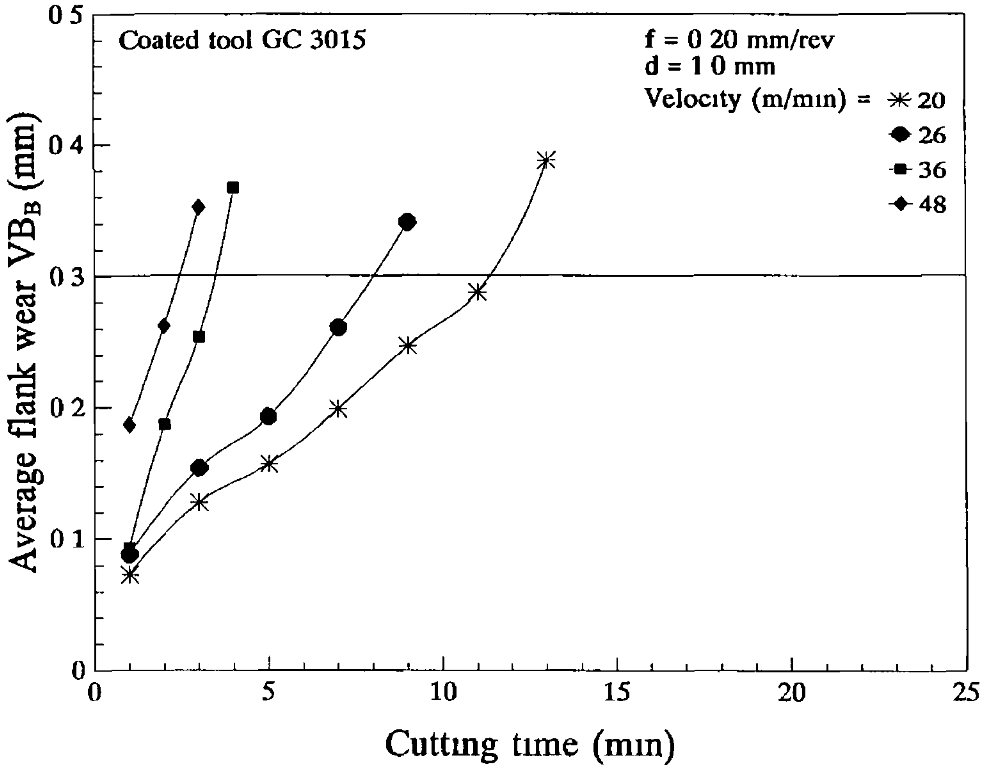


Figure 6.29 Tool wear of coated carbide inserts at different cutting speeds

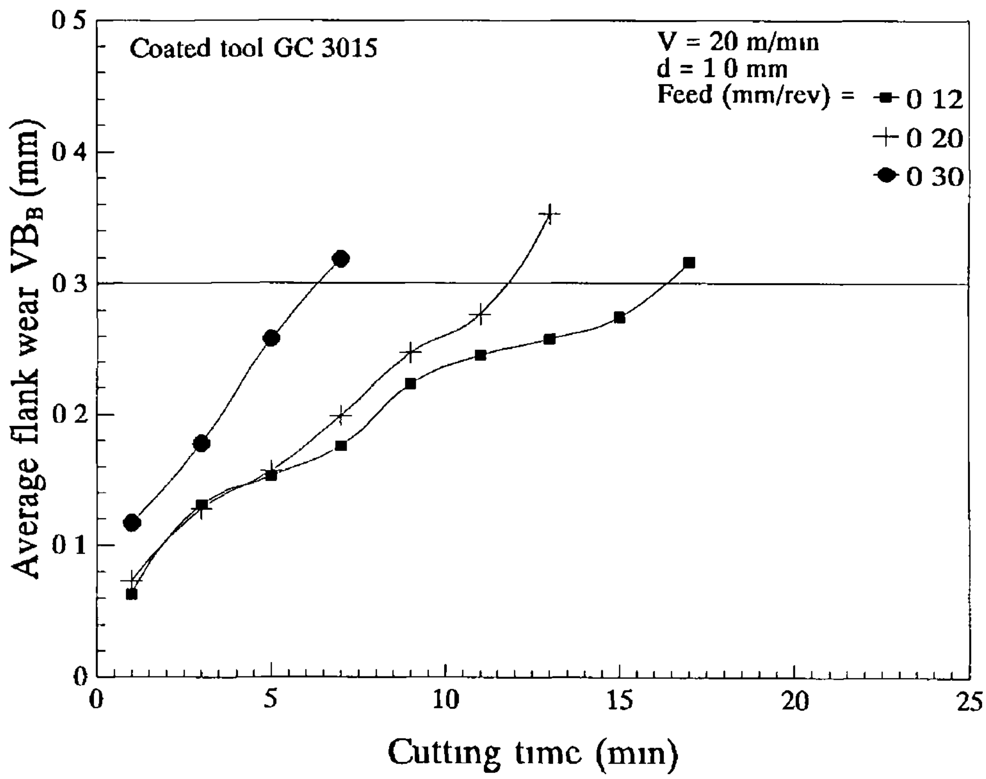


Figure 6.30 Tool wear of coated carbide inserts at different feed rates

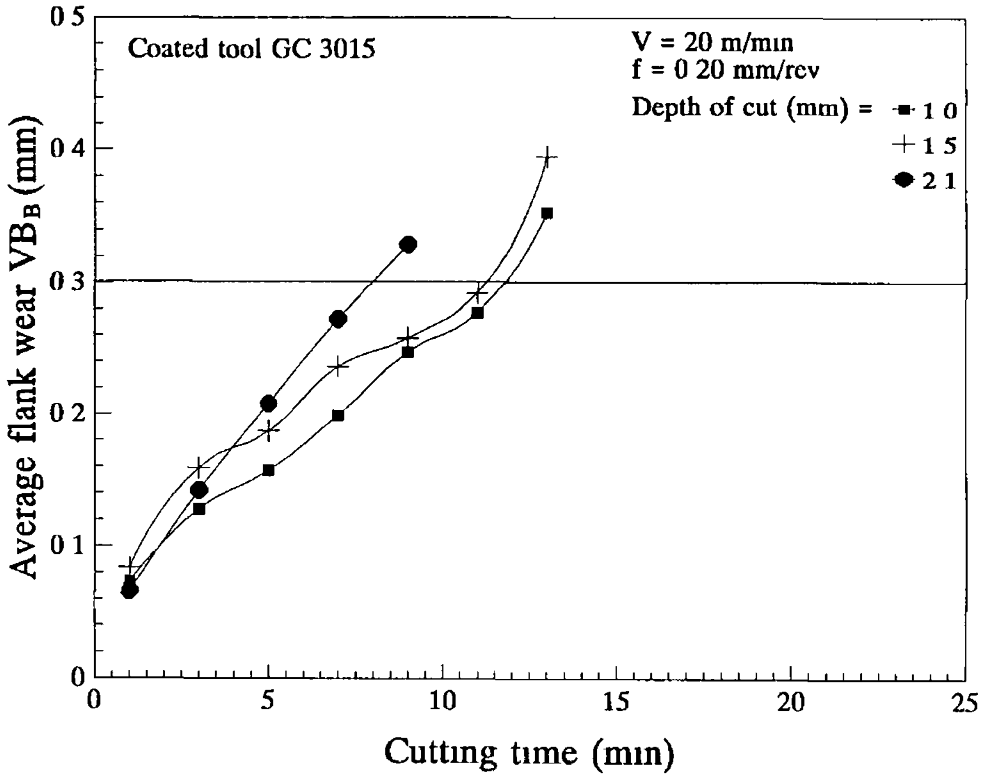


Fıgure 6.31 Wear of coated carbıde ınserts at dıfferent depth of cuts

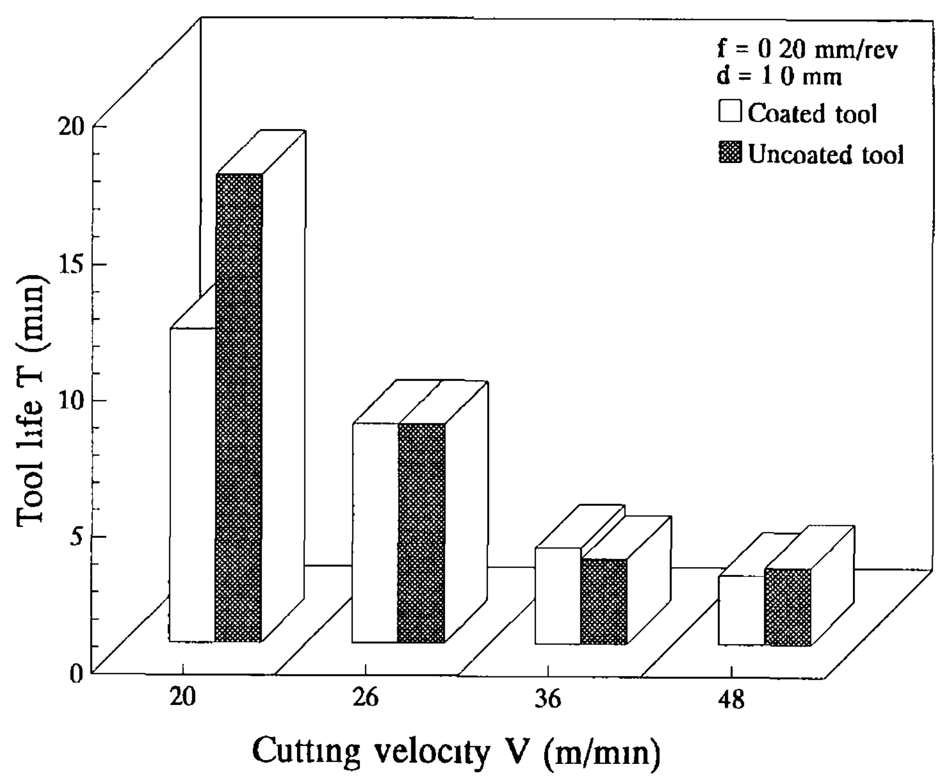


Figure 6.32 Tool life dependence on tool material at different cuttıng speeds

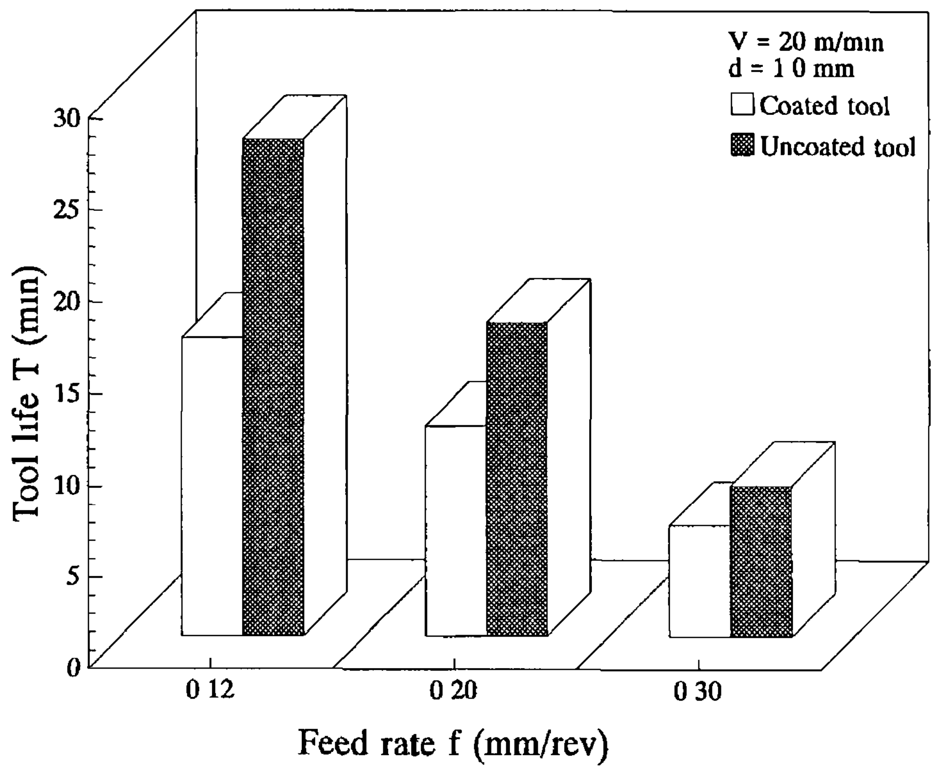


Fıgure 6.33 Tool lıfe dependence on tool materıal at dıfferent feed rates

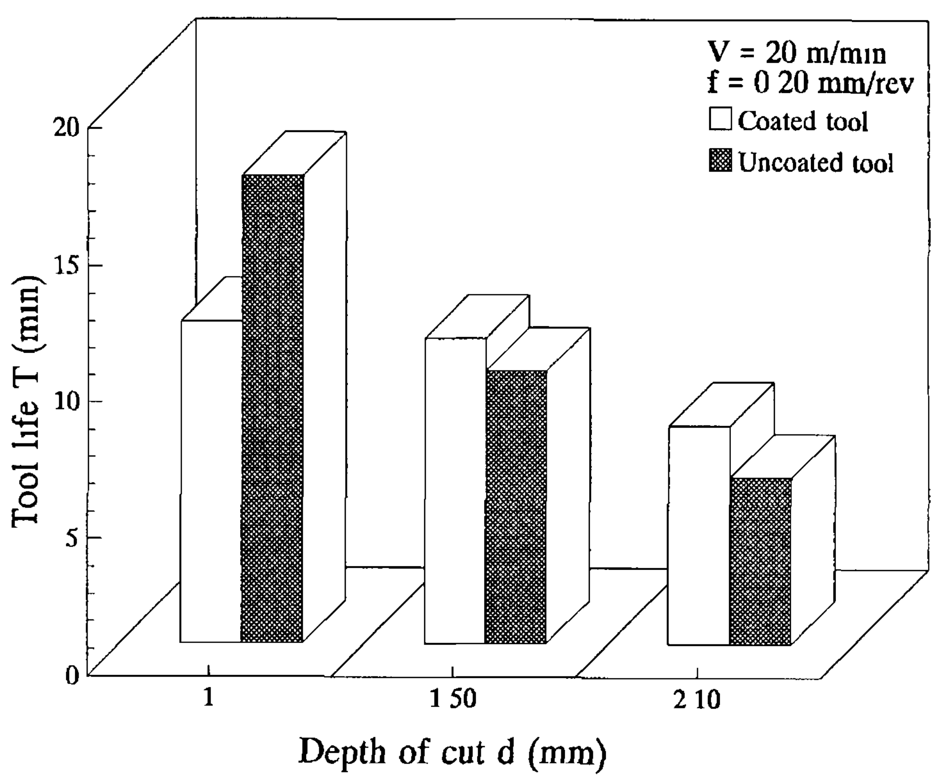


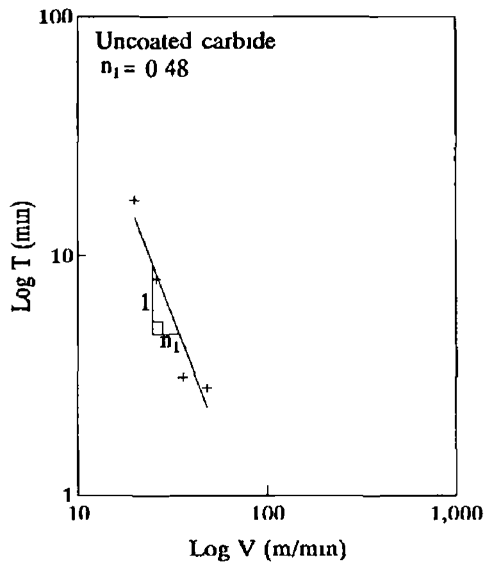
Fıgure 6.34 Tool lıfe dependence on tool materıal at dıfferent depth of cuts

At low cutting speed, the shorter tool life of coated tools suggested that the toughness of the tool might be important to resist the wear mechanism of the tool At speeds greater than 20 m/min, the toughness of coated tools seem to have improved with temperature and its performance with regard to the tool wear improved significantly

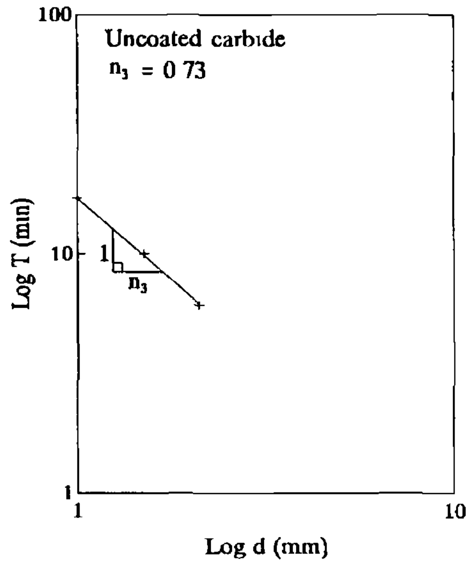
Coated tool gave higher tool lives at 1 5 and 2 1 mm depths of cut than the uncoated tools Flank wear may be considered as a combination of abrasive and diffusion wear At high speeds, carbide tools failed due to thermal softening of the cobalt binder phase and subsequent plastic deformation of the cutting edges

The three exponents (cutting velocity, feed rate, and depth of cut) of the Taylor's tool life equation have been determined graphically for uncoated and coated carbide inserts and are presented in Figures 6 35 and 6 36 respectively The speed exponents in both cases as shown in Figure 6 35 (a) and Figure 6 36 (b) were within the range (0 2-0 49) for carbide tools [96] In case of the uncoated carbide tool, the effect of depth of cut and feed on the tool life was noticeably same (Figure 6 35 (b) and Figure 6 35 (c))

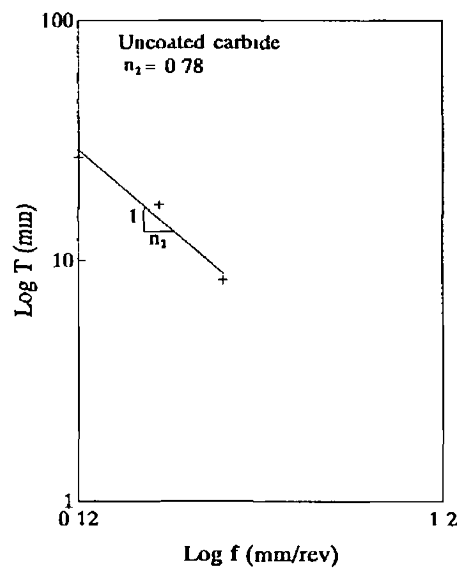
The effect of depth of cut on the coated carbide is rather interesting Figure 6 36 (b) depicts that the depth of cut has very negligible effect on the flank wear compared to the effect of the velocity and feed rate This might explain as to why the coated tools performed better at higher depth of cuts Comparing the feed and depth of cut exponents, we see that the uncoated tools are most sensitive to feed and depth of cut changes than the coated tools



(a)

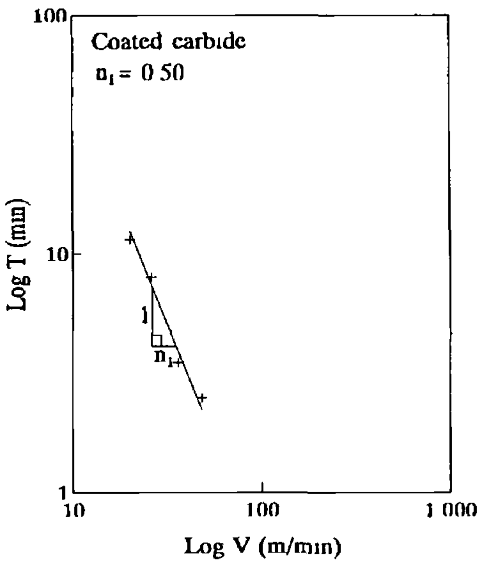


(b)

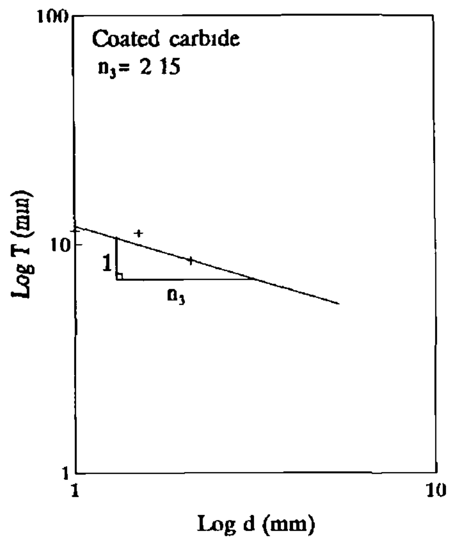


(d)

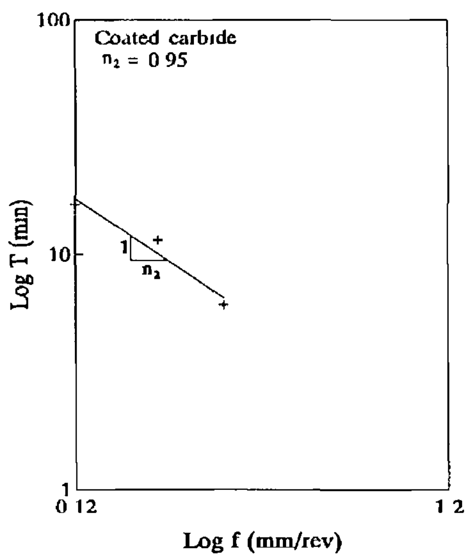
Figure 6.35 Graphical calculation of tool life exponents (a) speed, (b) depth of cut, and (c) feed for uncoated carbide insert



(a)



(b)



(c)

Figure 6.36 Graphical calculation of tool life exponents (a) speed, (b) depth of cut, and (c) feed for coated carbide insert

The followıng conclusıons could be made wıth regard to the turnıng of ınconel 718 wıth uncoated and coated carbıde tools

1 Uncoated carbıde cuttıng tools showed better performance wıth respect to dıfferent cuttıng speeds and feed rates In the speed range of 26 to 48 m/mın, no sıgnıficant dıfference ın tool lıfe values were observed for the coated and uncoated tools At hıgher speeds, the cuttıng forces dıd not decrease because of hıgher shear stress

2 The use of coated tools were justıfied only when the depths of cut exceeded 1 0 mm The depth of cut exponents also suggest that ıt has relatıvely less ınfluence on the wear of coated tools than the uncoated tools

3 The effect of cuttıng speed on tool lıfe ıs more pronounced than the effect of feed rate and depth of cut for coated tools In case of uncoated tools, the effect of speed on tool wear ıs followed by the effect of depth of cut and feed rate

4 In general, the uncoated carbıde tools gave hıgher tool lıfe than the coated carbıde tools when machınıng ınconel-718

5 The recommended cuttıng speed for machınıng ınconel usıng the uncoated tungsten carbıde should be wıthın 15 - 25 m/mın, feed rate should be 0 15 - 0 20 mm/rev, and depth of cut should be 1 0 -1 5 mm

CHAPTER 7

EXPERIMENTAL RESULTS AND DISCUSSIONS: DESIGN OF EXPERIMENTS

7.1 Introduction

This chapter is divided into two sections Section 7 2 describes the experimental results and discussions for EN24T steel based on the design of experiment Tool life, surface roughness, and cutting force models have been developed and presented with figures based on the design of experiment The experimental results and discussions together with the mathematical models on tool life, surface roughness, and cutting force for inconel 718 have been described in Section 7 3

7.2 Design of Experiment for EN24T Steel

In order to establish an adequate functional relationship between the machining response (tool life, surface roughness, cutting force) and the cutting parameters (cutting speed, feed, and depth of cut), a large number of cutting tests are needed It requires a separate set of tests for each and every combination of cutting tool and workpiece material This increases the total number of tests and as a result experimentation cost also increases

The design of experiments takes into account the simultaneous variation of speed, feed, and depth of cut, and predicts the response This approach is known as response surface methodology where the response of the dependent variable (tool life, surface roughness, or cutting force) is viewed as a surface and was first pioneered by Wu [115] Factorial designs are widely used in experiments involving several factors where it is necessary to study the combined effect of these factors on a response The meaning of the factorial design is that each complete trial or replication of the all possible combinations of the levels of the factors are investigated By using the response surface methodology and 2^3 factorial design of experiment, first and second order models have been developed with 95% confidence level These model equations have been used to develop the response contours for different cutting conditions

The proposed functional relationship between the machining response and machining independent variables can be represented by the following

$$R = C\,(V^l f^m d^n)\,\epsilon \tag{7.1}$$

where R is the response, $V, f,$ and d are the cutting speed (m/min), feed (mm/rev), and depth of cut (mm) respectively, and C, l, m, n are constants and ϵ is a random error The response R may be tool life T in minutes, or surface roughness R_a in microns, or cutting force F in newton Equation (7 1) can be written in the following logarithmic form

$$lnR = lnC + l\ lnV + m\ lnf + n\ lnd + \ln\epsilon \tag{7.2}$$

The linear model of equation (7 2) is

$$y = \beta_0 x_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \epsilon \tag{7.3}$$

where y is the measured response in a logarithmic scale, $x_0 = 1$ (dummy variable), $x_1 = \ln V$, $x_2 = \ln f$, $x_3 = \ln d$, $\epsilon = \ln\epsilon'$ where ϵ is assumed to be a normally distributed uncorrelated random error with zero mean and constant variance, $\beta_0 =$

$\ln C$, β_1, β_2, and β_3 are the model parameters The estimated response can be written as

$$\hat{y} = y - \varepsilon = b_0x_0 + b_1x_1 + b_2x_2 + b_3x_3 \tag{7.4}$$

where $\hat{y}$ is the estimated response, b_0, b_1, b_2, and b_3 are estimates of β_0, β_1, β_2, and β_3 respectively The second order model can be expressed as

$$\hat{y} = y - \varepsilon = b_0x_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \tag{7 5}$$

Equation (7 5) is useful when second order effects of V, f, d, and the two way interactions among V, f, and d are significant The significance of these variables are judged by statistical analysis The parameters of equations (7 4) and (7 5) have been estimated by the method of least squares using a Matlab computer package

