Mathematical model to predict surface finish

in end milling of aluminum

by

Laxmi Narasimham Peri

A Thesis Submitted to the

Graduate Faculty in Partial Fulfillment of the

Requirements for the Degree of

MASTER OF SCIENCE

Major: Mechanical Engineering

Iowa State University
Ames, Iowa
1990

# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

.

# ACKNOWLEDGEMENTS

enjoyable.

Ramans, Molians, Vamsi, Chopra, Gupta, Dinesh and lot of other friends made my stay at Iowa State University a pleasant and memorable experience. I express my sincere thanks to all of them.

# 1. INTRODUCTION

The selection of cutting tools, machining methods and machining parameters greatly influences overall manufacturing costs. These decisions also affect the setting of time standards, overall production control, cutting tool inventory and machine tool utilization. Historically, these decisions have relied heavily on the experience of the machinist, and become critical when experienced personnel are continuously being removed from the production environment through promotion and retirement. In current practice, the process planner selects the cutting tools required for a part's production. For conventional machining the machine tool operator decides the machining method (size and number of cuts) and