A design consisting of twelve experiments has been used to develop the first-order model Eight experiments represents a 2^3 factorial design, where the experimental points are located at the vertices of a cube illustrated in Figure 4 1(a) Four experiments represent an added centre point to the cube, repeated four times to estimate pure error The complete design consists of twelve experiments in two blocks, each block containing six experiments The 'b' parameters of equation (7 4) were calculated on the basis of only six tests of the first block consisting of experiment numbers 1, 4, 6, 7, 9, and 10 Another second block of six tests (2, 3, 5, 8, 11, & 12) were added with the first block results to provide a precise estimate of the 'b' parameters The combined blocks improve the confidence interval of the parameters and help improve precision in the analysis of variance The design provides three levels for each of the independent variables

As the first-order model is only limited over a narrow range of variables, the experiments were extended to obtain a second-order model Six augment points were added to the face of the cube, where each was chosen at a selected augment length of $\sqrt{2}$ The six experiments were repeated twice to increase the model accuracy as shown in Figure 4 1(b) The resulting twelve or twenty four experiments form the central composite design [121] Such a design has been used by Taraman [7], Bandyopadhyay & Teo [46], El-Baradie [54], and the authors [143] in order to investigate the effects of cutting variables on the tool life and surface finish In this turning investigation, uncoated carbide cutting tools have been used

Depending on the cutting conditions and wear rate, machining was stopped at various intervals of time varying from 1/2 minute to 5 minutes to record wear on the insert Flank wear has been considered as the criteria for tool failure and the wear was measured under a Mitutoyo TM300 Toolmakers microscope Further testing was stopped and an insert was rejected when average flank wear greater than 0 30 mm was recorded [106]

Surface roughness was measured using a Mitutoyo Surftest The various roughness height parameters such as average roughness R_a, smoothening depth R_p, root mean square R_q, and maximum peak to valley height R_t can be closely correlated [144] The present study uses the average roughness (R_a) for characterisation of surface roughness It is most widely used in industry for specifying surface roughness A cut off value of 0 8 or 2 5 was selected depending on the magnitude of roughness All the experiments were run dry and each experiment was started with a new cutting edge At each experimental condition, three readings were recorded along the diameter of the work piece and the average values are taken and presented

To measure the different cutting force components, the tool holder was mounted on the dynamometer connected to a PC based data acquisition system through the charge amplifiers The Kistler piezoelectric dynamometer was mounted on a lathe A UV chart recorder was also incorporated in the data acquisition system to measure the force components and compare with those obtained through the computer output Three cutting tests were conducted at each experimental point and average cutting force have been taken into consideration

The levels of independent variables and coding identifications are presented in Table 7 1 Table 7 2 shows the experimental cutting conditions together with the measured tool life, surface roughness, and cutting force

The transforming equations for each of the independent variables are

$$x_1 = \frac{\ln(V) - \ln(65)}{\ln(117) - \ln(65)}$$

$$x_2 = \frac{\ln(f) - \ln(0\ 25)}{\ln(0\ 40) - \ln(0\ 25)} \tag{7.6}$$

$$x_3 = \frac{\ln(d) - \ln(0\ 75)}{\ln(1\ 125) - \ln(0\ 75)}$$

Table 7.1 Levels of independent variables

Levels	Lowest	Low	Centre	High	Highest
Coding	$-\sqrt{2}$	-1	0	1	$\sqrt{2}$
Speed V (m/min)	28	36	65	117	150
Feed f (mm/rev)	0 12	0 15	0 25	0 40	0 50
Doc d (mm)	0 42	0 50	0 75	1 125	1 33

Table 7.2 Experimental conditions and results

Trial No	Speed V (m/min)	Feed f (mm/rev)	Doc d (mm)	Coding			Response		
				x_1	x_2	x_3	Tool life T (min)	Surface roughness R_a (μm)	Cutting force F (N)
1	36	0 15	0 500	-1	-1	-1	24 60	1 8	447
2	117	0 15	0 500	1	-1	-1	2 30	1 233	363
3	36	0 40	0 500	-1	1	-1	10 80	5 3	833
4	117	0 40	0 500	1	1	-1	1 60	5 067	703
5	36	0 15	1 125	-1	-1	1	14 80	2 133	1023
6	117	0 15	1 125	1	-1	1	2 14	1 45	789
7	36	0 40	1 125	-1	1	1	12 25	6 233	1610
8	117	0 40	1 125	1	1	1	1 35	5 167	1386
9	65	0 25	0 750	0	0	0	5'22	2 433	772
10	65	0 25	0 750	0	0	0	4 82	2 3	756
11	65	0 25	0 750	0	0	0	5 00	2 367	767
12	65	0 25	0 750	0	0	0	5 12	2 467	762
13	28	0 25	0 750	$-\sqrt{2}$	0	0	18 0	3 633	972
14	150	0 25	0 750	$\sqrt{2}$	0	0	0 86	2 767	696
15	65	0 12	0 750	0	$-\sqrt{2}$	0	5 00	1 153	526
16	65	0 50	0 750	0	$\sqrt{2}$	0	3 60	6 333	12678
17	65	0 25	0 420	0	0	$-\sqrt{2}$	5 80	2 533	473
18	65	0 25	1 330	0	0	$\sqrt{2}$	3 75	3 2	1290
19	28	0 25	0 750	$-\sqrt{2}$	0	0	18 35	3 233	1015
20	150	0 25	0 750	$\sqrt{2}$	0	0	0 88	2 967	681
21	65	0 12	0 750	0	$-\sqrt{2}$	0	5 70	1 21	508
22	65	0 50	0 750	0	$\sqrt{2}$	0	3 90	6 733	1237
23	65	0 25	0 420	0	0	$-\sqrt{2}$	6 40	2 833	437
24	65	0 25	1 330	0	0	$\sqrt{2}$	4 30	3 267	1359

7.2.1 Tool life model

7 2 1 1 Results, discussions, and optimization First-order model

The tool life models based on the first and second block of six experiments are

$$\hat{y} = 1\,6941 - 1\,1194x_1 - 0\,247x_2 - 0\,1016x_3 \qquad (7.7)$$

and

$$\hat{y} = 1\,575 - 0\,9853x_1 - 0\,212x_2 - 0\,0544x_3 \qquad (7.8)$$

respectively Table 7 3 of Appendix C shows the 95% confidence interval for the first block of six tests Draper and Smith [120] have given the details of variance calculations The 95% F-test for one degree of freedom is 161 while the ratio of the mean square of lack of fit to mean square of pure error is 6 18 95% confidence interval of the second block is shown in Table 7 4 of Appendix C The calculated F-value is found to be 22 36 Hence both of the models are found to be adequate However, if we look at Table 7 3 & 7 4, the 95% confidence intervals are rather large As such, test results of block 1 & 2 are combined and analyzed

The predicted tool life model for the combined blocks in coded form is

$$\hat{y} = 1\,6345 - 1\,0523x_1 - 0\,2295x_2 - 0\,078x_3 \qquad (7.9)$$

The analysis of variance and 95% confidence interval are shown in Table 7 5 and Table 7 6 of Appendix C respectively The ratio of lack of fit to pure error is 3 91 while F-statistics is 9 01 Therefore, the model is adequate Equation (7 9) describing the too life model can be transformed by using equation (7 6) into the following form

$$T = 4564\ V^{-1\,7903} f^{-0\,4883}\ d^{-0\,1924} \qquad (7.10)$$

The equation shows that the tool life decreases with the increase of cutting speed, feed, and depth of cut The cutting speed has the most dominant effect on tool life followed by the feed and depth of cut The equation of metal removal rate Q (cm^3/min) in logarithmic form is given by

$$\ln Q = \ln V + \ln f + \ln d \tag{7.11}$$

where d is in mm, f is in mm/rev, and V is in m/min Combining equations (7 6) & (7 11), the metal removal rate for a specific depth of cut (0 75 mm) becomes

$$\ln Q = 2\,5004 + 0\,5878x_1 + 0\,47x_2 \tag{7.12}$$

Equation (7 9) is utilised to develop tool life contours in speed-feed plane at the selected level of depth of cut Figure 7 1 through 7 3 shows the contours at three different depths of cut These contours help predict the tool life at any zone of experimental domain

The response contours generated by Equation (7 12) is superimposed on Figure 7 2 and is shown in Figure 7 4 These contours would be useful in finding the maximum attainable tool life for a given metal removal rate Comparing the points A and B of Figure 7 4, one can select the cutting parameters (velocity and feed rate) at A which will result in a gain in tool life by 50% for the same metal removal rate

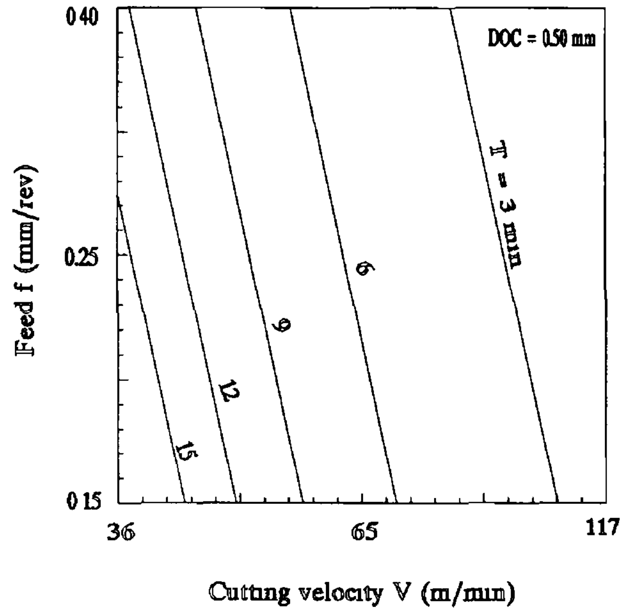


Figure 7.1 Tool life contour in velocity-feed plane at a depth of cut of 0.50 mm

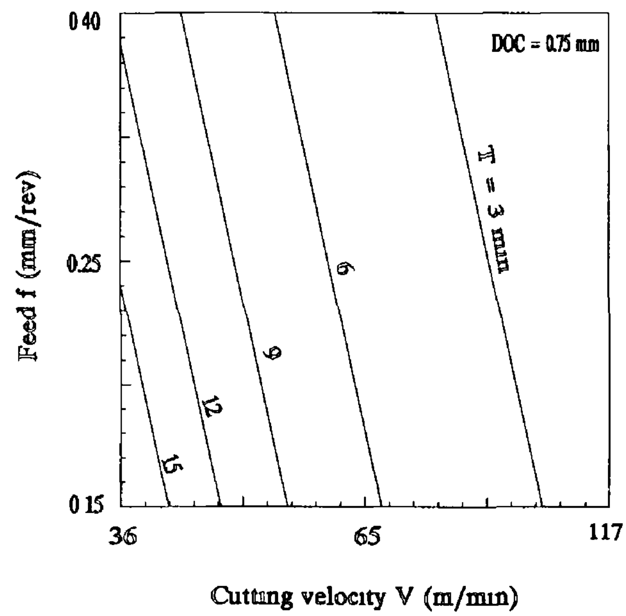


Figure 7.2 Tool life contour in velocity-feed plane at a depth of cut of 0.75 mm

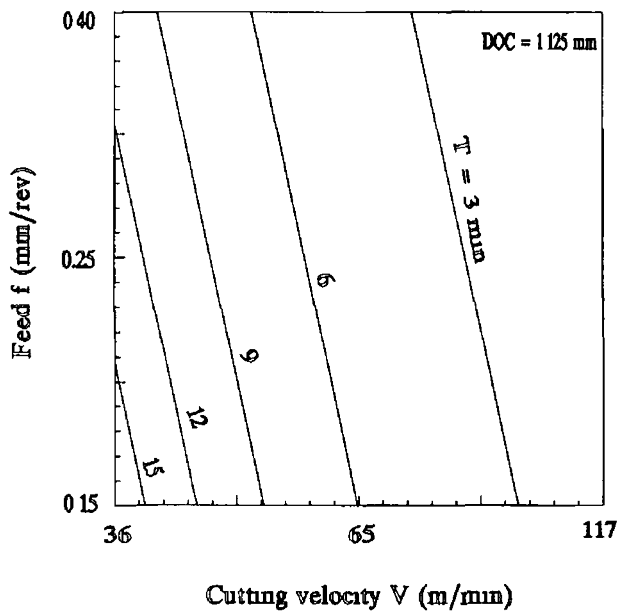


Figure 7.3 Tool life contour in velocity-feed plane at a depth of cut of 1 125 mm

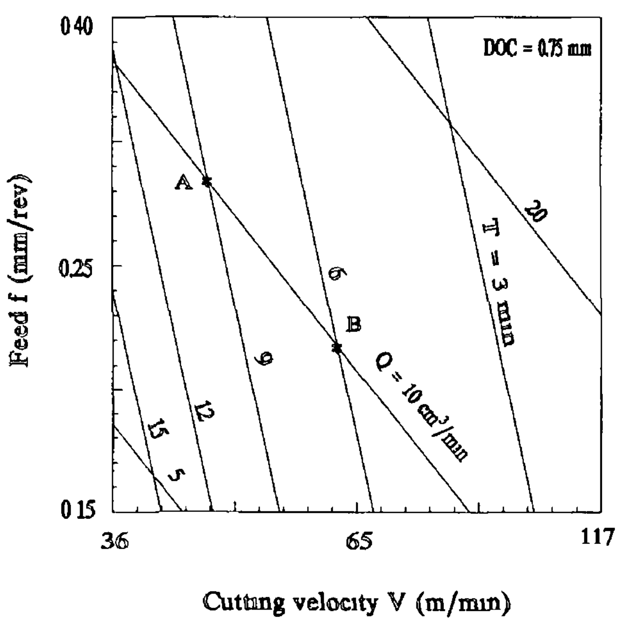


Figure 7.4 Dual response contours of tool life and metal removal rate in velocity-feed plane at 0.75 mm depth of cut.

7.2 1 2 Results, dıscussıons, and optımızatıon· Second-order model

Even though the first-order model was found to be adequate, the second-order model was postulated to extend the varıables range ın obtaınıng the relatıonshıp between the surface roughness and the machınıng ındependent varıables The model was based on the central composıte desıgn wıth added augment poınts to the nucleus of the desıgn The dıstance of the augment poınt was 1 4142 unıts The model equatıon ıs gıven by

$$\hat{y} = 1\,546 - 1\,064x_1 - 0\,177x_2 - 0\,113x_3 - 0\,047x_1^2 + 0\,012x_2^2 + 0\,062x_3^2 + 0\,024x_1x_2 + 0\,018x_1x_3 + 0\,067x_2x_3 \qquad (7.13)$$

The analysıs of varıance ıs shown ın Table 7 7 whıle the 95% confidence level ıs shown ın Table 7 8 of Appendıx C Table 7 7 shows that the ınteractıon terms are not sıgnıficant at 95% confidence level The second order terms are almost ınsıgnıficant The 95% confidence ınterval ıs found to be large The model equatıon (7 13) ıs plotted ın speed-feed plane for three selected level of depth of cuts ın Fıgure 7 5 through 7 7 The contours do not show any sıgn of non-lınearıty and thereby conforms that the first order model ıs adequate Fıgure 7 8 ıs a plot of dual response of metal removal rate and tool lıfe The tool lıfe profile for T = 3 mınutes ıntersects metal removal rate Q at 10 and 20 cm^3/mın If we select the cuttıng speed and feed at the ıntersectıon of T = 3 and Q = 20 cm^3/mın, a 100% gaın ın metal removal rate wıll be obtaıned from the ıntersectıon at Q = 10 cm^3/mın

Table 7.7 Analysıs of variance for twenty four tests

Source	Sum of Squares	Degrees of Freedom	Mean Squares	F_{cal}	F_{tab}
Zero-order term	58 66189	1	58 662	9071 8	
Fırst-order terms	18 801614	3	6 2672	758 05	
Second-order terms	0 098244	3	0 03275	3 99	4 07
Interactıon terms	0 0429	3	0 0143	1 73	
Block	0 16771	3	0 0559	6 76	
Lack of fit	0 047202	3	0.0157	1.90	
Pure error	0 06614	8	0 0082675		
Total	77 8857				

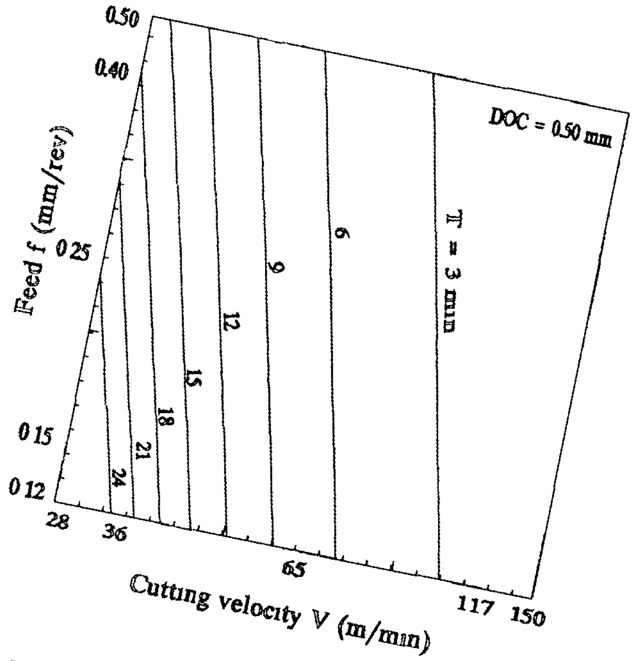


Figure 7.5 Tool life (2nd order) contour in velocity-feed plane at a depth of cut of 0.50 mm.

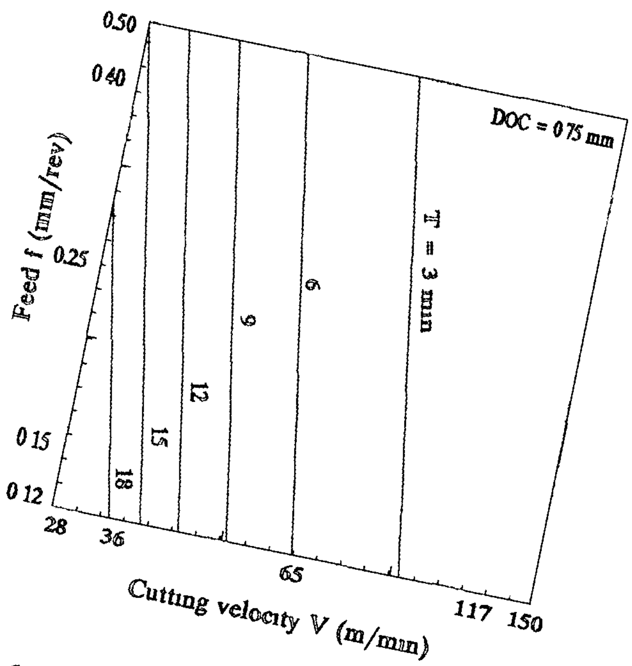


Figure 7.6 Tool life (2nd order) contour in velocity-feed plane at a depth of cut of 0.75 mm.

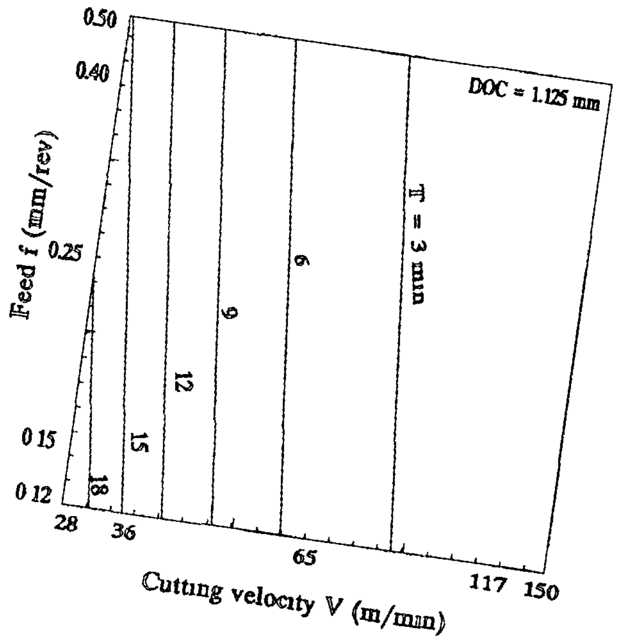


Figure 7.7 Tool life contour (2nd order) in velocity-feed plane at a depth of cut of 1.125 mm.

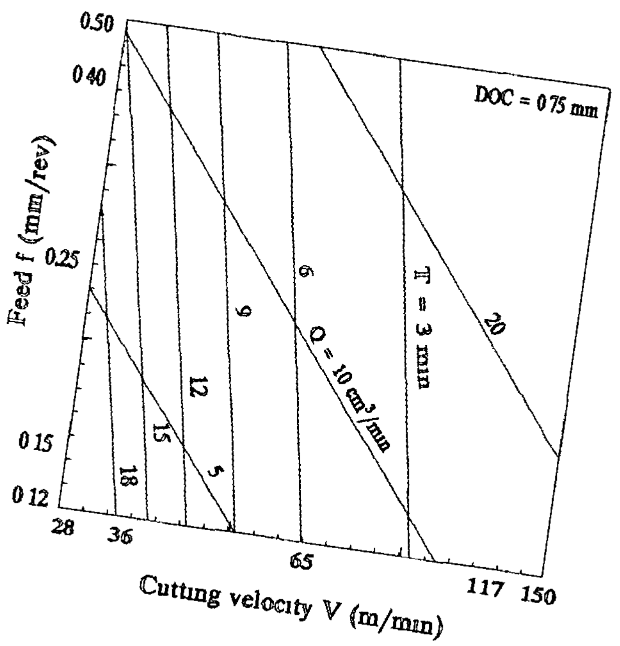


Figure 7.8 Dual response contours of tool life (2nd order) and metal removal rate in velocity-feed plane at 0.75 mm depth of cut.

7.2.2 Surface roughness model

7.2 2 1 Results, discussions, and optimization· First-order model

The postulated model for surface roughness based on the twelve set of experiments are

$$\hat{y} = 1\,0146 - 0\,1246x_1 + 0\,6045x_2 + 0\,0642x_3 \qquad (7.14)$$

Equation (7 14) describing the roughness model can be transformed by using equation (7 6) into the following form

$$R_a = 41\,6\ V^{-0\,212}\ f^{1.2861}\ d^{0\,1583} \qquad (7.15)$$

The equation indicates that the surface finish improves with the increase of speed while it deteriorates with the increase of feed or depth of cut Combining Equation (7 6) & Equation (7 11), the metal removal rate equation for a specific depth of cut (0 50 mm) could be written as

$$\ln Q = 2\,0949 + 0\,5878x_1 + 0\,47x_2 \qquad (7.16)$$

Equation (7 14) is plotted in Figure 7 9 through 7 11 at three different depth of cuts These response contours help predict surface roughness at any zone of experimental domain Figure 7 12 represents dual response contours of metal removal rate and surface roughness at 0 50 mm depth of cut However, the analysis of variance as shown in Table 7 9 of Appendix C reveals that the first order model is inadequate at 95% confidence interval The ratio of lack of fit to pure error at 95% confidence is found to be 34 5 while its tabulated value is 9 01 Having found the first order model inadequate, the levels of the independent variables were extended to postulate a second order model

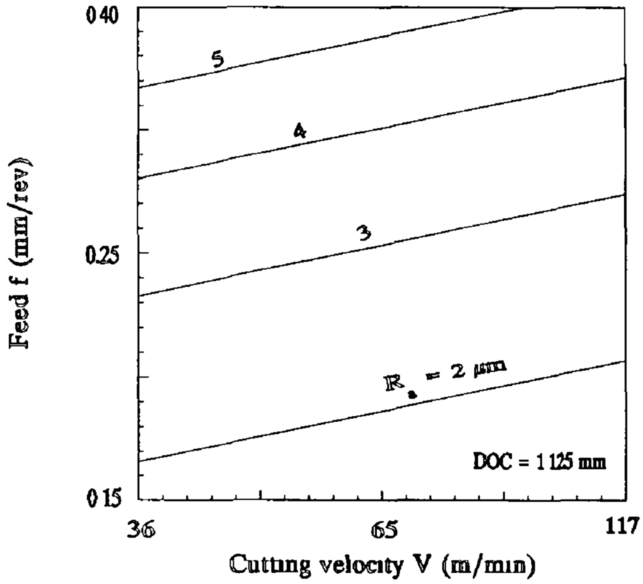


Figure 7.9 Surface roughness (1st order) contour in velocity-feed plane at a depth of cut of 0.50 mm.

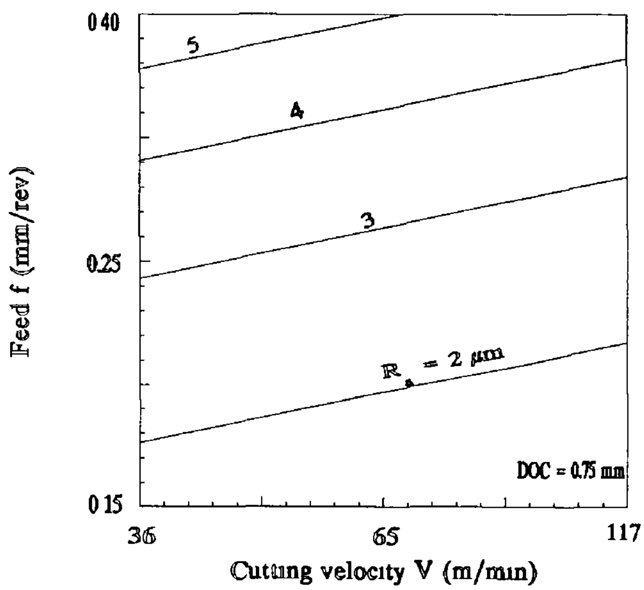


Figure 7.10 Surface roughness (1st order) contour in velocity-feed plane at a depth of cut of 0.75 mm.

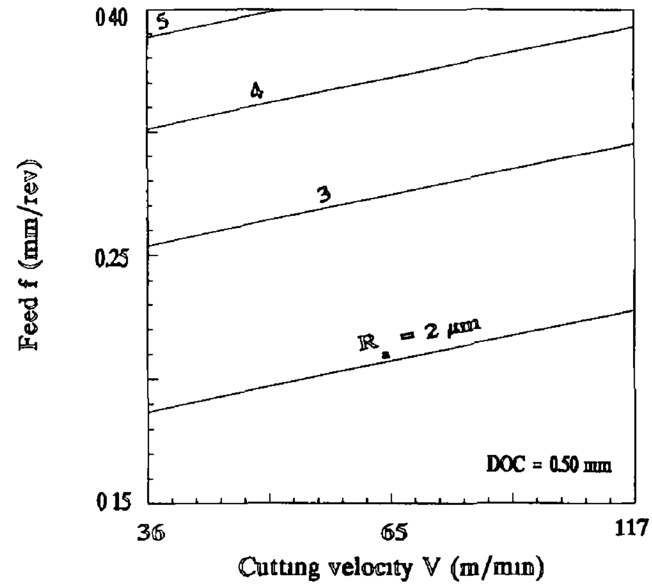


Figure 7.11 Surface roughness (1st order) contour in velocity-feed planes at a depth of cut of 1.125 mm.

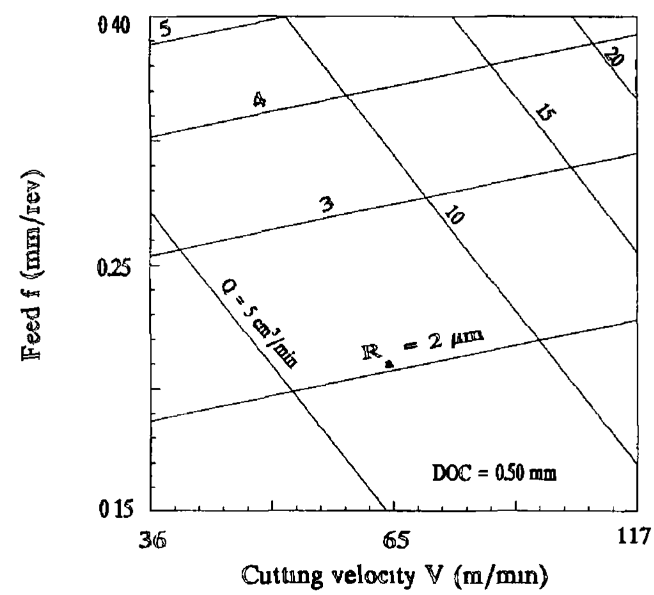


Figure 7.12 Dual response contours of surface roughness and metal removal rate in velocity-feed plane at 0.50 mm depth of cut.

7 2 2 2 Results, dıscussıons, and optımızatıon Second-order model

A second-order model was postulated to extend the varıables range ın obtaınıng the relatıonshıp between the surface roughness and the machınıng ındependent varıables The model ıs based on twenty four set of experıments and the parameters of Equatıon (7 5) are gıven by

$$\hat{y} = 0\,905 - 0\,094x_1 + 0\,604x_2 + 0\,064x_3 + 0\,102x_1^2 + 0\,042x_2^2 + 0\,071x_3^2 + 0\,066x_1x_2 - 0\,019x_1x_3 - 0\,019x_2x_3 \tag{7.17}$$

The estımated response and the 95% confidence ınterval for each of the twenty four test condıtıons were calculated and shown ın Table 7 11 of Appendıx C The formulae for calculatıng the confidence ınterval at the corner, central and augment poınts are

$$\hat{y} + t_{df,\alpha/2}\sqrt{\frac{15\,5}{24}\frac{\Sigma(y-\hat{y})^2}{df}}\,,$$

$$\hat{y} + t_{df,\alpha/2}\sqrt{\frac{5}{24}\frac{\Sigma(y-\hat{y})^2}{df}}\,, \tag{7.18}$$

$$\hat{y} + t_{df,\alpha/2}\sqrt{\frac{1}{3}\frac{\Sigma(y-\hat{y})^2}{df}}$$

respectıvely The *df* ıs the degrees of freedom whıch ıs 14 ın thıs case The analysıs of varıance as shown ın Table 7 10 of Appendıx C depıcts that the ınteractıon terms are not sıgnıficant at the 95% confidence level but the lınear and square terms are sıgnıficant The final model becomes

$$\hat{y} = 0\ 905 - 0\ 094x_1 + 0\ 604x_2 + 0\ 064x_3 + 0\ 102x_1^2 + 0\ 042x_2^2 + 0\ 071x_3^2 \tag{7.19}$$

Equation (7 19) is plotted in Figures 7 13 through 7 15 as contours for each of the response surfaces at three selected levels of depth of cuts (0 50, 0 75, & 1 125 mm) It is clear from these figures that surface finish improves with the increase of cutting speed at constant feed rate and constant depth of cut However, it decreases with the increase of feed rate

Equation (7 16) can be superimposed on Figure 7 13 for different values of metal removal rate Q Figure 7 16 is a plot of one of this superimposition From Figure 7 16, cutting parameters (speed, feed, and depth of cut) at point *A* would result in a surface finish of 3 μm at the rate of 10 cm^3/min metal removal rate, while those at the point *B* would result the same surface finish at the rate of metal removal of 20 cm^3/min

The cutting conditions at *B* is giving exactly one and half times the metal removal rate than that at *A* Hence, one can choose the cutting parameters at *B* without sacrificing the surface finish This reduces machining time since metal removal rate at *B* is 50% higher than that of *A*

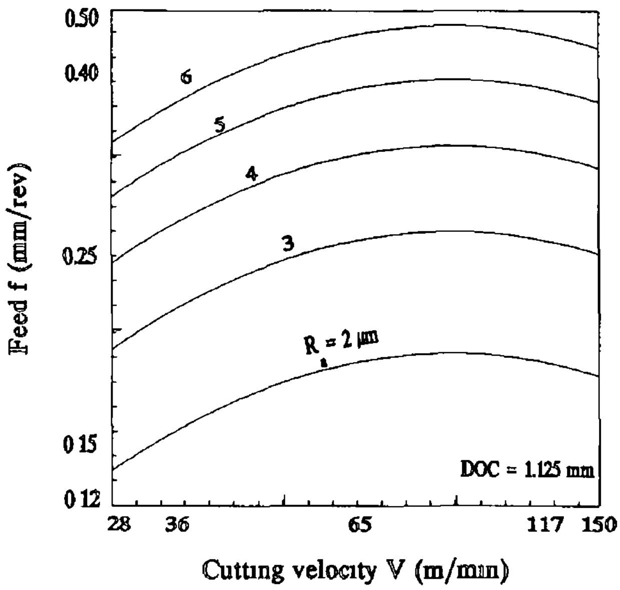


Figure 7.13 Surface roughness (2nd order) contour in velocity-feed plane at a depth of cut of 0.50 mm.

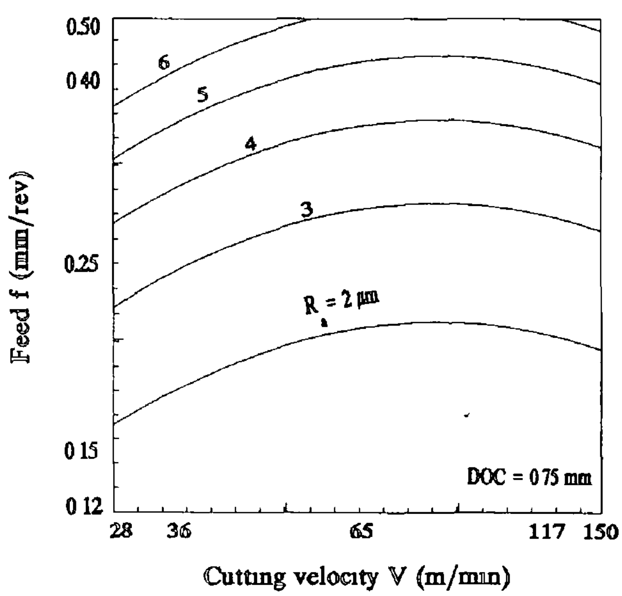


Figure 7.14 Surface roughness (2nd order) contour in velocity-feed plane at a depth of cut of 0.75 mm.

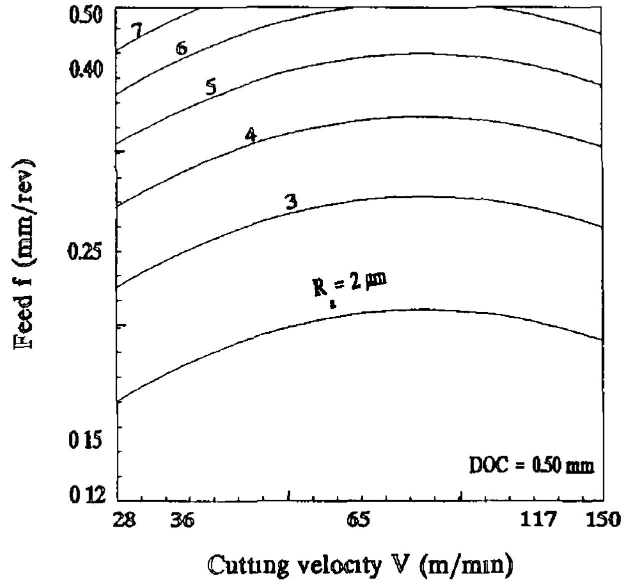


Figure 7.15 Surface roughness (2nd order) contour in velocity-feed plane at a depth of cut of 1.125 mm.

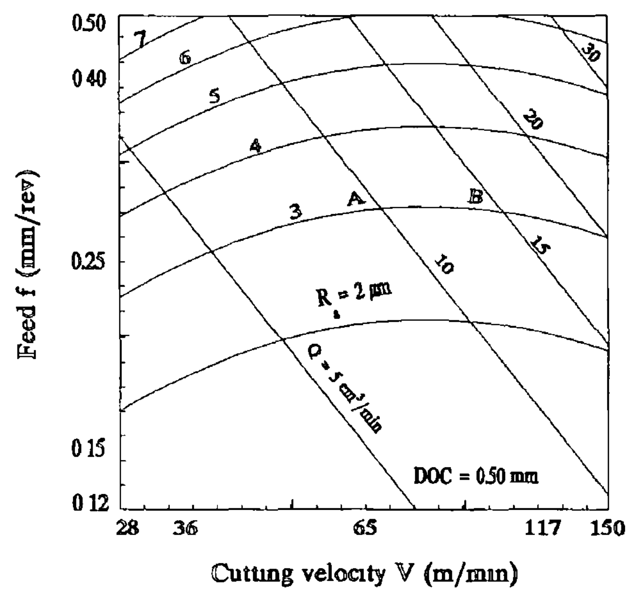


Figure 7.16 Dual response contours of surface roughness and metal removal rate in velocity-feed plane at 0.50 mm depth of cut.

7.2.3 Cuttıng force model

7 2 3 1 Results and dıscussıons Fırst-order model

The postulated model for the cuttıng force based on the twelve set of experıments are

$$\hat{y} = 6\,671 - 0\,0984x_1 + 0\,2875x_2 + 0\,3678x_3 \qquad (7.20)$$

Equatıon (7 20) descrıbıng the force model can be transformed by usıng equatıon (7 6) ınto the following form

$$F = 4854\ V^{-0\,1673}\ f^{0\,6124}\ d^{0\,9085} \qquad (7.21)$$

The equatıon ındıcates that the cuttıng force decreases wıth the ıncrease of speed whıle ıt ıncreases wıth the ıncrease of feed or depth of cut The depth of cut ıs found to have the maxımum ınfluence on the cuttıng force However, the model was found to be ınadequate based on the analysıs of varıance at 95% confidence ınterval The ratıo of lack of fit to pure error was 45 5 whıle ıts *F*-statıstıcs was 9 01 Sınce the first-order model was ınadequate, the levels of the ındependent varıables were extended and further experımentatıon were carrıed out

7 2 3 2 Results and dıscussıons on second-order model

A second-order model was postulated to extend the varıables range ın obtaınıng the relatıonshıp between the cuttıng force and the machınıng ındependent varıables The model ıs based on twenty four set of experıments and the parameters of Equatıon (7 5) are gıven by

$$\hat{y} = 6\,647 - 0\,114x_1 + 0\,3001x_2 + 0\,3728x_3 + 0\,0313x_1^2 \qquad (7.22)$$
$$+ 0\,0175x_2^2 - 0\,0006x_3^2 + 0\,0185x_1x_2 - 0\,004x_1x_3 - 0\,0333x_2x_3$$

The analysıs of varıance has shown that lack of fit was ınsıgnıficant at the 95% confidence level

The following conclusions/recommendations could be made out of the test results

1 Response surface methodology combined with the factorial design of experiments are useful techniques for the prediction of tool life, surface roughness, and power (cutting force) Relatively, a small number of designed experiments are required to generate much useful information which are used to develop the predicting equations for the response Depending on the response data provided by the design of experiment, first order and second order predicting equations have been developed

2 The tool life equation shows that the cutting speed is the main influencing factor on the tool wear followed by the feed rate and depth of cut Increasing either of these three cutting variables retard the tool life First order and second order surface roughness prediction equations have been developed from the factorial design of experiments Analysis of variance has indicated that the second order model is more adequate for the surface roughness and cutting force while first order model is adequate for tool life

3 Dual response contours provide useful information about the maximum attainable tool life for a given metal removal rate as a function of all three cutting independent variables

4 The results have revealed that the effect of feed on the surface roughness is much more pronounced than the effects of velocity and depth of cut However, higher cutting speed improves the surface finish

5 If the first order model is found to be adequate on the basis of statistical analysis, there is no need for additional twelve tests on the augment points As in this study, the variance analysis for the second order tool life model shows that interaction terms and the square terms are statistically insignificant

6 The tool life contours are useful to find out the optimum cutting conditions for a given tool life

7.3 Design of Experiment for Inconel-718

The levels of independent variables and coding identifications used in this design are presented in Table 7 12 Two types of carbide inserts were used for this turning investigation Table 7 13 shows the experimental conditions and results obtained by using uncoated carbide cutting tool inserts while Table 7 14 is obtained by using the coated carbide cutting inserts Tool life and surface roughness were investigated when machining inconel with the coated tools while all the three responses were investigated when the uncoated carbide inserts were used The tool life, surface roughness, and cutting force measurement procedures described in section 7 2 were followed

Table 7.12 Levels of independent variables for inconel-718

Levels	Lowest	Low	Centre	High	Highest
Coding	$-\sqrt{2}$	-1	0	1	$\sqrt{2}$
Speed V (m/min)	7	10	18	33	45
Feed f (mm/rev)	0 12	0 15	0 20	0 25	0 30
Doc d (mm)	0 80	0 90	1 25	1 75	2 0

The transforming equations for each of the independent variables are

$$x_1 = \frac{\ln(V) - \ln(18)}{\ln(33) - \ln(18)}$$

$$x_2 = \frac{\ln(f) - \ln(0\ 20)}{\ln(0\ 25) - \ln(0\ 20)} \qquad (7.23)$$

$$x_3 = \frac{\ln(d) - \ln(1\ 25)}{\ln(1\ 75) - \ln(1\ 25)}$$

Table 7.13 Experimental conditions and results (uncoated carbide inserts)

Trial No	Speed V (m/min)	Feed f (mm/rev)	Doc d (mm)	Coding			Response		
				x_1	x_2	x_3	Tool life T (min)	Surface roughness R_a (μm)	Cutting force F (N)
1	10	0 15	0 900	-1	-1	-1	64 2	2 667	906
2	33	0 15	0 900	1	-1	-1	6 0	1 8	777
3	10	0 25	0 900	-1	1	-1	34 8	4 167	1222
4	33	0 25	0 900	1	1	-1	2 8	4 433	1167
5	10	0 15	1 750	-1	-1	1	41 7	3 233	1830
6	33	0 15	1 750	1	-1	1	2 75	1 867	1365
7	10	0 25	1 750	-1	1	1	16 9	4 333	2428
8	33	0 25	1 750	1	1	1	1 3	4 1	2123
9	18	0 20	1 250	0	0	0	11 7	3 067	1439
10	18	0 20	1 250	0	0	0	15 2	3 467	1404
11	18	0 20	1 250	0	0	0	12 3	2 667	1417
12	18	0 20	1 250	0	0	0	13 5	3 1	1419
13	7	0 20	1 250	$-\sqrt{2}$	0	0	33 0	3 767	1721
14	45	0 20	1 250	$\sqrt{2}$	0	0	1 44	2 9	1255
15	18	0 12	1 250	0	$-\sqrt{2}$	0	37 1	1 637	985
16	18	0 30	1 250	0	$\sqrt{2}$	0	3 7	6 3	1981
17	18	0 20	0 80	0	0	$-\sqrt{2}$	20 8	2 5	930
18	18	0 20	2 0	0	0	$\sqrt{2}$	7 0	3 2	2105
19	7	0 20	1 250	$-\sqrt{2}$	0	0	39 0	3 9	1680
20	45	0 20	1 250	$\sqrt{2}$	0	0	1 6	3 3	1243
21	18	0 12	1 250	0	$-\sqrt{2}$	0	32 8	1 197	979
22	18	0 30	1 250	0	$\sqrt{2}$	0	4 3	6 433	1887
23	18	0 20	0 80	0	0	$-\sqrt{2}$	24 6	2 6	877
24	18	0 20	2 0	0	0	$\sqrt{2}$	8 3	2 7	2120

Table 7 14 Experimental conditions and results (Coated carbide inserts)

Trial No	Speed V (m/min)	Feed f (mm/rev)	Doc d (mm)	Coding			Response	
				x_1	x_2	x_3	Tool life T (min)	Surface roughness R_a (μm)
1	10	0 15	0 900	-1	-1	-1	30 1	2 967
2	33	0 15	0 900	1	-1	-1	6 5	3 433
3	10	0 25	0 900	-1	1	-1	20 8	7 133
4	33	0 25	0 900	1	1	-1	1 6	4 233
5	10	0 15	1 750	-1	-1	1	21 4	2 867
6	33	0 15	1 750	1	-1	1	3 5	2 6
7	10	0 25	1 750	-1	1	1	16 0	4 8
8	33	0 25	1 750	1	1	1	0 95	4 967
9	18	0 20	1 250	0	0	0	12 2	3 267
10	18	0 20	1 250	0	0	0	10 7	4 2
11	18	0 20	1 250	0	0	0	12 8	5 467
12	18	0 20	1 250	0	0	0	10 0	5 533
13	7	0 20	1 250	$-\sqrt{2}$	0	0	21 8	6 067
14	45	0 20	1 250	$\sqrt{2}$	0	0	2 1	4 267
15	18	0 12	1 250	0	$-\sqrt{2}$	0	17 8	2 3
16	18	0 30	1 250	0	$\sqrt{2}$	0	6 3	5 933
17	18	0 20	0 80	0	0	$-\sqrt{2}$	12 5	4 367
18	18	0 20	2 0	0	0	$\sqrt{2}$	9 4	3 8
19	7	0 20	1 250	$-\sqrt{2}$	0	0	24 7	5 567
20	45	0 20	1 250	$\sqrt{2}$	0	0	1 8	3 567
21	18	0 12	1 250	0	$-\sqrt{2}$	0	20 0	1 5
22	18	0 30	1 250	0	$\sqrt{2}$	0	5 18	6 1
23	18	0 20	0 80	0	0	$-\sqrt{2}$	12 1	3 767
24	18	0 20	2 0	0	0	$\sqrt{2}$	8 6	4 1

7.3.1 Tool life model

The tool life equation of uncoated carbide insert based on the first twelve experimental results (Table 7 13) in coded form are

$$\hat{y}_{uncoated\ carbide} = 2\,3882 - 1\,2718x_1 - 0\,3784x_2 - 0\,3377x_3 \qquad (7.24)$$

The analysis of variance at 95% confidence interval has shown that the ratio of lack of fit to pure error was 3 65 while the F-statistics was 9 01 (Table 7 15 of Appendix C) Therefore, the model was adequate Equation (7 24) describing the tool life model can be transformed by using equation (7 23) into the following form

$$T_{uncoated\ carbide} = 383\,5\ V^{-2\,0985}\ f^{-1\,6952}\ d^{-1\,003} \qquad (7.25)$$

The equation shows that the tool life decreases with the increase of cutting speed, feed, and depth of cut The cutting speed has the most dominant effect on tool life followed by the feed and depth of cut Combining equations (7 23) & (7 11), the metal removal rate for a specific depth of cut (1 25 mm) becomes

$$\ln Q = 1\,501 + 0\,606x_1 + 0\,223x_2 \qquad (7.26)$$

Equation (7 24) is utilised to develop tool life contours in speed-feed plane at the selected level of depth of cut Figure 7 17 through 7 19 shows the contours at three different depth of cuts These contours help predict the tool life at any zone of experimental domain

The response contours generated by Equation (7 26) is superimposed on Figure 7 18 and is shown in Figure 7 20 Since the first-order model was found adequate, the model based on the twenty experimental results are not presented

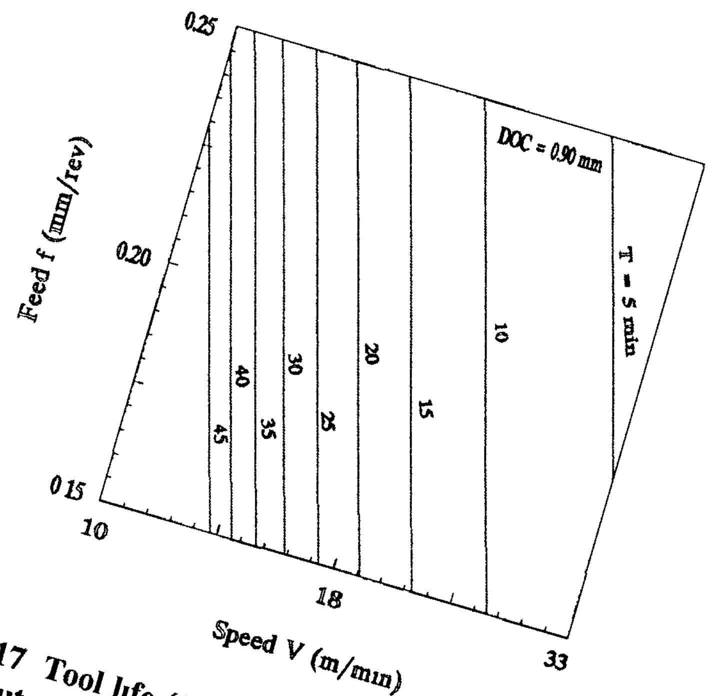


Figure 7.17 Tool life (1st order) contour in speed-feed plane at a depth of cut of 0.90 mm.

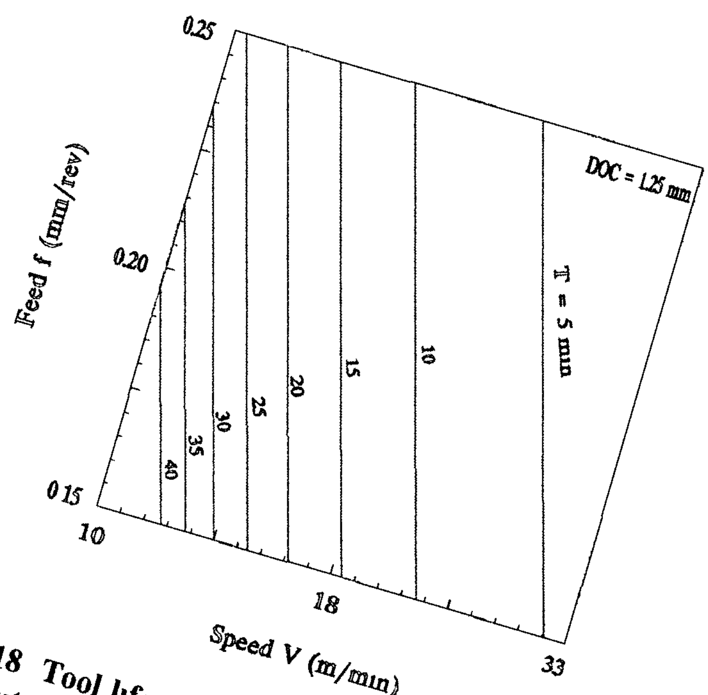


Figure 7.18 Tool life (1st order) contour in speed-feed plane at a depth of cut of 1.25 mm.

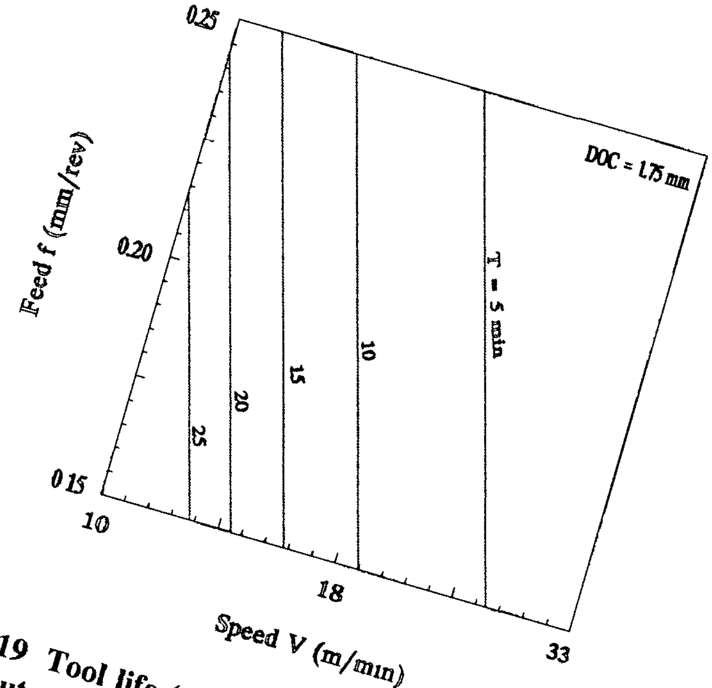
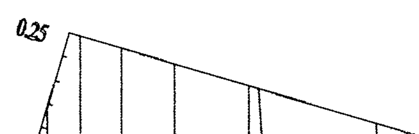


Figure 7.19 Tool life (1st order) contour in speed-feed plane at a depth of cut of 1.75 mm.



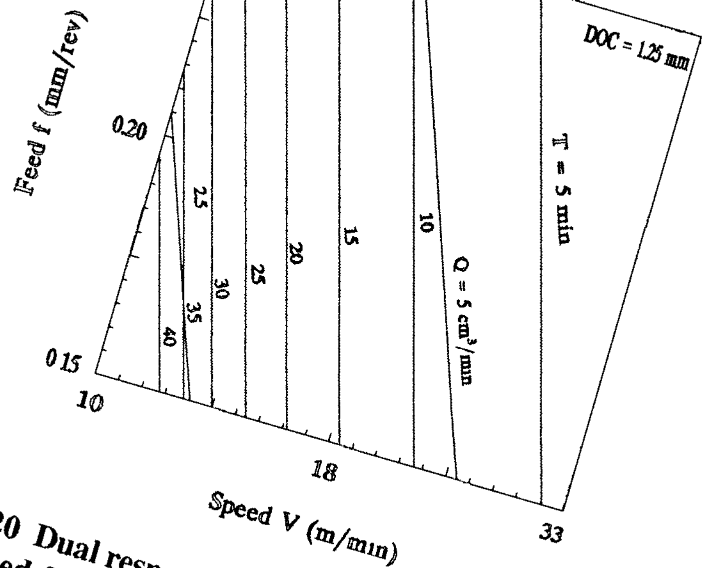


Figure 7 20 Dual response contours of tool life and metal removal rate in speed-feed plane at a depth of cut of 1.25 mm.

Based on the experimental results of Table 7 14, the first-order tool life equation in coded form using coated carbide insert is given by

$$\hat{y}_{coated\ carbide} = 2\ 1285 - 1\ 0915x_1 - 0\ 4208x_2 - 0\ 218x_3 \qquad \textbf{(7.27)}$$

Equation (7 27) describing the tool life model can be transformed by using equation (7 23) into the following form

$$T_{coated\ carbide} = 85\ 2\ V^{-1\ 801}\ f^{-1\ 885}\ d^{-0\ 647} \qquad \textbf{(7.28)}$$

7.3.2 Surface roughness model and optimization

The postulated model for surface roughness based on the twelve set of experiments of Table 7 13 is

$$\hat{y}_{uncoated\ carbide} = 1\ 1364 - 0\ 117x_1 + 0\ 3034x_2 + 0\ 0237x_3 \qquad \textbf{(7.29)}$$

Equation (7 29) describing the roughness model can be transformed by using equation (7 23) into the following form

$$R_{a_{uncoated\ carbide}} = 47\ 8\ V^{-0\ 193}\ f^{1\ 3596}\ d^{0\ 0704} \qquad \textbf{(7.30)}$$

The expected effects of the cutting variables on the response were observed A second-order model was postulated to extend the variables range in obtaining the relationship between the response and the cutting independent variables The model based on twenty four set of experiments is given by

$$\hat{y}_{uncoated\ carbide} = 1.107 - 0.096x_1 + 0.419x_2 + 0.037x_3 + 0.071x_1^2 \tag{7.31}$$
$$- 0.001x_2^2 - 0.044x_3^2 + 0.119x_1x_2 - 0.034x_1x_3 - 0.0335x_2x_3$$

Equation (7 31) is plotted in Figure 7 21 through 7 23 as contours for each of the response surfaces at three selected levels of depth of cuts (0 90, 1 25, & 1 75 mm) It is clear from these figures that surface finish improves with the increase of cutting speed at constant feed rate and constant depth of cut However, it decreases with the increase of feed rate

Equation (7 26) can be superimposed on Figure 7 22 for different values of metal removal rate Q Figure 7 24 is the plot of superimposition of surface roughness and metal removal rate contours at a depth of cut of 1 25 mm From Figure 7 24, comparing the points *A* & *B*, one can choose the cutting parameters (speed and feed) at *B* without sacrificing the surface finish This reduces machining time since the metal removal rate at *B* is 100% higher than that at *A*

Figure 7 25 represents dual response contours of tool life and surface roughness It is interesting to note that a particular surface roughness profile intersects through different tool life contours and vice versa Looking at the points *A* and *B* on the surface roughness profile of 3 2 μm, the cutting speed and feed at *A* will yield a tool life of 20 minutes while that at point *B*, the tool life is 10 minutes A net gain of 100% tool life is possible if one selects the cutting parameters at the point *A*

Based on the experimental results of Table 7 14, the first-order surface roughness equation for the coated carbide insert is

$$\hat{y}_{coated\ carbide} = 1.4114 - 0.0549x_1 + 0.2812x_2 - 0.0686x_3 \tag{7.32}$$

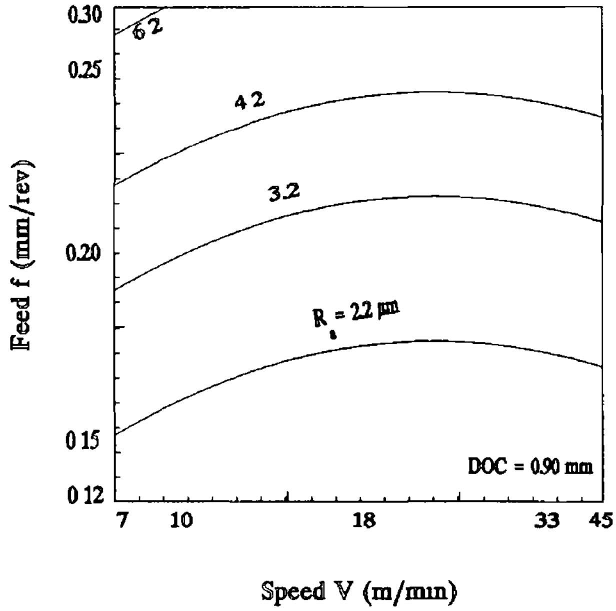


Figure 7.21 Surface roughness (2nd order) contours in speed-feed plane at a depth of cut of 0.90 mm.

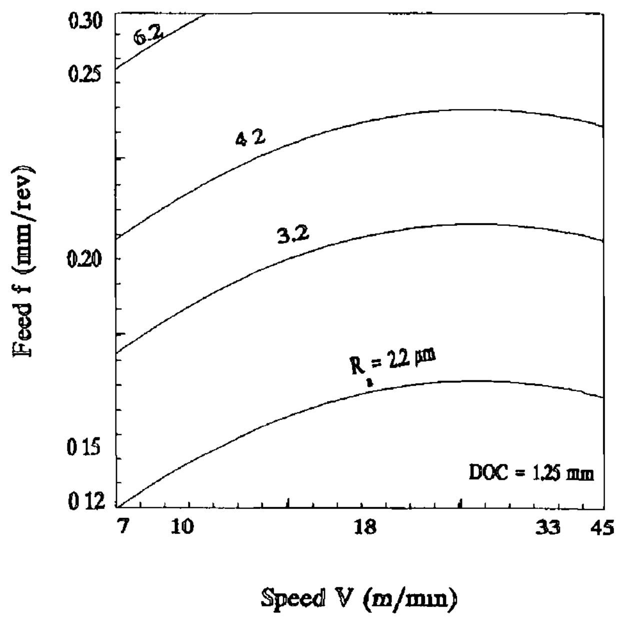


Figure 7.22 Surface roughness (2nd order) contour in speed-feed plane at a depth of cut of 1.25 mm.

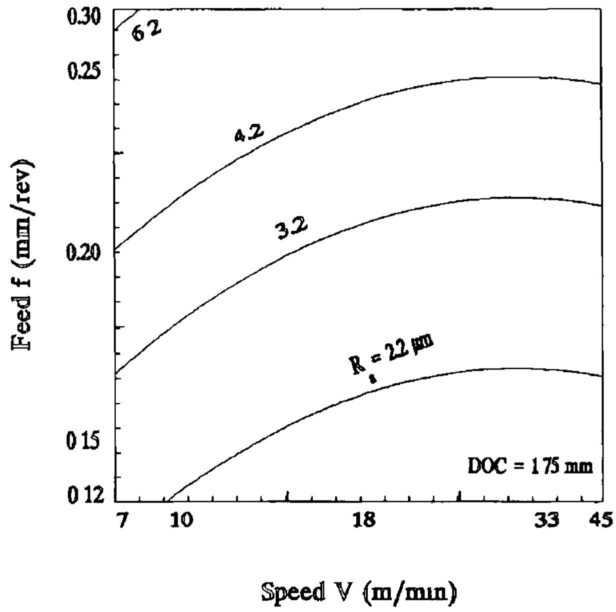


Figure 7.23 Surface roughness (2nd order) contour in speed-feed plane at a depth of cut of 1.75 mm.

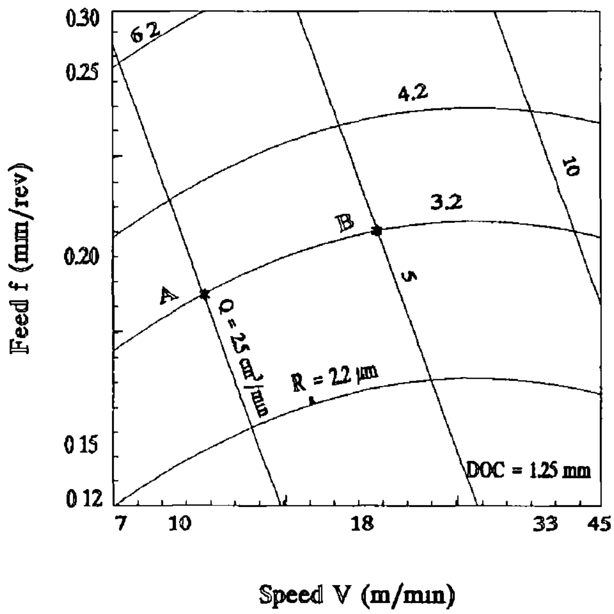


Figure 7.24 Dual response contours of surface roughness and metal removal rate in speed-feed plane at 1.25 mm depth of cut

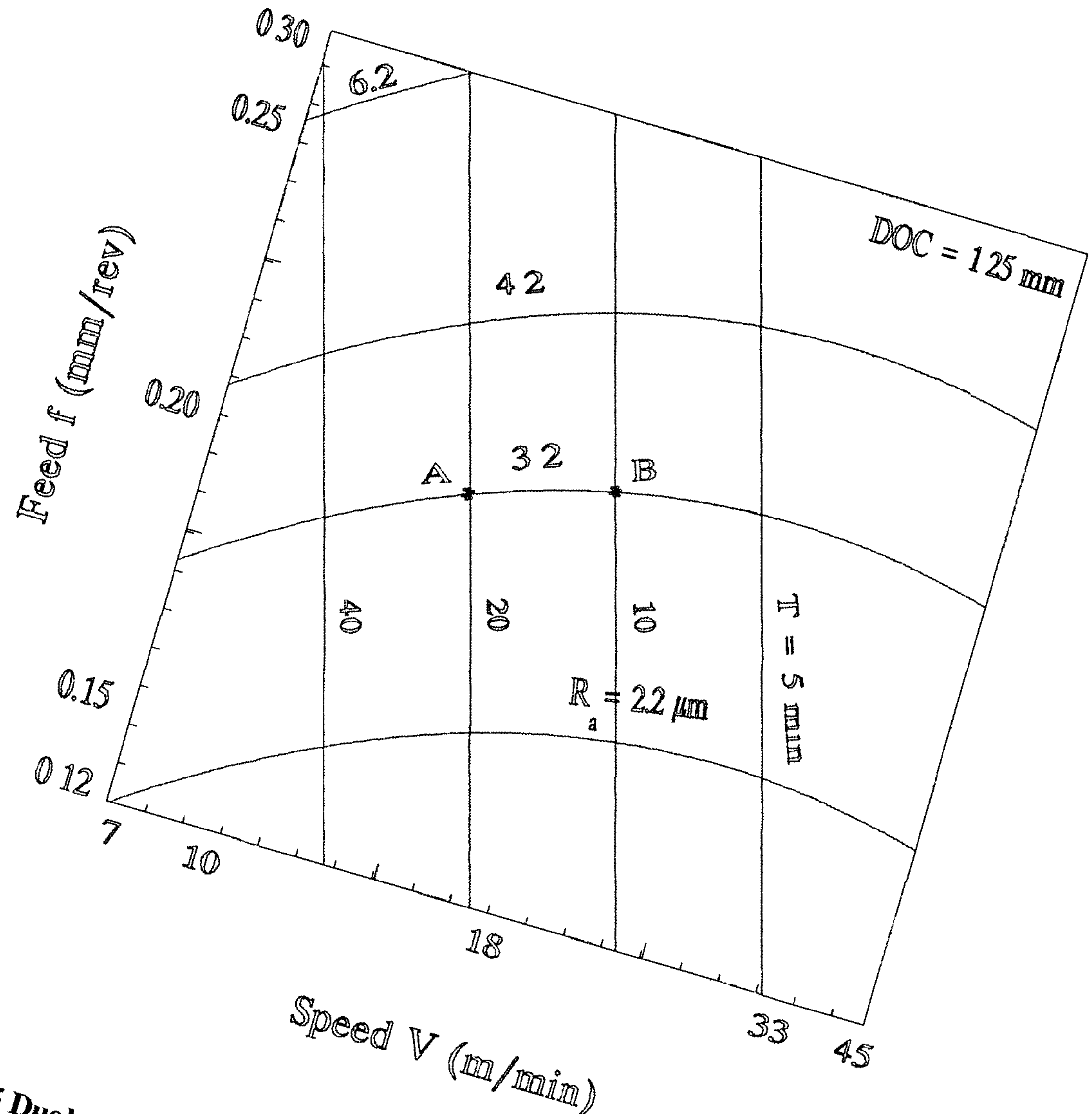


Figure 7.25 Dual response contours of tool life and surface roughness in speed-feed plane at a depth of cut of 1.25 mm.

Equation (7 32) can be transformed by using equation (7 23) into the following form

$$R_{a_{coated\ carbide}} = 42\,35\ V^{-0\,091}\ f^{1\,2598}\ d^{-0.204} \tag{7.33}$$

The effects of the cutting variables on the response are rather interesting The surface finish was observed to improve with increase of speed or depth of cut Noticeably, the effect of depth of cut on the improvement of surface finish was more than the effect of the speed Perhaps with higher depth of cut, material becomes more rigid and surface finish improves A second-order model was postulated to extend the variables range in obtaining the relationship between the response and the cutting independent variables The model based on twenty four set of experiments is given by

$$\begin{aligned}\hat{y}_{coated\ carbide} &= 1\,494 - 0\,098x_1 + 0\,348x_2 - 0\,039x_3 + 0\,04x_1^2 \\ &- 0\,137x_2^2 - 0\,047x_3^2 - 0\,067x_1x_2 + 0\,039x_1x_3 + 0\,009x_2x_3\end{aligned} \tag{7.34}$$

7.3.3 Cutting force model

The first order model for cutting force is

$$\hat{y}_{uncoated\ carbide} = 7\,238 - 0\,0784x_1 + 0\,1787x_2 + 0\,319x_3 \tag{7.35}$$

Equation (7 35) can be transformed by using equation (7 23) into the following form

$$F = 5938\ V^{-0\,1294}\ f^{0\,801}\ d^{0\,948} \tag{7.36}$$

The equation shows that the cutting force decreases with the increase of speed while it increases with the increase of feed or depth of cut The depth of cut is found to have the maximum influence on the cutting force However, the model was found to be inadequate based on the analysis of variance at 95% confidence interval The ratio of lack of fit to pure error was 35 9 while its F-statistics was 9 01 Since the first-order model was inadequate, the levels of the independent variables were extended and further experimentation were carried out

A second-order model was postulated to extend the variables range in obtaining the relationship between the cutting force and the machining variables The model is based on twenty four set of experiments and is given by

$$\hat{y}_{uncoated\ carbide} = 7\,263 - 0\,094x_1 + 0\,209x_2 + 0\,310x_3 + 0\,008x_1^2 - 0\,02x_2^2 - 0\,019x_3^2 + 0\,033x_1x_2 - 0\,028x_1x_3 + 0\,002x_2x_3 \tag{7.37}$$

The analysis of variance has shown that lack of fit was insignificant at 95% confidence level Equation (7 37) is plotted in speed-feed plane at three levels of depth of cuts and are shown in Figure 7 26 through 7 28 Comparing the figures, we can say that the cutting force increases with the increase of depth of cut or feed while with the increase of the speed, it decreases Figure 7 29 is a dual response contours of the force and the metal removal rate The intersections of Q = 2 5 and 5 cm^3/min with F = 1500 N reveals that the cutting parameters at the intersection of Q = 5 cm^3/min and F = 1500 N gives a net gain of 100% increase in metal removal rate for the same spindle power

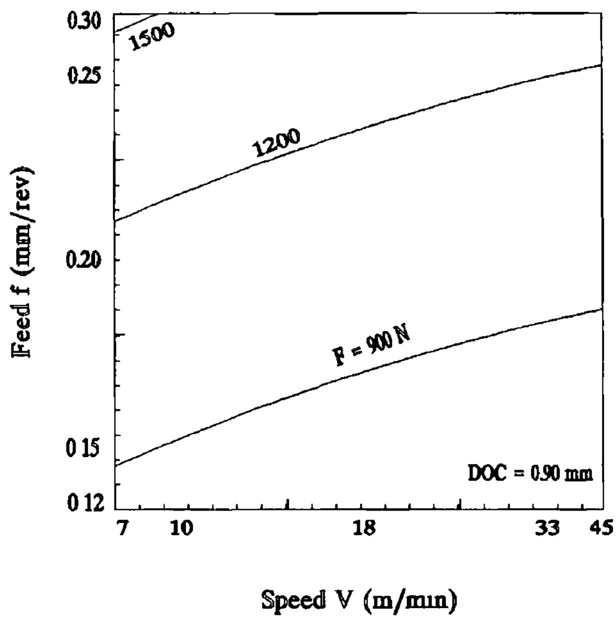


Figure 7.26 Cutting force (2nd order) contour in speed-feed plane at a depth of cut of 0.90 mm.

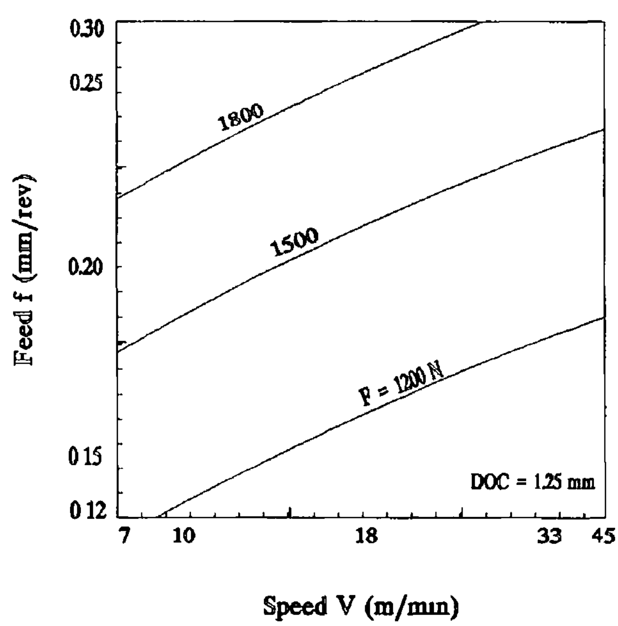


Figure 7.27 Cutting force (2nd order) contour in speed-feed plane at a depth of cut of 1.25 mm.

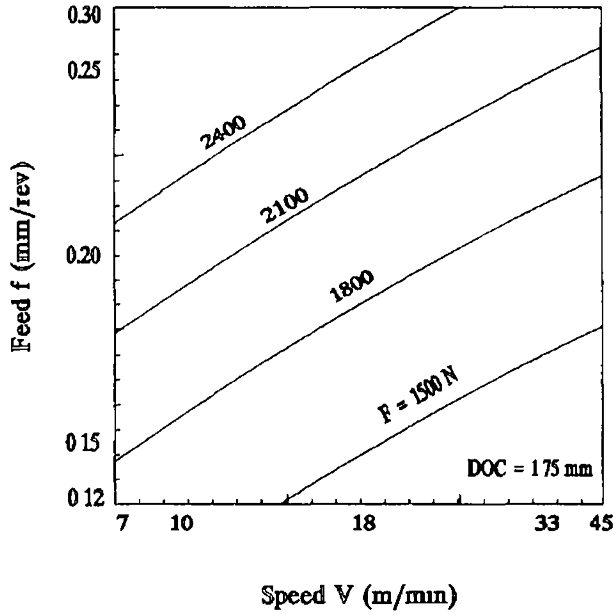


Figure 7.28 Cutting force (2nd order) contour in speed-feed plane at a depth of cut of 1.75 mm.

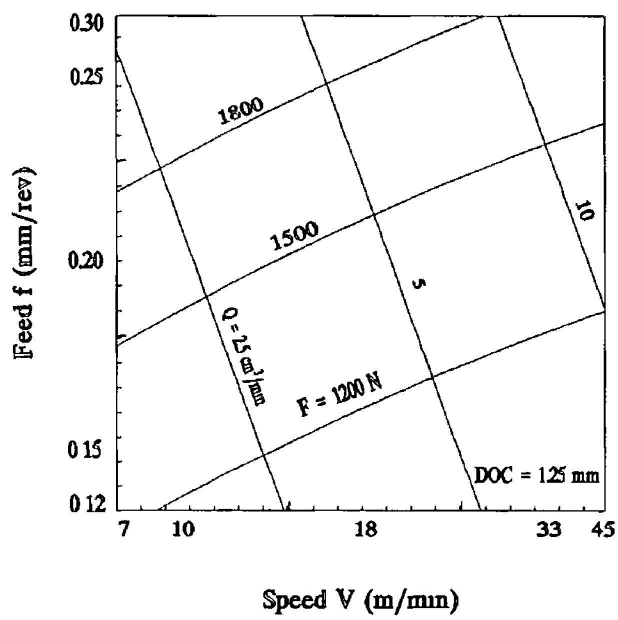


Figure 7.29 Dual response contours of cutting force and metal removal rate in speed-feed plane at a depth of cut of 1.25 mm.

The followıng conclusıons/recommendatıons could be made out of the test results

1 In the case of coated tools, the effect of feed on tool lıfe ıs much more pronounced than the effect of speed The magnıtude of the feed exponent ıs found to be greater than the velocıty exponent as presented ın Equatıon (7 28)

2 The effect of depth of cut on the tool lıfe ıs greater ın the case of uncoated carbıde than the coated carbıde The depth of cut exponents ($d_{uncoated}$ = -1 003, d_{coated} = -0 647) for uncoated tool ıs hıgher

3 The surface roughness generated by the uncoated and coated tools are mostly ınfluenced by the change ın feed The ıncrease ın depth of cut ımproves the surface finısh produced by the coated carbıde tools whıle ıt ıs the opposıte when the uncoated tool have been used

4 The cuttıng force decreases when the speed ıs ıncreased whıle ıt ıncreases when the feed or depth of cut ıs ıncreased

5 The dual response contours of tool lıfe and surface roughness ıs very useful ın assessıng the maxımum attaınable tool lıfe for the same surface finısh

CHAPTER 8

ANALYSIS OF EXPERIMENTAL RESULTS BY STATISTICAL PACKAGES AND SEQUENTIAL ESTIMATION

8.1 Introduction

Section 8 2 of this chapter presents model parameters obtained by the different statistical regression model building techniques The techniques are

(i) backward elimination,
(ii) forward selection,
(iii) stepwise regression, and
(iv) all possible subset regression

The model parameters presented in different tables are based on the experimental results for tool life, surface roughness, and cutting forces given in Tables 7 2, 7 13 and 7 14 for both steel and inconel While section 8 3 of the chapter presents model parameters based on the sequential estimation

8.2 Statistical Regression Packages

SPSS and BMDP programmes have been used for building different models The all possible subset regression has been carried out by using BMDP package while the remaining three techniques have been conducted by using SPSS computer package In all cases, programmes have been written to run the package

For building a first order model given by equation (7 4), the natural variables (both response and independent) are converted into the design variables by their logarithmic transformations For developing a second order model as per Equation (7 5), the squares and cross product variables are computed from the respective first order design variables

The reasons for using data transformations are

1 to stabilize the variance of the dependent variable,
2 to normalize the dependent variable if the normality assumption is violated, and
3 to linearize the regression model if the original data suggest a model that is nonlinear in either the regression coefficients and/or the variables (response or independent)

A detailed discussion of the properties of various transformations can be found in references [120, 145-148] It is rather fortunate that the same transformation often helps to accomplish the first two goals and sometimes even the third, rather than achieving one goal at the expense of either of the other two

The logarithmic transformation (**y = lnR**) can i) stabilizes the variance of the response variable, ii) normalizes the response variable if the distribution of the residuals for response is positively skewed, and iii) linearizes the regression model if the relationship of response to some independent variable suggests a model with consistently increasing slope

F_{in} and F_{out} values determine the number of variables in the final model of backward elimination, forward selection, and stepwise regression techniques The values for F_{in} and F_{out} are related to t-statistic by the relation of $F = t^2$ The t-statistic of the coefficient, defined as the ratio of the coefficient value to its standard deviation, indicates the significance of the variable in the model A 95% confidence level for the set of data size in this analysis has t value of about 2 0 The corresponding F value should be 4 0 and for this reason F_{in} = 4 0 and F_{out} = 3 9 have been assigned to the programme

A variable must pass both the tolerance and minimum tolerance test in order to enter and remain in the regression equation A variable's tolerance is the proportion of variance remaining after the effects of the independent variables already in the equation have been partitioned out It is one minus the squared multiple correlation of that independent variable with the other independent variables already in the equation The minimum tolerance is the minimum of recomputed tolerances of the variables in the equation when a variable is entered at the next step A value of 0 0001 has been used which applies to both tolerance tests This signifies that a variable does not enter an equation if it's squared multiple correlation with all the independent variables is greater than 1 - 0 0001 = 0 9999, nor does it enter if it would cause the squared multiple correlation for any variable already in the equation to exceed 0 9999 The choice of fitting a first order or second order model is not obvious from the data

However, if the first order effect is predominant in the data, fitting a second order model by the techniques described, would result in a first order model Hence, the selection of the order of the equation is automated by the different techniques if all the independent variables are included in the programme

8.2.1 EN24T Steel

Tables 8 1 through 8 3 of Appendix D show the estimated parameters of the best models calculated by the different model building techniques using the data of Table 7 2 for tool life, surface roughness, and cutting forces respectively The various parameter values i e , the model co-efficients are shown in each box while its t-statistics are shown within the parenthesis below Additional statistics such as R^2, *adjusted* R^2, and standard error of estimate s, are also given in the table The statistical parameters of the full form of the first order and the second order model are also included in the table

8.2.2 Inconel 718

Tables 8 4 through 8 6 show the estimated parameters of the best models calculated by the different model building techniques using the data of Table 7 13 for tool life, surface roughness, and cutting forces respectively While Tables 8 7 and 8 8 of Appendix D show the estimated parameters for tool life and surface roughness respectively when using the data of Table 7 14

Having chosen a model that is best suited for a particular sample of data, the regression diagnostic methods such as residual analysis are necessary to demonstrate the adequacy of the model We define the ith residual ε_i, to be the difference between the measured value y_i and the predicted value $\hat{y}_i$ namely, $\varepsilon_i = y_i - \hat{y}_i$, $i = 1,2, \ldots ,n$ The error ε_i reflects the amount of discrepancy (residual) between the observed and predicted values that is still present after having fitted the model The usual assumptions made about the error ε of Equation (7 4) or Equation (7 5) for regression analysis are that they are independent, have zero mean, have a constant variance, and follow a normal distribution

The residuals derived from the predicted equations obtained by the different techniques should agree with these assumptions In order to investigate whether there is any deviation from these assumptions, residual plots have been carried out These are (i) plot of standardized residuals, and (iii) normal probability plot of residuals

Table 8.4 Statistical parameters for tool life (uncoated carbide)

Inconel 718	Coefficients and t-values										Selection criteria		
	b_o	b_1	b_2	b_3	b_{11}	b_{22}	b_{33}	b_{12}	b_{13}	b_{23}	R^2	Adj R^2	s
Backward	-0 597 (-0 53)	1 898 (2 5)	-2 0 (-11 5)		-0 642 (-4 8)				-0 376 (-7 1)		97 55	97 04	0 203
Forward	3 758 (18 8)				-0 508 (-22 0)			-0 687 (-10 9)	-0 375 (-6 6)		97 04	96 60	0 218
Stepwise	3 758 (18 8)				-0 508 (-22 0)			-0 687 (-10 9)	-0 375 (-6 6)		97 04	96 60	0 218
All Possible	3 758 (18 8)				-0 508 (-22 0)			-0 687 (-10 9)	-0 375 (-6 6)		97 04	96 60	0 218
1st order	4 8 (8 45)	-1 892 (-15 98)	-2 016 (-7 94)	-1 094 (-4 83)							94 47	93 64	0 297
2nd order	-4 133 (-1 2)	2 469 (2 0)	-5 497 (-2 0)	-1 072 (-0 6)	-0 711 (-4 5)	-0 97 (-1 4)	0 027 (0 04)	0 124 (0 25)	-0 254 (-0 66)	-0 427 (-0 48)	97 97	96 66	0 216

Table 8.5 Statistical parameters for surface roughness (uncoated carbide)

Inconel 718	Coefficients and t-values										Selection criteria		
	b_o	b_1	b_2	b_3	b_{11}	b_{22}	b_{33}	b_{12}	b_{13}	b_{23}	R^2	Adj R^2	s
Backward	2 516 (22 5)				0 118 (9 16)			0 512 (14 5)			91 20	90 36	0 122
Forward	1 937 (3 76)		-0 675 (-1 15)		0 181 (3 23)			0 738 (3 7)			91 74	90 50	0 122
Stepwise	2 516 (22 5)				0 118 (9 16)			0 512 (14 5)			91 20	90 36	0 122
All Possible	2 516 (22 5)				0 118 (9 16)			0 512 (14 5)			91 20	90 36	0 122
1st order	3 924 (14 28)	-0 152 (-2 53)	1 464 (11 38)	0 109 (0 95)							87 25	85 34	0 151
2nd order	2 615 (1 28)	0 162 (0 23)	0 448 (0 29)	0 146 (0 14)	0 174 (1 93)	0 353 (0 91)	-0 324 (-0 91)	0 787 (2 76)	-0 174 (-0 79)	-0 382 (-0 75)	94 02	90 17	0 123

Table 8.6 Statistical parameters for cutting force (uncoated carbide)

Inconel 718	Coefficients and t-values										Selection criteria		
	b_o	b_1	b_2	b_3	b_{11}	b_{22}	b_{33}	b_{12}	b_{13}	b_{23}	R^2	Adj R^2	s
Backward	7 779 (307 7)			1 419 (11 78)	0 049 (17 08)		-0 18 (-3 06)	0 248 (37 6)	-0 136 (-3 36)		99 62	99 51	0 023
Forward	7 94 (85 4)		0 189 (1 79)	1 441 (12 6)	0 031 (3 1)		-0 196 (-3 5)	0 184 (5 15)	-0 14 (-3 68)		99 68	99 56	0 021
Stepwise	7 779 (307 7)			1 419 (11 78)	0 049 (17 08)		-0 18 (-3 06)	0 248 (37 6)	-0 136 (-3 36)		99 62	99 51	0 023
All Possible	7 779 (307 7)			1 419 (11 78)	0 049 (17 08)		-0 18 (-3 06)	0 248 (37 6)	-0 136 (-3 36)		99 62	99 51	0 023
1st order	8 643 (120 4)	-0 151 (-9 61)	0 723 (21 53)	0 943 (31 46)							98 72	98 53	0 039
2nd order	7 884 (20 6)	0 058 (0 44)	0 228 (0 78)	1 474 (7 37)	0 028 (1 63)	0 032 (0 44)	-0 191 (-2 87)	0 207 (3 87)	-0 142 (-3 45)	0 019 (0 196)	99 69	99 49	0 023

The analysis of tool life data set of Table 8 4 are presented and discussed Figure 8 1 shows the plots of standardized residuals against predicted values of tool life for inconel when uncoated carbide tools were used It should be noticed from Table 8 4 that the backward elimination (BE) and all possible subset regression (APS) have resulted in identical model parameters while the stepwise regression (SR) and forward selection (FS) have produced a different set of identical parameters The standardized residual $z_i = \varepsilon_i/s$ is often examined rather than ε_i in a residual analysis, where s is the standard error of estimate of the model The standardized residuals fall within the bounds of plus or minus two standard deviations limits, and are positively and negatively signed with equal frequency No model inadequacies are revealed in these plots This confirms that the basic assumptions about the error are holding

Figure 8 2 depicts the standardized normal probability plot obtained by backward elimination/all possible subset The solid diagonal line indicates the expected normality of the residuals and the observed normality are shown by (+) sign These plots show that the residuals are normally distributed, as there is little deviation of the observed normality

Figure 8 3 and 8 4 show the residual plot and normal probability plot respectively from stepwise regression/forward selection Again the identical model parameters have been obtained by these two techniques

The different model building techniques do not necessarily produce the same best model as shown in Table 8 1 through 8 8 for different responses and for different materials and cutting tools In order to compare the advantage of one technique over the others, some criterion has to be established for selecting the best model and the best model building technique The various uses of regression models are [149] model building, prediction, and estimation of parameters In the case of machinability data base systems, optimization of machining responses is the main objective and therefore, the main use of the model is the estimation and prediction of parameters The commonly used criteria for this purpose are *adjusted* R^2 and variance s of the predicted values in the model

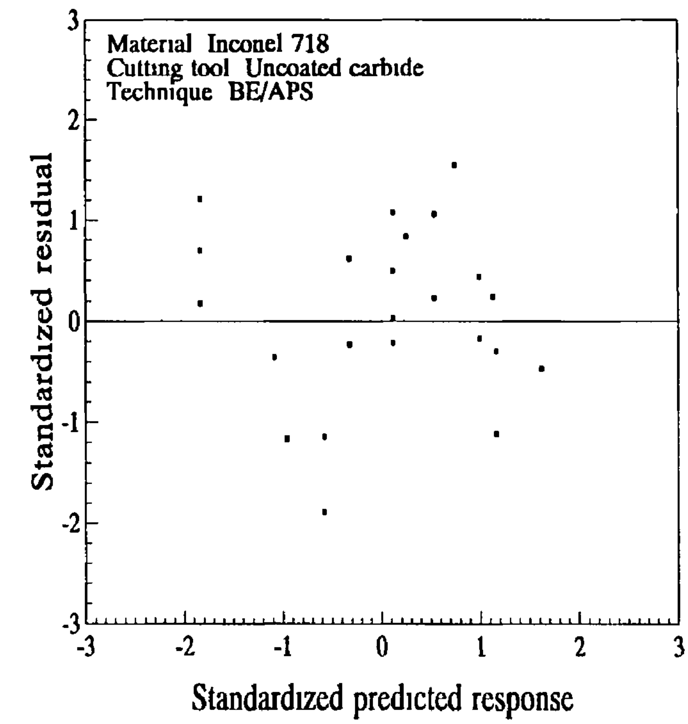


Figure 8.1 Standardized scatter plot of residuals from BE/APS

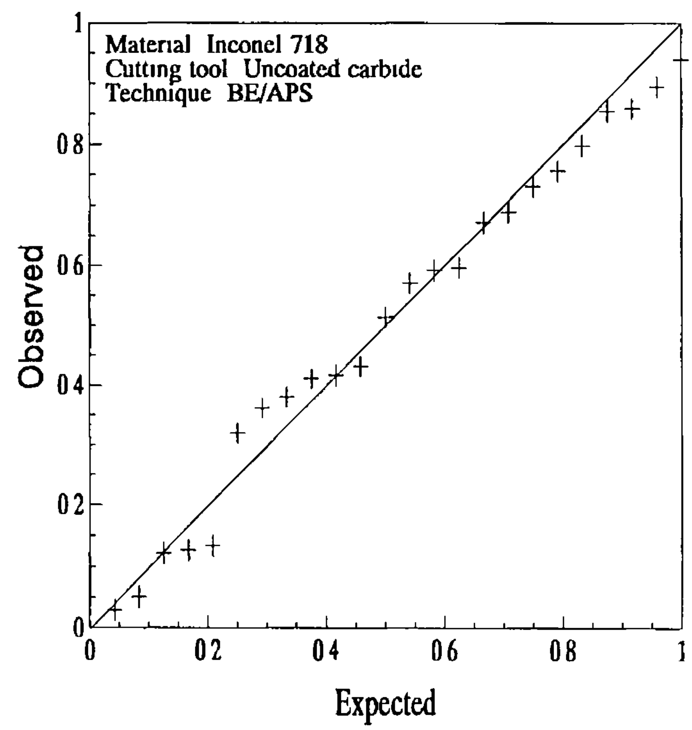


Figure 8.2 Standardized normal probability plot from BE/APS

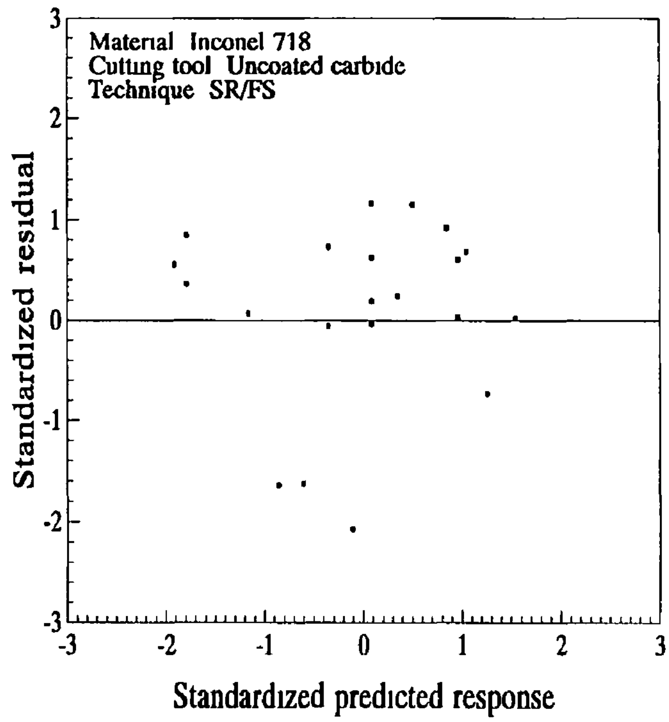


Figure 8.3 Standardized scatter plot of residuals from SR/FS

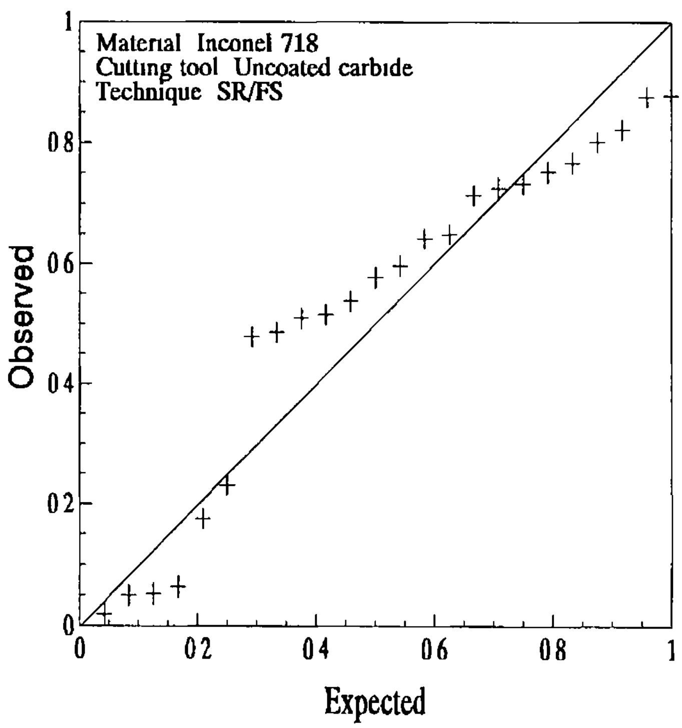


Figure 8.4 Standardized normal probability plot from SR/FS

It is evident from Table 8 4 that the backward elimination and all possible subset regression have $s = 0\ 203$, *adj* $R^2 = 97\ 04$ while the stepwise regression and forward selection output have $s = 0\ 218$, and *adj* $R^2 = 96\ 60$ Each pair of model building techniques (backward elimination/all possible subset regression and stepwise regression/forward selection) have produced a different set of identical parameters for a particular material

The main disadvantage of the forward selection technique is that once a variable is entered into the model, it could never be eliminated at a later stage (Table 8 5, and 8 6) even if its t-statistic falls below a pre-selected ($t = 2$) value However, this has not been observed in the analysis of tool life data The stepwise technique, on the other hand, is capable of eliminating a variable which becomes non-significant at a later stage This technique has its own limitations as well The selection procedure starts with one variable depending on F_{in} value Had there been F_{in} value less than 4 for all the variables at the beginning, the technique would have produced no solution at all However, this was not the case in our analysis Hence the choice has been limited between the backward elimination and all possible subset regression

In the backward elimination technique, elimination procedure starts from the full model depending on the significance of each variable If we compare its s and *adj* R^2 with those of stepwise and forward selection in Table 8 4, it is evident that the backward elimination has higher *adj* R^2 and lower s values These indicate that the model is better than stepwise regression or forward selection The all possible subset regression has also produced identical results together with backward elimination technique The second order model with all the variables have adjusted R^2 comparable to those obtained by all possible subsets and backward elimination However, if we look at t-statistics of the coefficients, most of its values are lower than 2

A comparative analysis of the models obtained from four different techniques has been made in order to evaluate the relative advantages of one over the other for application in the machinability data base systems The following conclusions can be made depending on the comparison

1 The stepwise regression and forward selection have produced identical model parameters in most cases, while the backward elimination and all possible subset regression have resulted in a different set of identical model parameters in all cases

2 The standard error of estimate s, has been found to be smaller for backward elimination and all possible subset regression in most cases The $adj\ R^2$ is found to be larger for backward elimination and all possible subset regression Smaller value of s and larger value of $adj\ R^2$ are an indication of the accuracy of the model

3 With all the parameters in the model (2nd order MLR, Table 2), s is greater than that obtained by the backward elimination and subset regression The smaller value of s with the lesser number of variables, indicates that the model is more accurate

4 Between the forward selection and stepwise regression, forward selection has its own limitations Once a variable is entered into the model, this technique can not remove it even if its F statistic becomes smaller than F_{out} (Table 8 5 and 8 6) The stepwise regression, not having this drawback, would be a better choice

5 The backward elimination and all possible subset regression are better techniques for model building in the machinability data base system As long as the product of input array of data matrix (X^T*X) is non-singular, the backward elimination will yield a solution and may be a better choice than the subset regression But if the product matrix becomes singular, all possible subset would be the best choice

8.3 Sequential Estimation

A detailed analysis of tool life data set of Table 7 2 are presented here Since the tool life model has proved to be of first-order in general, hence the tool life data are analyzed only by the sequential estimation In the case of tool life data of inconel for the uncoated and coated carbide tools, final models are presented without giving the detailed iterative analysis The procedure is similar to that shown in the subsection 8 3 1

8.3.1 EN24T Steel

The experimental tool life data generated during the turning of EN24T steel as given in Table 7 2 have been used A computer programme, written in Fortran, uses equations (4 23-4 28) of chapter 4, to estimate the model parameters sequentially Appendix E describes this programme

The model parameters and their relevant statistics were calculated using a statistical package The model given by the regression analysis is

$$\hat{y} = 8\,4895 - 1\,7981x_1 - 0\,3566x_2 - 0\,2777x_3 \qquad (8.1)$$

The standard error of the variables x_1, x_2, x_3, and the constant are 0 0616, 0 0732, 0 0891, and 0 2796 respectively The other statistical parameters are R^2 = 97 8, *adjusted* R^2 = 97 5, standard error s = 0 1458, and F statistics (3,20) = 294 86

8 3 1 1 Sequential estimation without prior information

The parameter estimates based on multiple regression analysis serves as a basis for evaluating the suitability of sequential estimation The same parameters could be obtained by sequential estimation using Equations (4 23-4 28) In starting the sequential procedure, the initial values of $\mathbf{b}_{u\,0}$, $\mathbf{P}_{uv\,0}$, and σ_i^2 are required In the OLS analysis, σ_i^2 is constant, initial values of $\mathbf{b}_{u\,0}$ are unknown and $\mathbf{P}_{uv\,0} = \mathbf{KI}$ where $\mathbf{I}$ is the identity matrix and K is a number Let the initial values of $\mathbf{b}_{u,0}$ be zero, the value of $K = 10^7$ and $\sigma^2 = 1$ for $i = 1,2,\ \ ,n$ The values of parameters and their variances computed at each step during sequential estimation are given in the Table 8 9

Table 8.9 Sequential analysis of the tool life data set without prior information

No of obs	Model parameter estimate				Variances			
	b_0	b_1	b_2	b_3	P_{00}	P_{11}	P_{22}	P_{33}
0	0 0	0 0	0 0	0 0	10^7	10^7	10^7	10^7
1	0 179	0 640	-0 339	-0 124	$9*10^6$	$2\ 8*10^6$	$7\ 99*10^6$	$9\ 7*10^6$
2	2 049	-2 011	-3 887	-1 420	$8*10^6$	1 440	$2\ 91*10^6$	$9\ 1*10^6$
3	5 955	-2 011	- 8393	-4 127	$3*10^6$	1 440	2 079	$6\ 8*10^6$
4	5 705	-1 815	- 6046	-3 954	$3*10^6$	0 720	1 039	$6\ 8*10^6$
5	8 110	-1 815	- 6046	- 4847	13 892	0 720	1 039	2 661
6	7 955	-1 751	- 6046	- 3577	12 192	0 480	1 039	1 521
7	8 391	-1 793	- 4764	- 2027	7 679	0 450	0 650	0 950
8	8 381	-1 786	- 4679	- 1924	7 483	0 360	0 520	0 760
9	8 383	-1 786	- 4677	- 1924	7 467	0 360	0 520	0 760
10	8 377	-1 786	- 4683	- 1924	7 453	0 360	0 520	0 760
11	8 375	-1 786	- 4684	- 1924	7 442	0 360	0 519	0 760
12	8 376	-1 786	- 4683	- 1924	7 433	0 360	0 519	0 760
13	8 133	-1 731	- 4696	- 1924	6 057	0 291	0 519	0 760
14	8 370	-1 794	- 4715	- 1924	5 309	0 239	0 519	0 760
15	8 480	-1 794	- 3805	- 1924	5 155	0 239	0 415	0 760
16	8 469	-1 794	- 3872	- 1924	4 950	0 239	0 340	0 760
17	8 465	-1 794	- 3870	- 2177	4 947	0 239	0 340	0 613
18	8 447	-1 794	- 3875	- 2547	4 921	0 239	0 340	0 505
19	8 323	-1 767	- 3880	- 2547	4 260	0 206	0 340	0 505
20	8 443	-1 798	- 3887	- 2548	3 867	0 179	0 340	0 505
21	8 465	-1 798	- 3699	- 2548	3 796	0 179	0 290	0 505
22	8 486	-1 798	- 3572	- 2548	3 693	0 179	0 252	0 505
23	8 482	-1 798	- 3568	- 2932	3 692	0 179	0 252	0 435
24	8 489	-1 798	- 3566	- 2777	3 678	0 179	0 252	0 378

The final parameter values obtained by the sequential estimation is observed to be the same as the ones obtained by regression analysis even though $\sigma^2 = 1$, and $\mathbf{b}_{u\,0} = 0$ were used as the start-up values Therefore, the final parameter values are not affected by an arbitrary value of $\sigma = 1$ in the sequential estimation The covariance matrix $\mathbf{P}_{uv\,n}$ is equal to $[\mathbf{X}^T\mathbf{X}]^{-1}$, whereas this matrix from regression analysis is given by $s^2 * [\mathbf{X}^T\mathbf{X}]^{-1} = (0\ 1458)^2 * [\mathbf{X}^T\mathbf{X}]^{-1}$ This can be checked by multiplying the final variances of the various parameters in Table 8 9 by $(0\ 1458)^2$ and comparing with those from the regression analysis

The discrepancy in the values of the standard deviation for the different parameters obtained from the sequential estimation and regression analysis is due to initial value ($\sigma_i = 1$) assumed for sequential analysis If the initial value is taken as equal to the standard error of estimate $s = 0\ 1458$, then sequential estimation would yield the same standard deviation of the parameters as those obtained by the regression analysis However, the parameter estimates are not affected by σ_i even though an arbitrary value of $\sigma_i = 1$ was taken as the start up value An estimate of σ_i, known as s can however, be computed using the parameter values obtained from sequential estimation

The actual values of σ_i is calculated by the equation

$$s^2 = \sigma_i^2 = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n-p} \tag{8.2}$$

where $\hat{y}_i$ is calculated from Equation (7 4) The different parameters used to calculate s is taken from the final step of sequential estimation From the analysis, it is clear that, sequential estimation provide the same information as the multiple regression technique The important advantage is that even if the matrix $[\mathbf{X}^T\mathbf{X}]$ does not have any inverse, this method can still yield a solution Since no matrix inverse is necessary in this analysis, it is very useful for ill-conditioned data

Table 8 10 illustrates the relative errors in the parameters for different values of K Small and large values of K in $P_{uv\,0}$ = KI can lead to inaccurate parameter values Small values imply prior estimates are accurately known, which is not compatible with OLS estimation The results in the Table indicate that a value of K between 10^7 to 10^{12} is appropriate for this analysis since the difference in parameter estimates in these cases and the regression analysis are negligible

Table 8.10 Relative errors in parameter estimates for different values of K

K value	Parameter estimates			
	b_0	b_1	b_2	b_3
1	1 8238	-0 3715	-0 7979	-0 3458
10	6 1520	-1 3157	-0 5593	-0 3322
10^2	8 1774	-1 7340	-0 3844	-0 2855
10^3	8 4571	-1 7914	-0 3595	-0 2785
10^4	8 4862	-1 7974	-0 3566	-0 2778
10^5	8 4891	-1 7980	-0 3566	-0 2777
10^6	8 4894	-1 7981	-0 3566	-0 2777
10^7	8 4894	-1 7981	-0 3566	-0 2777
10^8	8 4894	-1 7981	-0 3566	-0 2777
10^9	8 4894	-1 1981	-0 3566	-0 2777
10^{10}	8 4894	-1 7981	-0 3566	-0 2777
10^{11}	8 4894	-1 7981	-0 3566	-0 2777
10^{12}	8 4894	-1 7981	-0 3566	-0 2777
10^{13}	8 4894	-1 7974	-0 3555	-0 2764
10^{14}	8 4851	-1 7963	-0 3544	-0 2743
10^{15}	7 8349	-1 3157	-0 0204	-0 1719
MLR	8 4895	-1 7981	-0 3566	-0 2777

The proper value of K depends on the parameter values, the magnitude of the independent variable and the number of significant calculated digits For K = 10^{n_k} where K is large, the condition for K not too large is given [132] as

$$n_k \leq n_c - \log\left(\frac{\sum_{k=1}^{p} x_{1k}^2}{\sigma_1^2}\right) \tag{8.3}$$

where n_c is the number of significant calculated digits used in the computer Using x_{1k} from Table 7 2, Equation (8 3) gives $n_k \leq 12.5$ with $n_c = 14$ (double precision) *In other words*, K *should be less than* 12 5 *in order not to be too large* This is consistent with the results shown in Table 8 10 As the range of K is observed to be wide, a value of K between 10^6 and 10^{12} should be adequate for analysing these type of data

From Table 8 9, it is observed that parameter estimates and their variances stabilizes at fifth iteration The high variances observed up to fourth step are due to the effect of zero initial parameter values and high variances assumed as the start-up values If prior information are available, reasonable estimates could be obtained

8 3 1 2 Sequential estimation using prior information

The sequential estimation procedure given by Equations (4 23-4 28) can also be used when prior information regarding the parameter estimates and the covariance matrix are available The subjective prior information about the initial parameters $\mathbf{b}_{u\,0}$, the covariance matrix $\mathbf{P}_{uv\,0}$ and σ_ι for the tool life data set is

$$b_{u\,0} = \begin{bmatrix} 8.4894 \\ -1.7981 \\ -0.3566 \\ -0.2777 \end{bmatrix}, \quad P_{uv\,0} = \begin{bmatrix} 0.0782 & -0.0158 & 0.0075 & 0.0023 \\ -0.0158 & 0.0038 & 0.0000 & 0.0000 \\ 0.0075 & 0.0000 & 0.0053 & 0.0000 \\ 0.0023 & 0.0000 & 0.0000 & 0.0080 \end{bmatrix}, \quad \sigma_\iota = 0.1458$$

These values are obtained form Table 8 9 which are based on analysis without prior information The covariance matrix $\mathbf{P}_{uv\,0}$ is equal to $\mathbf{P}_{uv\,24}$* $(0.1458)^2$ $\mathbf{P}_{uv\,24}$ is taken from Table 8 9 Using these prior information, the sequential estimation was performed on the same tool life data given in Table 7 2 The results of the analysis are tabulated in Table 8 11 The results indicate that the parameter values and their variances up to the fourth steps do not differ from those in the subsequent steps significantly Hence the model obtained at each sequence could be used for selecting the machining conditions at the subsequent sequence It is also apparent form Table 8 9 & Table 8 11 that the importance of the prior information diminishes as the number of observations increases Hence if sufficient number of data are available and parameter estimates obtained from the first few iterations are not required, prior information is then not important Otherwise, prior information is necessary

Table 8.11 Sequential analysis of the tool life data set with prior information

No of obs	Model parameter estimate				Variances			
	b_0	b_1	b_2	b_3	P_{00}	P_{11}	P_{22}	P_{33}
0	8 4894	-1 7981	-0 3566	-0 2777	0782	0 0038	0 0053	0080
1	8 5524	-1 8220	-0 3846	-0 3132	0769	0 0036	0 0051	0076
2	8 5472	-1 8210	-0 3855	-0 3143	0701	0 0034	0 0048	0073
3	8 4458	-1 8051	-0 4089	-0 2902	0642	0 0032	0 0045	0069
4	8 4366	-1 8013	-0 4044	-0 2947	0631	0 0030	0 0043	0067
5	8 4317	-1 7999	-0 4028	-0 2972	0614	0 0029	0 0041	0063
6	8 3713	-1 7865	-0 4153	-0 2773	0583	0 0028	0 0040	0059
7	8 4588	-1 7982	-0 3980	-0 2567	0527	0 0027	0 0038	0056
8	8 4510	-1 7932	-0 3921	-0 2495	0524	0 0025	0 0036	0054
9	8 4537	-1 7931	-0 3918	-0 2495	0524	0 0025	0 0036	0054
10	8 4533	-1 7931	-0 3919	-0 2495	0524	0 0025	0 0036	0054
11	8 4543	-1 7931	-0 3918	-0 2495	0523	0 0025	0 0036	0054
12	8 4559	-1 7930	-0 3916	-0 2495	0523	0 0025	0 0036	0054
13	8 3726	-1 7748	-0 3923	-0 2495	0484	0 0024	0 0036	0054
14	8 4522	-1 7961	-0 3931	-0 2495	0459	0 0022	0 0036	0054
15	8 4839	-1 7963	-0 3662	-0 2495	0455	0 0022	0 0033	0054
16	8 4787	-1 7963	-0 3693	-0 2495	0448	0 0022	0 0031	0054
17	8 4782	-1 7963	-0 3692	-0 2559	0448	0 0022	0 0031	0049
18	8 4720	-1 7964	-0 3695	-0 2679	0447	0 0022	0 0031	0046
19	8 4136	-1 7835	-0 3699	-0 2679	0418	0 0020	0 0031	0046
20	8 4688	-1 7982	-0 3704	-0 2679	0400	0 0019	0 0031	0046
21	8 4781	-1 7982	-0 3625	-0 2679	0397	0 0019	0 0029	0046
22	8 4871	-1 7982	-0 3571	-0 2679	0392	0 0019	0 0027	0046
23	8 4858	-1 7981	-0 3568	-0 2848	0392	0 0019	0 0027	0043
24	8 4894	-1 7981	-0 3566	-0 2777	0391	0 0019	0 0027	0040

8.3.2 Inconel 718

The tool life model obtained by the sequential estimation of experimental data set of Table 7 13 and 7 14 are

$$\hat{y}_{uncoated\ carbide} = 4\,8004 - 1\,8919\ x_1 - 2\,0164\ x_2 - 1\,0936\ x_3 \qquad (8.4)$$

and

$$\hat{y}_{coated\ carbide} = 4\,4654 - 1\,5564\ x_1 - 1\,419\ x_2 - 0\,5003\ x_3 \qquad (8.5)$$

respectively

In computer integrated manufacturing system (CIM), the need for automatic selection of machining data in a mathematical model type machinability data base system requires a suitable model building technique The Sequential Maximum a Posteriori (MAP) method is proposed as a mathematical tool for use in the model building module This technique appears to be suitable since

1 The computation is efficient and can continually update parameter estimates as new observations are added
2 Computer memory storage requirement is small
3 Matrix inversion may not be needed
4 If there is only one independent observation at each step i, only a scalar needs to be inverted regardless of how many parameters are present and there are no simultaneous equations to solve
5 Prior information of the parameter estimates and co-variance matrix can be used
6 The results indicate that the sequential estimation technique provides the same information as the regression analysis

CHAPTER 9

DEVELOPMENT OF THE COMPUTERIZED MACHINABILITY DATA BASE SYSTEM

9.1 Introduction

In this chapter, a computerized machinability data base system has been developed using the results of chapter 8 Once the mathematical models of machining responses relating the machining variables have been determined in the previous chapter, these equations have been utilised in developing the data base The data base system presented here is valid for EN24T steel and inconel 718 only

9.2 Machinability Data Base Systems

The objectives of the computerized machinability data base systems are i) to provide recommendations for optimum cutting data, ii) to provide a link between the shop floor and production environments, and iii) to provide a means by which adjustments made on the shop floor can be reflected in future recommendations of cutting data made by the data base system

The existing computerized machinability data base systems (CMDBS) can be classified as (i) Data storage and Retrieval systems, (ii) Empirical equation systems, (iii) Mathematical model systems, and (iv) Expert system [63,150] Figure 9 1 shows the different types of data base systems

In the data storage and retrieval systems, a series of recommended cutting speeds, feeds, and other related information is stored in computer data storage and retrieval files, which can be retrieved through a user friendly interface program This information comes from shop experience, laboratory experiments, and machining data handbooks The main disadvantage of this system is that it requires highly experienced personnel to evaluate the incoming data and to update the data files

Empirical equation systems utilize the extended Taylor's tool-life equations to calculate the cutting parameters The data for a particular condition is reduced to an empirical form and expressed as a generalized empirical equation The systems exclude the need to store the tremendous amount of data for a wide combination of materials, tools, and operations

Mathematical model systems are based on equations obtained from experimental data which closely match the machining situation Mathematical models of response such as tool-life (extended Taylor's tool life equation) are developed as a function of speed, feed, and depth of cut for selecting economical cutting conditions Once the model is developed, the coefficients of the model are stored in a file and these are used instead of the original data in an optimization algorithm designed to obtain an optimum set of cutting conditions

Expert system can be developed using a commercially available expert system shell Expert system implies that the system is equipped with domain specific knowledge and pattern directed inference so that it simulates human experts in sensing, reasoning, and giving answers to specific problems The knowledge that an expert system needs are domain facts (type of operation, workpiece materials, cutting tools etc), relationship between the facts (work piece material and cutting tool), and methods for employing these relationships in problem solving (forward chaining, backward chaining, or mixed use of both)

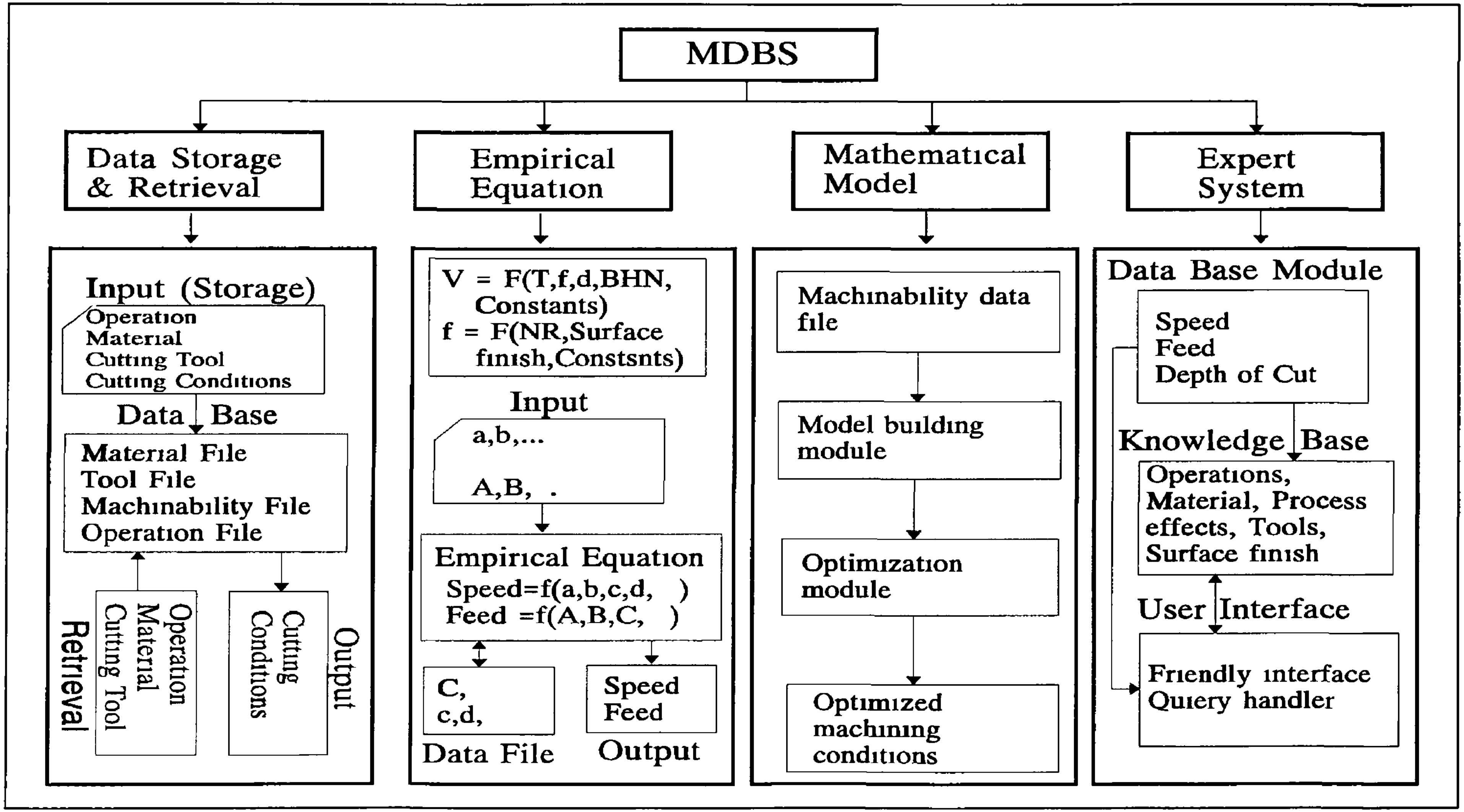


Figure 9.1 Different types of machinability data base systems (MDBS)

9.3 Development of the Data Base System

There are two types of cutting conditions namely; (i) recommended (non-optimum) cutting conditions or (ii) optimum cutting conditions which are usually derived by the existing computerized machinability data base systems. Recommended cutting conditions are those where a particular machining operation can be performed easily within the recommended conditions. Optimum cutting conditions, on the contrary, are based on some economic or performance objectives such as given tool life, cost functions, surface finish, power.

The existing CMDBS adopts different methods to obtain either of the two cutting conditions. To obtain the recommended cutting conditions; empirical equation or machinability chart or storage/retrieval method is used. The empirical equation method uses empirical equations for speed and feed which considers different cutting variables. In the machinability chart method, the data is converted into chart form to relate speed, feed, and tool life. These charts are stored in files for different materials. In the storage/retrieval method, speeds and feeds are stored in the form of actual values or as coefficients and factors. Feed rate is obtained from the tool diameter through interpolation of the feed curve using the feed factors.

The optimum cutting conditions can be obtained by generalized minimum cost/ or minimum production time equations or by Taylor's equation or by extended Taylor's equation. In the generalized cost and production methods, the cost and time for an operation depending on the input parameters (speed, feed, depth of cut, and cut geometry) are calculated for various combinations of cutting conditions and the choice is left to the user. In Taylor's tool-life equation, the equations for cost and time are obtained as a function of cost parameters and cutting speed. The extended Taylor's tool life equation is used in obtaining the optimum cutting conditions for a given tool life or for minimum cost or for minimum production time.

The objective is to provide mathematical equations which correlates the machining responses (tool life, surface finish, cutting force etc.) with the machining variables (cutting speed, feed rate, depth of cut). A mathematical model type data base system is based on this predicted equation fitted to an experimental data. There are different commercial regression analysis packages [126-128,151] available to predict a mathematical equation from experimental data These regression techniques are i) all possible subset regression, ii) backward elimination, iii) stepwise regression, and iv) forward selection In predicting the model equation, we have used the backward elimination technique After the model is developed, the co-efficients of the model are stored in a file and these co-efficients are used to derive the optimum cutting data based on a given tool life

In this project, a mathematical model type data base systems have been developed where the cutting conditions (speed, feed, and depth of cut) are displayed for a given tool life A block diagram of the proposed data base structure is shown in Figure 9 2

9.3.1 Mathematical model systems

The mathematical model systems are based on the mathematical models fitted to experimental data These data have been generated experimentally by the design of experiments outlined in chapter 7 Mathematical models of tool life, in the form of extended Taylor's tool-life equation have been developed Only a first-order form of the tool life equation has been considered since it was observed that the tool life equation is first-order

In the case of surface roughness and cutting forces, the backward elimination algorithm has been used to determine the corresponding response equation Once the equations have been developed by this algorithm (Table 8 1 - Table 8 8), the co-efficients of these equations are stored in a file and used instead of the original data The tool life co-efficients are used to derive cutting data for a given tool life After the cutting conditions are obtained, the model co-efficients for surface roughness and cutting forces evaluates the surface finish to be achieved and the required power Figure 9 3 shows the operation module of the data base in the form of input and output

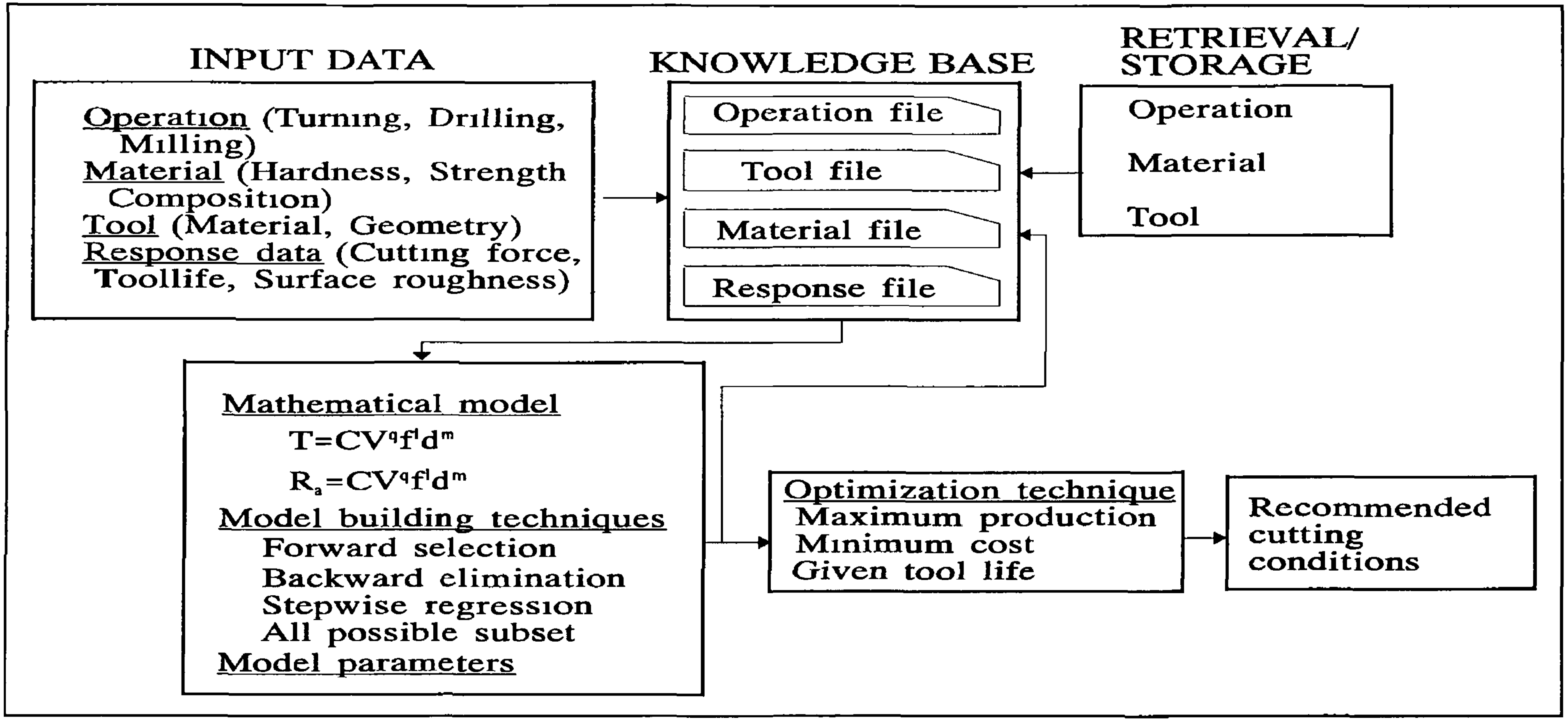


Figure 9.2 Mathematical model type machinability data base system

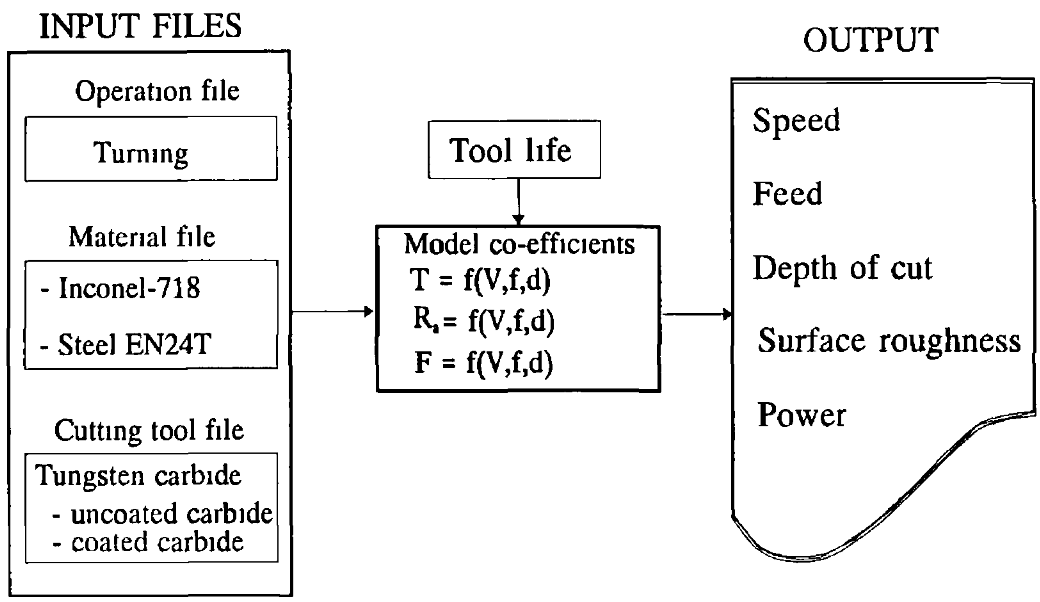


Figure 9.3 Machinability data base in the form of input and output

9.3.2 Methodology and environments

The methodology and the environment adopted for the development of the data base are described in this section The data base is limited to only one type of tool and two types of work materials combination However, there is a provision for further inclusion of tool and work material if the experimental data are available The data base has the tool and work material combination of uncoated tungsten carbide and EN24T steel and tungsten carbide and inconel 718

The structure of the machinability data base systems as shown in Figure 9 4 consists of the following modules

(i) data base module,

(ii) model equation module,

(iii) knowledge base module and

(iv) user interface module

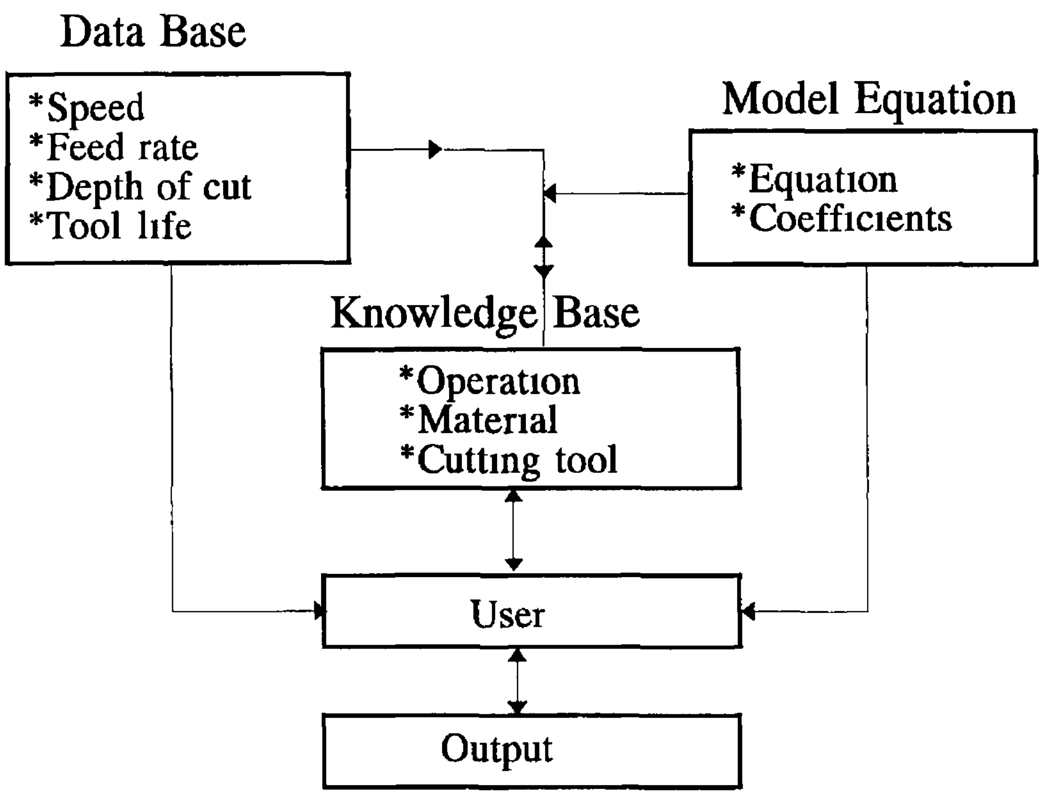


Figure 9.4 Structure of the machinability data base

The data base module consists of the experimental data file of Tables 7 2, 7 13, and 7 14 relating to the speed, feed rate, and depth of cut to the tool life The model equation module contains the equations developed by the regression analysis and the coefficient of the equation from Chapter 8

The knowledge base module consists of the following information

1 Machining operation

   a) Turning

2 Work materials

   a) Inconel-718

   b) EN24T steel

3 Tool materials

c) Tungsten carbide inserts (Uncoated and Coated carbide)

The user interface module enables the user to interact and execute the programme

Depending on the user's input of the work material / tool combination, the system displays a response file which shows the different combinations of speed, feed rate, and depth of cut together with the tool life achieved A separate file stores the model co-efficients obtained by the regression analysis of the experimental data The user is then asked if he wants the cutting data for a tool life different from the already displayed data If the answer is yes, the user is requested to give a value of tool life in minutes Given the input value of the tool life, the programme calculates the cutting parameters and displays different combinations of recommended speed, feed, and depth of cut The surface roughness value and power requirement could be obtained by providing the values of speed, feed, and depth of cut A flow chart of the programme is shown in Figure 9 5

Written in FORTRAN using the Microsoft FORTRAN Compiler version 3 2, the programme at the moment is valid only for turning operation and is designed for running on a PC Appendix F gives the detailed programme The programme derives the cutting conditions for EN24T steel and inconel 718 with carbide tools A programme output is outlined in Section 9 3 2 1

A general structure of the computerized machinability data base has been presented in this chapter The main objective of the data base is to generate the optimum cutting speed, feed rate, and depth of cut using the model coefficients obtained by regression analysis of the experimental data

Although the overall data base module is not fully developed, the use of model coefficients for generating the optimum cutting data have been attempted The data base module can be extended to include different combinations of cutting tools and work materials as well

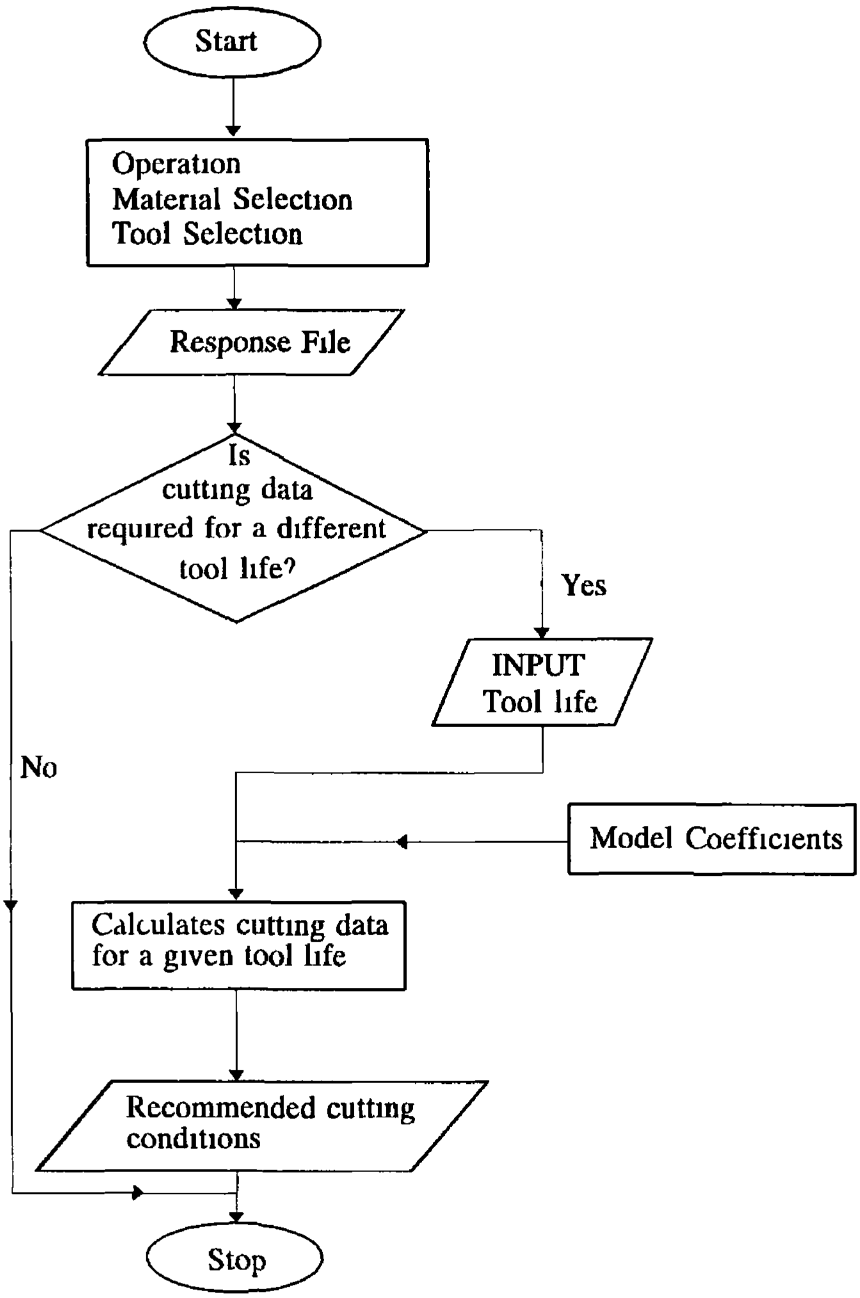


Figure 9.5 Programme flow chart

9 3.2.1 Programme Output

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 W E L C O M E   TO   M D B S
*******************************************

========================================
>>  OPERATION MODULE  <<
(1) TURNING
(2) MILLING
PLEASE TYPE (1)/(2) AND PRESS ENTER
        1

========================================
>>  MATERIAL SELECTION  <<
???SELECT YOUR MATERIAL???
1 INCONEL-718/2  Steel EN24T
PLEASE TYPE (1) / (2) AND PRESS ENTER
        1
========================================

PLEASE TYPE MATERIAL HARDNESS IN BHN
      425

========================================
>>  TOOL SELECTION  <<
???SELECT YOUR CUTTING TOOL???
1  UNCOATED CARBIDE / 2  COATED CARBIDE
PLEASE TYPE (1) / (2) AND PRESS ENTER
        1
```

= =

AN EXPERIMENTAL DATA FILE

VELOCITY (m/mın)	FEED (mm/rev)	DOC (mm)	TLIFE (mın)
10 0	150	900	64 20
33 0	150	900	6 00
10 0	250	900	34 80
33 0	250	900	2 80
10 0	150	1 750	41 70
33 0	150	1 750	2 75
10 0	250	1 750	16 90
33 0	250	1 750	1 30
18 0	200	1 250	13 20
7 0	200	1 250	33 00
45 0	200	1 250	1 44
18 0	120	1 250	37 10
18 0	300	1 250	3 70
18 0	200	800	20 80
18 0	200	2 000	7 00

DO YOU WANT CUTTING PARAMETER VALUES FOR A DIFFERENT TOOL LIFE?
IF YES PLEASE TYPE 1, IF NO PLEASE TYPE 2 AND PRESS ENTER

1

TOOL LIFE = 12 0 mın

==

TURNING OPERATION

MATERIAL INCONEL-718

HARDNESS IN BHN= 425

CUTTING TOOL UNCOATED TUNGSTEN CARBIDE

feed (mm/rev)	Velocity (m/min)				
12	48 6	32 6	28 6	25 7	21 8
15	38 3	25 7	22 6	20 3	17 2
20	28 2	18 9	16 6	14 9	12 7
25	22 2	14 9	13 1	11 8	10 0
30	18 3	12 3	10 8	9 7	8 2
DOC (mm) =	0 50	1 0	1 25	1 50	2 0

==

To have surface roughness estimate, select velocity, feed, depth of cut from the table and type the values of velocity, feed, and doc

16 6, 0 20, 1 25

Roughness in micron = 3 102801

Power watt = 396 2 W

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

10.1 Conclusions

After the analysis of the test results, the following conclusions could be made about the machinability assessment of steel and inconel 718 and the development of the machinability data base systems

10 1.1 Machinability of EN24T steel (290 BHN)

i) Cutting forces

One-variable-at-a-time

— Cutting forces in dry turning of EN24T steel decreases as the speed increases above 130 m/min The average tangential force F_z, which is the main component of the cutting forces is about 450 N at a feed of 0 25 mm/rev and depth of cut of 0 25 mm

— With the increase of feed rate or depth of cut, cutting forces increase almost linearly At 1 0 mm depth of cut, F_z is about 800 N while at 1 5 mm it is 1200 N when feed rate is 0 25 mm/rev F_z changed from 800 N to 1300 N when the feed is changed form 0 25 to 0 50 mm/rev

— At a depth of cut lower than 0 25 mm, the radial component of the cutting force F_y is higher than F_x However when the depth of cut exceeds 0 50 mm, F_x becomes higher

Design of experiment

— The first-order force model equation has shown that a change in the depth of cut has the maximum affect on the cutting force followed by the effect of feed and speed However, increasing the cutting speed reduces the force

— From the first-order force equation, the different values of exponents are, n_1 = -0 1673, n_2 = 0 6124, and n_3 = 0 9085

— The second-order and the interactive effects of the main cutting variables on the cutting force are significant

ii) Tool life

One-variable-at-a-time

— The cutting speed seems to have a pronounced effect on the tool life The progression of tool flank wear is extremely faster when the speed exceeds 100 m/min

— The different values of tool life exponents calculated graphically from the extended Taylor's tool life equation are, speed exponent n_1 = -0 5, feed exponent n_2 = -2 25, and depth of cut exponent n_3 = -3 9 Tool wear is influenced mostly by the change in cutting speed followed by feed and depth of cut

Design of experiment

— From the analysis of the experimental tool life data set of the design of experiments, the cutting speed is the main influencing factor on the tool life followed by the effect of feed and depth of cut The various exponents calculated are, n_1 = -0 558, n_2 = -2 05, n_3 = -5 2

— The second-order and interactive effects of the main cutting variables on tool life is not significant

iii) Surface roughness

Design of experiment

— The effect of feed on surface roughness is much more pronounced than the effects of speed or depth of cut As the cutting speed increases, the surface finish improves

— From the first-order surface roughness equation, the different exponents calculated are, speed n_1 = -0 212, n_2 = 1 2861, n_3 = 0 1583

— In addition to the effect of the main cutting variables, the second-order effects are also significant on the surface roughness

— Within the speed range of 36 - 150 m/min, feed range of 0 15 - 0 25 mm/rev and depth of cut up to 1 5 mm, a reasonably good surface finish (2 - 4 μm) is attainable

Cutting conditions

— The high hardness of EN24T steel (290 BHN) limits the cutting speed beyond 150 m/min The recommended speed range should be within 60 - 130 m/min, feed range 0 15 - 0 25 mm/rev, and depth of cut could be as high as 1 5 mm

10.1.2 Machinability of inconel 718

i) Cutting forces

One-variable-at-a-time

— The magnitude of the feed force F_x is comparable with the tangential force F_z It is about one half of the tangential force

— The magnitude of the resultant cutting force is almost doubled as the depth of cut is doubled When the depth of cut is increased from 0 5 to 1 0 mm, resultant force F increases from 500 to 1000 N Identical trend is observed even when the feed rate is doubled

— In general, the cutting forces stabilizes as the cutting speed is increased The cutting force increases linearly with the feed and depth of cut

Design of experiment

- The depth of cut has the most significant effect on the cutting force followed by the feed and cutting speed With the increase of feed or depth of cut, cutting forces increase
- From the first-order force equation, the different values of exponents are, $n_1 = -0\ 1294$, $n_2 = 0\ 801$, and $n_3 = 0\ 948$
- The second-order and the interactive effects of the main cutting variables on the cutting force are significant

ii) Tool life

One-variable-at-a-time

- When the cutting speed is more than 40 m/min, tool life is very low (about 2 minutes) and this is true for both coated and uncoated carbide inserts
- The performance of uncoated carbide tools appears to be better than that of the coated carbide tools
- The use of coated carbide tool is justified when the depth of cut is higher than 1 0 mm
- In general, the tool life of uncoated carbide is higher than that of the coated carbide tools
- The graphical calculation of tool life exponents show that for uncoated carbide tools, $n_1 = -0\ 48$, $n_2 = -0\ 78$, $n_3 = -0\ 73$ while for the coated carbide tools, $n_1 = -0\ 50$, $n_2 = -0\ 95$, $n_3 = -2\ 75$

Design of experiment

- The effect of depth of cut on tool life of the coated carbide seems to be very insignificant while the effect of feed is more pronounced than the effect of speed
- The tool life exponents calculated form the first-order equations for uncoated and coated tools are, $n_1 = -0\ 48$, $n_2 = -0\ 59$, $n_3 = -0\ 997$ and $n_1 = -0\ 55$, $n_2 = -0\ 53$, $n_3 = -1\ 545$ respectively

iii) Surface roughness

Design of experiment

- Surface roughness produced by the carbide tools is mostly affected by the change in feed The increase in depth of cut increases surface roughness when uncoated tools are used but in the case of coated tools, increase in depth of cut improves the surface finish
- From the first-order surface roughness equation, the different exponents for uncoated and coated tools calculated are, speed n_1 = -0 193, n_2 = 1 3596, n_3 = 0 0704 and speed n_1 = -0 091, n_2 = 1 2598, n_3 = -0 204 respectively
- Within the speed range of 10 - 30 m/min and feed up to 0 20 mm/rev, a reasonably good surface finish (2 - 4 μm) is attainable

Cutting conditions

- The recommended cutting speed for machining inconel with the carbide tools is 15 - 25 m/min, feed range should be 0 15 - 0 20 mm/rev, and depth of cut could be as high as 1 5 mm

Model building

- Response surface methodology can be used successfully and efficiently to develop mathematical models for machining responses (cutting force, tool life, and surface roughness) in turning operation of any material and tool combinations This provides a large amount of information with a small amount of experimentations
- Response contours would be very useful in optimizing the cutting variables with respect to different responses These may be either to increase the tool life or to improve the surface finish or to minimize the power requirement for maximum metal removal rate
- The different regression model building techniques can also be used for developing mathematical models These techniques are backward elimination, stepwise regression, forward selection, and all possible subset regression technique

- Out of the four model building techniques, it is recommended that backward elimination and all possible subset regression techniques would be most suitable in model building for the machinability data base systems
- The sequential estimation technique was found to be a better alternative to regression techniques as a model building tool The advantages of this technique is that the computation is efficient, matrix solution is not required, and data storage requirements are small It provides the same information as the regression analysis However, this technique is limited to the development of first-order model only The usefulness of this technique is yet to be verified for a second-order model Preliminary investigation has shown a variation of the second-order model co-efficients from the multiple linear regression techniques

10.1.3 Machinability data base systems

- The computerized machinability data base system developed in this project covers only EN24T steel and inconel 718 It provides the optimum cutting conditions for a given tool life However, it could be extended to incorporate any combinations of any other work material and tools in future

- For developing the machinability data base, the use of statistical regression packages can be employed to build adequate models Once a model is developed, its co-efficients can be stored and used to relate the corresponding response (tool life, surface roughness, cutting force) with the cutting variables These model equations will provide the recommended cutting conditions which relate the actual machining environments

10 2 Recommendations

- With a view to developing a comprehensive computerized machinability data base systems using mathematical models, a large quantity of experimental data are required These are necessary to validate the usefulness of a model

- It would be helpful to identify a model for a specific hardness group of materials and generalize it for that hardness range

- Machinability assessments of EN24T steel and inconel 718 are first steps towards the development of the data base The use of different tool materials and tool geometries may be useful to compare the variations in the surface roughness model and include it in the mathematical models

- Different cutting fluids may be used to machine the same materials under the same cutting conditions and compare the different responses with those under dry conditions

- The use of various ceramic tools for machining inconel 718 may be useful These will help compare the response models and may be incorporated in the mathematical model type data base system

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APPENDIX A

CRITERIA FOR ASSESSING REGRESSION EQUATION

APPENDIX A

Residual mean square s^2 (RMS_p): The estimated error of variance for the p-variable model is given by

$$RMS_p = \frac{RSS_p}{n-p}$$

where RSS_p = error (residual) sum of square of the p-variable model

n = total number of data points

p = number of parameters in the model

R square statistic: The sample squared multiple correlation R^2 is a natural candidate for deciding which model is the best and is given by

$$R^2 = 1 - \frac{RSS_p}{TSS}$$

R^2 is the square of the correlation between y and $\hat{y}$ and $0 \leq R^2 \leq 1$

$$where\ TSS = \sum_{i=1}^{n} (y_i - \bar{y})^2$$

is the total sum of squares for the response y

Adjusted R square: This has the following mathematical form

$$Adj\,R^2 = 1 - (1-R^2)(\frac{n-1}{n-p})$$

Mallows C_p. The statistic is defined as

$$C_p = \frac{RSS_p}{s^2} - (n-2p)$$

C_p is closely related to *adjusted* R^2 and is also related to R^2

APPENDIX B

MATRIX INVERSION LEMMA

APPENDIX B

Matrix Inversion Lemma

Let **A** be $p \times m$ and **B** be $m \times p$ matrices Let $\mathbf{I}_m$ be the $m \times m$ identity matrix An identity and some rearrangements of it are as follows

$$-A(I_m + BA) = -(I_p + AB)A \tag{B1}$$

$$I_p = (I_p + AB) - (I_p + AB)A(I_m + BA)^{-1}B \tag{B2}$$

Premultiplying (B2) by $(\mathbf{I}_p + \mathbf{AB})^{-1}$ gives

$$(I_p + AB)^{-1} = I_p - A(I_m + BA)^{-1}B \tag{B3}$$

Let **P** be defined by

$$P \equiv [x^T\psi^{-1}x + V_\beta]^{-1} = [V_\beta x^T\psi^{-1}x + I]^{-1}V_\beta \tag{B4}$$

Using Equation (B3) for (B4) and substituting $\mathbf{A} = \mathbf{V}_\beta \mathbf{x}^T \psi^{-1}$ and $\mathbf{B} = \mathbf{x}$ yields

$$P = V_\beta - V_\beta x^T(xV_\beta X^T + \psi)^{-1}xV_\beta \tag{B5}$$

This equation is called the Matrix Inversion Lemma Equation (4 15) is found from Equation (B5) by letting

$$P \to P_{t+1}\ ,\ V_\beta \to P_t\ ,\ x \to x_{t+1}\ ,\ \psi \to \phi_{t+1}$$

Equation (B1) can be written as

$$(I_p + AB)^{-1}A + A(I_m + BA)^{-1} \tag{B6}$$

Substituting the values for **A** and **B** results in

$$Px^T\psi^{-1} = V_\beta x^T(xV_\beta x^T + \psi)^{-1} \tag{B7}$$

Equation (4 16) is obtained from equation (B7)

APPENDIX C

ANOVA TABLES

APPENDIX C

Table 7.3 95% Confidence interval for block 1, Tool life ($\hat{y}$ = 1.6941 - 1.1194x_1 - 0.247x_2 - 0.1016x_3)

Trial No	T	y	$\hat{y}$	$\hat{T}$	$\hat{y}$ Lower	$\hat{y}$ Upper	$\hat{T}$ Lower	$\hat{T}$ Upper
1	24 6	3 2027	3 1621	23 62	2 5366	3 7876	12 64	44 15
4	1 6	0 47	0 4293	1 54	-0 1962	1 0548	0 82	2 87
6	2 14	0 7608	0 7201	2 05	0 0946	1 3456	1 10	3 84
7	12 25	2 5055	2 4649	11 76	1 8394	3 0904	6 29	21 98
9	5 22	1 6525	1 6941	5 44	1 4274	1 9608	4 17	7 10
10	4 82	1 5728	1 6941	5 44	1 4274	1 9608	4 17	7 10

Table 7.4 95% confidence interval for block 2, Tool life ($\hat{y}$ = 1.575 - 0.9853x_1 - 0.212x_2 - 0.0544x_3)

Trial No	T	y	$\hat{y}$	$\hat{T}$	$\hat{y}$ Lower	$\hat{y}$ Upper	$\hat{T}$ Lower	$\hat{T}$ Upper
2	2 30	0 8329	0 8561	2 35	0 5181	1 1741	1 68	3 23
3	10 48	2 3795	2 4027	11 05	2 0647	2 7407	7 88	15 50
5	14 8	2 6946	2 7179	15 15	2 3799	3 0559	10 80	21 24
8	1 35	0 3001	0 3233	1 38	-0 0147	0 6613	0 98	1 94
11	5 00	1 6094	1 5750	4 83	1 4309	1 7191	4 18	5 58
12	5 12	1 6332	1 5750	4 83	1 4309	1 7191	4 18	5 58

Table 7.5 Analysis of variance for twelve tests (Tool life)

Source	Sum of Squares	Degrees of Freedom	Mean Square	F_{cal}	F_{tab}
Zero-order term	32 059083	1	32 0591	9071 6	
First-order term	9 32881	3	3 109603	879 9	
Block	0 04255	2	0 02128	6 02	9 01
Lack of fit	0 069106	5	0 01382	3 91	
Pure error	0 003534	1	0 003534		
Total	41 5032				

Table 7.6 95% confidence interval for the combined block 1 & 2 (Tool life)
($\hat{y}$ = 1.6345 - 1.0523x_1 - 0.2295x_2 - 0.078x_3)

Trial No	T	y	$\hat{y}$	$\hat{T}$	$\hat{y}$		$\hat{T}$	
					Lower	Upper	Lower	Upper
1	24 6	3 2027	2 9943	19 97	2 807	3 1816	16 56	24 08
2	2 30	0 8329	0 8897	2 43	0 7024	1 077	2 02	2 93
3	10 8	2 3795	2 5353	12 62	2 348	2 7226	10 46	15 22
4	1 60	0 47	0 4307	1 54	0 2434	0 618	1 27	1 85
5	14 8	2 6946	2 8383	17 09	2 651	3 0256	14 17	20 61
6	2 14	0 7608	0 7337	2 08	0 5464	0 921	1 73	2 51
7	12 25	2 5055	2 3793	10 8	2 192	2 5666	8 95	13 02
8	1 35	0 3001	0 2747	1 32	0 0874	0 462	1 09	1 59
9	5 22	1 6525	1 6345	5 13	1 5546	1 7144	4 73	5 55
10	4 82	1 5728	1 6345	5 13	1 5546	1 7144	4 73	5 55
11	5 00	1 6094	1 6345	5 13	1 5546	1 7144	4 73	5 55
12	5 12	1 6332	1 6345	5 13	1 5546	1 7144	4 73	5 55

Table 7.8 95% confidence interval for the second order tool life model
($\hat{y} = 1.546 - 1.063x_1 - 0.177x_2 - 0.113x_3 - 0.047x_1^2 + 0.012x_2^2 + 0.062x_3^2 + 0.024x_1x_2 + 0.018x_1x_3 + 0.067x_2x_3$)

Trial No	T	y	$\hat{y}$	$\hat{T}$	$\hat{y}$		$\hat{T}$	
					Lower	Upper	Lower	Upper
1	24 6	3 2027	3 0339	20 78	2 9576	3 2790	19 25	26 55
2	2 30	0 8329	0 8245	2 28	0 5878	1 0696	1 80	2 91
3	10 8	2 3795	2 4981	12 16	2 1344	2 7432	8 45	15 54
4	1 60	0 47	0 3831	1 47	0 2249	0 6282	1 25	1 87
5	14 8	2 6946	2 6393	14 00	2 4495	2 8844	11 58	17 89
6	2 14	0 7608	0 5003	1 65	0 5157	0 7454	1 67	2 11
7	12 25	2 5055	2 3705	10 70	2 2604	2 6156	9 59	13 68
8	1 35	0 3001	0 3269	1 39	0 0818	0 5720	1 09	1 77
9	5 22	1 6525	1 5459	4 69	1 4067	1 6851	4 08	5 39
10	4 82	1 5728	1 5459	4 69	1 4067	1 6851	4 08	5 39
11	5 00	1 6094	1 5459	4 69	1 4067	1 6851	4 08	5 39
12	5 12	1 6332	1 5459	4 69	1 4067	1 6851	4 08	5 39
13	18 0	2 8904	2 9555	19 21	2 7794	3 1316	16 11	22 91
14	0 86	-0 1508	-0 0525	0 95	-0 2286	0 1236	0 95	1 13
15	5 0	1 6094	1 8198	6 17	1 6437	1 9959	6 17	7 36
16	3 6	1 2809	1 3184	3 74	1 1423	1 4945	3 13	4 46
17	5 8	1 7578	1 8291	6 23	1 6530	2 0052	5 22	7 43
18	3 75	1 3217	1 5103	4 53	1 3342	1 6864	3 80	5 40
19	18 35	2 9096	2 9555	19 21	2 7794	3 1316	16 11	22 91
20	0 88	-0 1278	-0 0525	0 95	-0 2286	0 1236	0 95	1 13
21	5 7	1 7405	1 8198	6 17	1 6437	1 9959	6 17	7 36
22	3 9	1 3610	1 3184	3 74	1 1423	1 4945	3 13	4 46
23	6 4	1 8563	1 8291	6 23	1 6530	2 0052	5 22	7 43
24	4 3	1 4586	1 5103	4 53	1 3342	1 6864	3 80	5 40

Table 7.9 Analysis of variance for twelve tests (Surface roughness)

Source	Sum of squares	Degrees of freedom	Mean square	F_{cal}	F_{tab}
Zero-order term	12 3538	1			
First-order term	3 08072	3	1 02678		
Lack of fit	0 16599	5	0 033198	34 5	9 01
Pure error	0 00289	3	0 000963		
Total	15 6034				

Table 7.10 Analysis of variance for twenty four tests (Surface roughness)

Source	Sum of squares	Degrees of freedom	Mean square	F_{cal}	F_{tab}
Zero-order term	26 3511222	1	26 3511	4765 1	
First-order terms	6 05672891	3	2 01891	365 35	
2nd-order term	0 15344598	3	0 05115	9 26	4 07
Interaction terms	0 04099516	3	0 01367	2 47	
Block	0 03034388	3	0 01011	1 83	
Lack of fit	0 02122935	3	0 00708	1 28	
Pure error	0 04420668	8	0 00553		
Total	32 6663				

Table 7.11 Second order surface roughness model and 95% confidence interval for twenty four tests

Trial No	R_a	y	$\hat{y}$	$\hat{y}$		$\hat{R}_a$	$\hat{R}_a$	
				Lower	Upper		Lower	Upper
1	1 8	0 5878	0 5724	0 4545	0 6903	1 773	1 575	1 994
2	1 233	0 2095	0 289	0 1711	0 4069	1 335	1 187	1 502
3	5 3	1 6677	1 686	1 5681	1 8039	5 398	4 798	6 073
4	5 067	1 6227	1 6686	1 5507	1 7865	5 305	4 715	5 968
5	2 133	0 7575	0 7784	0 6605	0 8963	2 178	1 936	2 45
6	1 45	0 3716	0 4198	0 3019	0 5377	1 522	1 352	1 712
7	6 233	1 8299	1 8168	1 6989	1 9347	6 152	5 468	6 922
8	5 167	1 6423	1 7242	1 6063	1 8421	5 608	4 984	6 309
9	2 433	0 8891	0 9049	0 838	0 9718	2 472	2 312	2 643
10	2 3	0 8329	0 9049	0 838	0 9718	2 472	2 312	2 643
11	2 367	0 8616	0 9049	0 838	0 9718	2 472	2 312	2 643
12	2 467	0 903	0 9049	0 838	0 9718	2 472	2 312	2 643
13	3 633	1 2901	1 242	1 1573	1 3267	3 463	3 183	3 768
14	2 767	1 0178	0 9762	0 8915	1 0609	2 654	2 439	2 889
15	1 153	0 1424	0 1334	0 0487	0 2181	1 143	1 05	1 244
16	6 333	1 8458	1 8432	1 7585	1 9279	6 317	5 804	6 875
17	2 533	0 9294	0 9538	0 8691	1 0385	2 595	2 385	2 825
18	3 20	1 1632	1 1388	1 0541	1 2235	3 123	2 869	3 399
19	3 233	1 1734	1 242	1 1573	1 3267	3 463	3 183	3 768
20	2 967	1 0876	0 9762	0 8915	1 0609	2 654	2 439	2 889
21	1 21	0 1906	0 1334	0 0487	0 2181	1 143	1 05	1 244
22	6 733	1 9070	1 8432	1 7585	1 9279	6 317	5 804	6 875
23	2 833	1 0413	0 9538	0 8691	1 0385	2 595	2 385	2 825
24	3 267	1 1839	1 1388	1 0541	1 2235	3 123	2 869	3 399

Table 7.15 Analysıs of varıance for twelve tests on ınconel (Tool lıfe, uncoated carbıde)

Source	Sum of Squares	Degrees of Freedom	Mean Square	F_{cal}	F_{tab}
0-order term	68 4400803	1	68 4400	5165	
1st-order term	14 9969056	3	4 99898	377 2	
Lack of fit	0 2461969	5	0 04839	3 65	9 01
Pure error	0 0397537	3	0 01325		
Total	83 7222167				

APPENDIX D

STATISTICAL MODEL PARAMETERS

APPENDIX D

Table 8.1 Statistical parameters for tool life

EN 24T Steel	Coefficients and t-values										Selection criteria		
	b_o	b_1	b_2	b_3	b_{11}	b_{22}	b_{33}	b_{12}	b_{13}	b_{23}	R^2	Adj R^2	s
Backward	4 78 (31 5)		-0 357 (-5 5)		-0 215 (-32 7)		0 433 (3 7)				98 24	97 98	0 13
Forward	4 78 (31 5)		-0 357 (-5 5)		-0 215 (-32 7)		0 433 (3 7)				98 24	97 98	0 13
Stepwise	4 78 (31 5)		-0 357 (5 5)		-0 215 (-32 7)		0 433 (3 7)				98 24	97 98	0 13
All Possible	4 78 (31 5)		-0 357 (-5 5)		-0 215 (-32 7)		0 433 (3 7)				98 24	97 98	0 13
1st order	8 489 (30 37)	-1 798 (-29 18)	-0 357 (-4 87)	-0 278 (-3 1)							97 79	97 46	0 146
2nd order	5 535 (2 32)	-0 426 (-0 42)	-0 555 (-0 64)	0 086 (0 09)	-0 148 (-1 26)	0 016 (0 096)	0 358 (1 43)	0 081 (0 47)	0 073 (0 35)	0 33 (1 3)	98 53	97 58	0 142

Table 8.2 Statistical parameters for surface roughness

EN 24T Steel	Coefficients and t-values										Selection criteria		
	b_o	b_1	b_2	b_3	b_{11}	b_{22}	b_{33}	b_{12}	b_{13}	b_{23}	R^2	Adj R^2	s
Backward	7 791 (7 5)	-2 40 (-5 4)	0 914 (2 4)	0 43 (5 7)		0 24 (3 3)	0 466 (4 2)	0 234 (3 1)			99 0	98 57	0 063
Forward	2 742 (34 1)		0 676 (4 6)					0 121 (3 7)		-0 114 (-2 4)	96 16	95 58	0 11
Stepwise	2 742 (34 1)		0 676 (4 6)					0 121 (3 7)		-0 114 (-2 4)	96 16	95 58	0 11
All Possible	7 791 (7 5)	-2 40 (-5 4)	0 914 (2 4)	0 43 (5 7)		0 24 (3 3)	0 466 (4 2)	0 234 (3 1)			99 0	98 57	0 063
1st order	3 452 (15 41)	-0 159 (-3 22)	1 213 (20 67)	0 161 (2 24)							95 68	95 03	0 117
2nd order	7 848 (7 32)	-2 42 (-5 3)	0 887 (2 27)	0 627 (1 45)	0 307 (5 8)	0 24 (3 2)	0 466 (4 2)	0 234 (2 99)	-0 079 (-0 83)	-0 094 (-0 83)	99 09	98 51	0 064

Table 8.3 Statistical parameters for cutting force

EN 24T Steel	Coefficients and t-values										Selection criteria		
	b_o	b_1	b_2	b_3	b_{11}	b_{22}	b_{33}	b_{12}	b_{13}	b_{23}	R^2	Adj R^2	s
Backward	10 288 (22 9)	-0 962 (-4 6)	0 834 (8 3)	0 685 (8 6)	0 092 (3 7)	0 099 (2 8)				-0 166 (-3 0)	99 58	99 43	0 031
Forward	7 719 (203)			0 687 (6 8)				0 133 (21 4)		-0 165 (-2 4)	99 1	98 97	0 042
Stepwise	7 719 (203)	-0 962 (-4 6)	0 834 (8 3)	0 687 (6 8)				0 133 (21 4)		-0 165 (-2 4)	99 1	98 97	0 042
All Possible	10 288 (22 9)			0 685 (8 6)	0 092 (3 7)	0 099 (2 8)				-0 166 (-3 0)	99 58	99 43	0 031
1st order	8 591 (96 81)	-0 193 (-9 86)	0 603 (25 93)	0 917 (32 24)							98 91	98 74	0 046
2nd order	9 995 (19 1)	-0 90 (-4 0)	0 585 (3 08)	0 765 (3 63)	0 094 (3 67)	0 103 (2 84)	0 02 (0 36)	0 062 (1 63)	-0 016 (-0 36)	-0 166 (-3 0)	99 65	99 43	0 031

Table 8.7 Statistical parameters for tool life (coated carbide)

Inconel 718	Coefficients and t-values										Selection criteria		
	b_o	b_1	b_2	b_3	b_{11}	b_{22}	b_{33}	b_{12}	b_{13}	b_{23}	R^2	Adj R^2	s
Backward	3 602 (19 2)				-0 75 (-8 31)	-1 064 (-3 78)	-1 019 (-3 72)	-1 707 (-5 34)			96 48	95 74	0 196
Forward	3 511 (18 3)				-0 692 (-7 5)	-0 901 (-3 12)		-1 523 (-4 64)	-0 178 (-3 4)		96 19	95 39	0 204
Stepwise	3 511 (18 3)				-0 692 (-7 5)	-0 901 (-3 12)		-1 523 (-4 64)	-0 178 (-3 4)		96 19	95 39	0 204
All Possible	3 602 (19 2)				-0 75 (-8 31)	-1 064 (-3 78)	-1 019 (-3 72)	-1 707 (-5 34)			96 48	95 74	0 196
1st order	4 465 (7 27)	-1 556 (-11 6)	-1 419 (-4 93)	-0 50 (-1 95)							89 06	87 42	0 337
2nd order	1 753 (0 5)	0 47 (0 38)	-1 228 (-0 45)	1 485 (0 79)	-0 772 (-4 82)	-1 267 (-1 83)	-0 931 (-1 48)	-1 543 (-3 06)	-0 352 (-0 9)	0 331 (0 36)	96 77	94 70	0 219

Table 8.8 Statistical parameters for surface roughness (coated carbide)

Inconel 718	Coefficients and t-values										Selection criteria		
	b_o	b_1	b_2	b_3	b_{11}	b_{22}	b_{33}	b_{12}	b_{13}	b_{23}	R^2	Adj R^2	s
Backward	2 885 (12 25)	-0 16 (-2 3)				-0 378 (-8 5)					78 84	76 83	0 173
Forward	2 885 (12 25)	-0 16 (-2 3)				-0 378 (-8 5)					78 84	76 83	0 173
Stepwise	2 885 (12 25)	-0 16 (-2 3)				-0 378 (-8 5)					78 84	76 83	0 173
All Possible	2 885 (12 25)	-0 16 (-2 3)				-0 378 (-8 5)					78 84	76 83	0 173
1st order	3 908 (11 53)	-0 16 (-2 17)	1 239 (7 82)	-0 121 (-0 86)							76 89	73 42	0 186
2nd order	3 723 (1 29)	-1 37 (-1 4)	-1 156 (-0 53)	-0 201 (-0 13)	0 07 (0 55)	-1 116 (-2 01)	-0 52 (-1 03)	-0 469 (-1 16)	0 196 (0 63)	0 153 (0 21)	85 59	76 33	0 175

APPENDIX E

COMPUTER PROGRAMME FOR SEQUENTIAL ESTIMATION

APPENDIX E

```
      PARAMETER (M = 1, N = 4, NN = 4, MM = 24)
      DOUBLE PRECISION X(MM,N), Y(MM), P(N,NN), B(N), E1, A(M,NN),
   +  SUM, SUM1, DEL, AT(NN,M), AK(N), PP(N,NN), BB(N)

       OPEN (UNIT = 9, STATUS= 'OLD', FILE = 'TOOLE2 DAT')
       OPEN (UNIT = 8, STATUS= 'UNKNOWN', FILE = 'TOOL2 OUT')
       OPEN (UNIT = 3, STATUS= 'UNKNOWN', FILE = 'TOOL3 OUT')
       READ (9,*) ((X(I,J), J = 1,4), I = 1,MM)
       READ (9,*) (Y(I), I = 1,MM)
       READ (9,*) ((P(J,JJ), JJ = 1,4), J = 1,4)
       READ (9,*) (B(I), I = 1,4)

************************************************************************
C      CALCULATION OF E1
************************************************************************
              E11 = 0
       DO 1 II =1, MM
        DO 2 I = 1, 4
              BB(I) = B(I)
2       CONTINUE
       DO 3 IJ = 1,4
       DO 3 KJ = 1,4
              PP(IJ, KJ) = P(IJ, KJ)
3      CONTINUE
               E11 = 0
        DO 4 I = 1,4
              E11 = E11 + X(II,I)*BB(I)
              E1 =  Y(II) - E11
4       CONTINUE
       WRITE(3,*) Y(II)
       WRITE(3,*) 'E1 = ', E1
```

```
************************************************************************
C     CALCULATION OF A(I,J) AND DEL
************************************************************************
      DO 5 I = 1, 1
      DO 5 J = 1, NN
            SUM = 0
            DO 6 K = 1, N
             SUM = SUM + X(II,K)*PP(K,J)
6      CONTINUE
            A(1,J) = SUM
5     CONTINUE
      WRITE (*,*) (A(1,J), J = 1,4)
            SUM1 = 0
      DO 7 J = 1, 4
      WRITE (3,*) A(1,J), X(II,J)
           AT(J,1) = A(1,J)
           SUM1 = SUM1 + X(II,J)*AT(J,1)
7     CONTINUE
            DEL = 1 0 + SUM1
C            DEL = 0 02125764 + SUM1
      WRITE (3,*) 'DEL = ', DEL

************************************************************************
C     CALCULATION OF B AND P
************************************************************************
      DO 8 I = 1, 4
            AK(I) = AT(I,1)/DEL
            B(I) = BB(I) + AK(I)*E1
       DO 9  J = 1,4
           P(I,J) = PP(I,J) - AK(I)*AT(J,1)
           IF (I  NE  J) THEN
           P(J,I) = P(I,J)
           ENDIF
9      CONTINUE
8     CONTINUE
      WRITE (*,*) (AK(I), I = 1,4)
      WRITE (*,*) 'E1= ',E1
      WRITE (8,13)
13    FORMAT (//9X, 'B = ')
```

```
      WRITE (8,11) (B(I), I = 1,4)
11    FORMAT (5X, F10 5)
      WRITE (8,14)
14    FORMAT (/5X, 'P(uv) = ')
      WRITE (8,12) ((P(I,J), J = 1,4), I = 1,4)
12    FORMAT (4(5x, F12 4))

1     CONTINUE
      STOP
      END
```

APPENDIX F

COMPUTER PROGRAMME FOR MACHINABILITY DATA BASE

APPENDIX F

```
      COMMON /CDATA/ T
      COMMON /IDATA/ K,L,KK,M,MM
      WRITE (*,*)'*********************************************'
      WRITE (*,*) ' W  E  L  C  O  M  E    TO    M  D  B  S'
      WRITE (*,*)'*********************************************'
C     *****************************************************
      WRITE (*,*) '> >   OPERATION MODULE   < <'
      WRITE (*,*) '(1) TURNING'
      WRITE (*,*) '(2) MILLING'
      WRITE (*,*) 'PLEASE TYPE (1)/(2) AND PRESS ENTER'
      READ  (*,*) K
C     *****************************************************
      WRITE (*,*) '> >   MATERIAL SELECTION   < <'
      WRITE (*,*) '???SELECT YOUR MATERIAL???'
      WRITE (*,*) '1 INCONEL-718/2  EN 24T'
      WRITE (*,*) 'PLEASE TYPE (1) / (2) AND PRESS ENTER'
      READ  (*,*) KK
C     *****************************************************
      WRITE (*,*) 'PLEASE TYPE MATERIAL HARDNESS IN BHN '
      READ  (*,*) L
C     *****************************************************
      WRITE (*,*) '> >   TOOL SELECTION   < <'
      WRITE (*,*) '???SELECT YOUR CUTTING TOOL???'
      WRITE (*,*) '1  UNCOATED CARBIDE / 2  COATED CARBIDE'
      WRITE (*,* )'PLEASE TYPE (1) / (2) AND PRESS ENTER'
      READ  (*,*) M
C     *****************************************************
      WRITE (*,*) 'AN EXPERIMENTAL DATA FILE'
      WRITE (*,5)
    5 FORMAT (2X,'VELOCITY',4X,'FEED',6X,'DOC',3X,'TLIFE')
      WRITE (*,6)
    6 FORMAT ('',2X,'(m/min)',3X,'(mm/rev)',3X,'(mm)',3X,'(min)')
C     *****************************************************
      IF (KK  EQ  1  AND  M  EQ  1) THEN
      CALL DATA1
      ELSEIF (KK  EQ  1  AND  M  EQ  2) THEN
      CALL DATA2
```

```
      ELSEIF (KK  EQ  2  AND  M  EQ  1) THEN
      CALL DATA3
      ENDIF
     WRITE (*,*) 'DO YOU WANT CUTTING PARAMETER VALUES FOR A DIFFERENT
    +TOOL LIFE? IF YES PLEASE TYPE 1, IF NO PLEASE TYPE 2 AND PRESS
    +ENTER'
     READ  (*,*) MM
      IF (MM  EQ  1) THEN
      GO TO 10
      ENDIF
      STOP
C     ************************************************************************
 10   WRITE (*,*) 'PLEASE TYPE EXPECTED TOOLLIFE T IN MIN  & PRESS ENTER'
      READ  (*,*) T
C     ************************************************************************
      IF (KK  EQ  1  AND  M  EQ  1) THEN
      CALL INC
      ELSEIF (KK  EQ  1  AND  M  EQ  2) THEN
      CALL CINC
      ELSEIF(KK  EQ  2  AND  M  EQ  1) THEN
      CALL EN24
      ENDIF
      END

C     ****************************************************
      SUBROUTINE DATA1
C     ****************************************************
      REAL X(15,4)
      COMMON /CDATA/ T
      COMMON /IDATA/ K,L,KK,M,MM
      OPEN  (UNIT = 8, STATUS = 'OLD', FILE = 'INC DAT')
      READ  (8,*) ((X(I,J), J = 1,4), I = 1,15)
      WRITE (*,9) ((X(I,J), J = 1,4), I = 1,15)
 9    FORMAT (2X, F5 1, 6X, F4 3,5X,F5 3,3X,F5 2)
      RETURN
      END
```

```
C     ******************************************************
      SUBROUTINE DATA2
C     ******************************************************
      REAL X(15,4)
      COMMON /CDATA/ T
      COMMON /IDATA/ K,L,KK,M,MM
      OPEN  (UNIT = 8, STATUS = 'OLD', FILE = 'CINC DAT')
      READ  (8,*)  ((X(I,J), J = 1,4), I = 1,15)
      WRITE (*,11) ((X(I,J), J = 1,4), I = 1,15)
 11   FORMAT (2X, F5 1, 6X, F4 3,5X,F5 3,3X,F5 2)
      RETURN
      END
C     ******************************************************
      SUBROUTINE DATA3
C     ******************************************************
      REAL X(15,4)
      COMMON /CDATA/ T
      COMMON /IDATA/ K,L,KK,M,MM
      OPEN  (UNIT = 8, STATUS = 'OLD', FILE = 'EN24 DAT')
      READ  (8,*)  ((X(I,J), J = 1,4), I = 1,15)
      WRITE (*,13) ((X(I,J), J = 1,4), I = 1,15)
 13   FORMAT (2X,F5 1,6X,F4 3,5X,F5 3,3X,F5 2)
      RETURN
      END

C     ******************************************************
      SUBROUTINE INC
C     ******************************************************
       REAL f(5), d(5), V(5,5), R, P, Force, Vel, feed, doc,b0,b1,b2,b3
     +,c0,c1,c2,c3,c11,c22,c33,c12,c13,c23,a0,a1,a2,a3,a11,a22,a33,a12
     +,a13,a23
       COMMON /CDATA/ T
       COMMON /IDATA/ K,L,KK,M,MM
      OPEN (UNIT = 8, STATUS = 'OLD', FILE = 'feeddoc dat')
      READ (8,*) (f(I), I = 1,5)
      READ (8,*) (d(II), II = 1,5)
      OPEN (UNIT = 9, STATUS =  OLD , FILE =  incc dat')
      READ (9,*) b0,b1,b2,b3,c0,c1,c2,c3,c11,c22,c33,c12,c13,c23,
     +a0,a1,a2,a3,a11,a22,a33,a12,a13,a23
```

```
      DO 100 I = 1,5
      DO 150 II = 1,5
      V(I,II) = EXP((ALOG(T) - b0-b2*ALOG(f(I)) - b3*ALOG(d(II)))/b1)
150   CONTINUE
100   CONTINUE
      IF (K EQ 1) THEN
      WRITE (*,*) ' TURNING OPERATION'
      ELSE
      WRITE (*,*) ' MILLING OPERATION'
      ENDIF
      IF (KK EQ 1) THEN
      WRITE (*,*) 'MATERIAL   INCONEL-718'
      ELSEIF (KK EQ 2) THEN
      WRITE (*,*) 'MATERIAL   EN 24T'
      ENDIF
      WRITE (*,*) 'HARDNESS IN BHN = ', L
      IF (M EQ 1) THEN
      WRITE (*,*) 'CUTTING TOOL  UNCOATED TUNGSTEN CARBIDE'
      ELSEIF (M EQ 2) THEN
      WRITE (*,*) 'CUTTING TOOL  COATED TUNGSTEN CARBIDE'
      ENDIF
      WRITE (*,11)
11    FORMAT ('1',5x,'f',9x,'Velocity')
      WRITE (*,12)
12    FORMAT (' ',3x,'(mm/rev)',3x,'(m/min)')
            DO 160 I = 1,5
        WRITE (*,13) f(I), (V(I,II), II = 1,5)
13     FORMAT (' ',5x,F4 2, 5(F7 1))
160         CONTINUE
      WRITE (*,14)
14    FORMAT (' ','DOC (mm) =',2X,'0 50',4X,'1 0',3X,'1 25',3X,'1 50',
     +4X,'2 0')
      WRITE (*,*) 'To have surface roughness and power estimate, select
     +Velocity, feed, depth of cut from the table and type the values
     +of Vel, feed, doc'
      READ (*,*) Vel,feed,doc
```

```
      R = EXP(c0 + c1*ALOG(Vel) + c2*ALOG(feed)+c3*ALOG(doc) +
     +c11*(ALOG(Vel))**2 + c22*(ALOG(feed))**2 +
     +c33*(ALOG(doc))**2 + c12*ALOG(Vel)*ALOG(feed) +
     +c13*ALOG(Vel)*ALOG(doc) + c23*ALOG(feed)*ALOG(doc))

      Force = EXP(a0 + a1*ALOG(Vel) + a2*ALOG(feed) + a3*ALOG(doc) +
     +a11*(ALOG(Vel))**2 + a22*(ALOG(feed))**2 +
     +a33*(ALOG(doc))**2 + a12*ALOG(Vel)*ALOG(feed) +
     +a13*ALOG(Vel)*ALOG(doc) + a23*ALOG(feed)*ALOG(doc))

      P = (Force*Vel)/60

      WRITE (*,*) 'Roughness in micron =', R
      WRITE (*,*) 'Power in Watt =', P
      RETURN
      END

C     ******************************************************
      SUBROUTINE CINC
C     ******************************************************
       REAL f(5), d(5), V(5,5), R, Vel,feed,doc,b0,b1,b2,b3,c0,c1,c2,
     + c3,c11,c22,c33,c12,c13,c23,a0,a1,a2,a3,a11,a22,a33,a12,a13,a23
       COMMON /CDATA/ T
       COMMON /IDATA/ K,L,KK,M,MM
      OPEN (UNIT = 8, STATUS = 'OLD', FILE = 'feeddoc dat')
      READ (8,*) (f(I), I = 1,5)
      READ (8,*) (d(II), II = 1,5)
      OPEN (UNIT = 9, STATUS = 'OLD', FILE = 'cincc dat')
      READ (9,*) b0,b1,b2,b3,c0,c1,c2,c3,c11,c22,c33,c12,c13,c23,
     +a0,a1,a2,a3,a11,a22,a33,a12,a13,a23
      DO 100 I = 1,5
      DO 150 II = 1,5
      V(I,II) = EXP((ALOG(T) - b0 - b2*ALOG(f(I)) - b3*ALOG(d(II)))/b1)
 150  CONTINUE
 100  CONTINUE
       IF (K EQ 1) THEN
       WRITE (*,*)  TURNING OPERATION
       ELSE
       WRITE (*,*) ' MILLING OPERATION'
```

```
 ENDIF
 IF (KK EQ 1) THEN
 WRITE (*,*) 'MATERIAL   INCONEL-718'
 ELSEIF (KK EQ 2) THEN
 WRITE (*,*) 'MATERIAL   EN 24T'
 ENDIF
WRITE (*,*) 'HARDNESS IN BHN = ', L
 IF (M EQ 1) THEN
 WRITE (*,*) 'CUTTING TOOL  UNCOATED TUNGSTEN CARBIDE'
ELSEIF (M EQ 2) THEN
 WRITE (*,*) 'CUTTING TOOL  COATED TUNGSTEN CARBIDE'
 ENDIF
WRITE (*,11)
11   FORMAT ('1',5x,'f',9x,'Velocity')
WRITE (*,12)
12   FORMAT (' ',3x,'(mm/rev)',3x,'(m/min)')
          DO 160 I = 1,5
   WRITE (*,13) f(I), (V(I,II), II = 1,5)
   13    FORMAT (' ',5x,F4 2, 5(F7 1))
160          CONTINUE
WRITE (*,14)
 14   FORMAT (' ','DOC (mm) =',2X,'0 50',4X,'1 0',3X,'1 25',3X,'1 50',
+4X,'2 0')
  WRITE (*,*) 'To have surface roughness estimate, select Velocity,
+feed, depth of cut from the table and type the values of Vel,
+feed, doc respectively'
     READ (*,*) Vel,feed,doc

R = EXP(c0 + c1*ALOG(Vel) + c2*ALOG(feed) + c3*ALOG(doc) +
+c11*(ALOG(Vel))**2 + c22*(ALOG(feed))**2 +
+c33*(ALOG(doc))**2 + c12*ALOG(Vel)*ALOG(feed) +
+c13*ALOG(Vel)*ALOG(doc) + c23*ALOG(feed)*ALOG(doc))

Force = EXP(a0 + a1*ALOG(Vel) + a2*ALOG(feed) + a3*ALOG(doc) +
+a11*(ALOG(Vel))**2 + a22*(ALOG(feed))**2 +
+a33*(ALOG(doc))**2 + a12*ALOG(Vel)*ALOG(feed) +
+a13*ALOG(Vel)*ALOG(doc) + a23*ALOG(feed)*ALOG(doc))

P = (Force*Vel)/60
```

```
      WRITE (*,*) 'Roughness in micron=',R
      WRITE (*,*) 'Power in Watt =',P
      RETURN
      END

C     *****************************************************
      SUBROUTINE EN24
C     *****************************************************
       REAL f(5), d(5), V(5,5), R,Vel,feed,doc,b0,b1,b2,b3,c0,c1,c2,c3,
     + c11,c22,c33,c12,c13,c23,a0,a1,a2,a3,a11,a22,a33,a12,a13,a23
       COMMON /CDATA/ T
       COMMON /IDATA/ K,L,KK,M,MM
      OPEN (UNIT = 8, STATUS = 'OLD',  FILE = 'feeddoc dat')
      READ (8,*) (f(I), I = 1,5)
      READ (8,*) (d(II), II = 1,5)
      OPEN (UNIT=9, STATUS='OLD', FILE='cincc dat')
      READ (9,*) b0,b1,b2,b3,c0,c1,c2,c3,c11,c22,c33,c12,c13,c23,
     +a0,a1,a2,a3,a11,a22,a33,a12,a13,a23
      DO 100 I = 1,5
      DO 150 II = 1,5
      V(I,II) = EXP((ALOG(T) - b0-b2*ALOG(f(I)) - b3*ALOG(d(II)))/b1)
 150  CONTINUE
 100  CONTINUE
       IF (K EQ 1) THEN
       WRITE (*,*) 'TURNING OPERATION'
       ELSE
       WRITE (*,*) 'MILLING OPERATION'
       ENDIF
       IF (KK EQ 1) THEN
       WRITE (*,*) 'MATERIAL   INCONEL-718'
       ELSEIF (KK EQ 2) THEN
       WRITE (*,*)'MATERIAL   EN 24T'
       ENDIF
      WRITE (*,*) 'HARDNESS IN BHN = ', L
       IF (M EQ 1) THEN
       WRITE (*,*)'CUTTING TOOL  UNCOATED TUNGSTEN CARBIDE'
      ELSEIF (M EQ 2) THEN
       WRITE (*,*)'CUTTING TOOL  COATED TUNGSTEN CARBIDE'
       ENDIF
```

```
   WRITE (*,11)
   WRITE (3,11)
11  FORMAT ('1',5x,'f',9x,'Velocity')
   WRITE (*,12)
12  FORMAT (' ',3x,'(mm/rev)',3x,'(m/min)')
          DO 160 I = 1,5
     WRITE (*,13) f(I), (V(I,II), II = 1,5)
13   FORMAT (' ',5x,F4 2, 5(F7 1))
160         CONTINUE
   WRITE (*,14)
14  FORMAT (' ','DOC (mm) = ',2X,'0 50',4X,'1 0',3X,'1 25',3X,'1 50',
   +4X,'2 0')
    WRITE (*,*) 'To have surface roughness estimate, select Velocity,
   +feed, depth of cut from the table and type the values of Vel,
   +feed, doc respectively'
        READ (*,*) Vel,feed,doc

   R = EXP(c0+c1*ALOG(Vel) + c2*ALOG(feed) + c3*ALOG(doc) +
   +c11*(ALOG(Vel))**2 + c22*(ALOG(feed))**2 +
   +c33*(ALOG(doc))**2 + c12*ALOG(Vel)*ALOG(feed) +
   +c13*ALOG(Vel)*ALOG(doc) + c23*ALOG(feed)*ALOG(doc))

   Force = EXP(a0+a1*ALOG(Vel) + a2*ALOG(feed) + a3*ALOG(doc) +
   +a11*(ALOG(Vel))**2 + a22*(ALOG(feed))**2 +
   +a33*(ALOG(doc))**2 + a12*ALOG(Vel)*ALOG(feed) +
   +a13*ALOG(Vel)*ALOG(doc) + a23*ALOG(feed)*ALOG(doc))

   P = (Force*Vel)/60
   WRITE (*,*) 'Roughness in micron = ', R
   WRITE (*,*) 'Power in Watt = ', P
   RETURN
   END
```

APPENDIX G

PUBLICATIONS

APPENDIX G

1 I A Choudhury, M A El-Baradie, and M S J Hashmi, "Machinability Assessment Cutting Forces and Tool Life for Turning High Strength Steel (290 BHN)", *Proc 11th Conf Irish Manufacturing Committee*", pp 167-173, Belfast, Northern Ireland, 1994

2 I A Choudhury and M A El-Baradie, "Surface Roughness Prediction in Turning of High Strength Steel by Factorial Design of Experiment", *Proc Int Conf on Mechanics of Solids and Materials Engineering*, Vol III, pp 1405-1413, Singapore, 1995

3 I A Choudhury and M A El-Baradie, "A Mathematical Model Based on Sequential Estimation for the Development of Machinability Data Base Systems", *Proc 5th Int Conf on Flexible Automation and Integrated Manufacturing (FAIM'95)*, pp 991-1002, Stuttgart, Germany, 1995

4 I A Choudhury and M A El-Baradie, "Tool-Life Prediction Model by Design of Experiments for Turning High Strength Steel (290 BHN)", *Proc Int Conf on Advances in Materials and Processing Technologies (AMPT'95)*, Vol III, pp 1396-1404, Dublin, Ireland, 1995

5 I A Choudhury and M A El-Baradie, "Machinability Assessment of Nickel Base Super Alloys A General Review", *Proc Int Conf on Advances in Materials and Processing Technologies (AMPT'95)*, Vol III, pp 1405-1413, Dublin, Ireland, 1995

6 I A Choudhury and M A El-Baradie, "Computer Aided Selection of Optimum Machining Parameters in Turning Operation", *Proc 12th Conf Irish Manufacturing Committee*", pp 205 -212, Cork, Ireland 1995

7 I A Choudhury and M A El-Baradie, "Machinability Assessment of Nickel Based Super Alloys Tool Life in Turning Inconel-718", *Proc 6th Cairo University Int Conf on Mechanical Design and Production*, pp 233-240, Cairo, January 2-4, 1996

8 I A Choudhury and M A El-Baradie, "Analysis of Model Building Techniques for the Development of Machinability Database Systems", Accepted for publication in the *Int Journal of Production Research*, (In press)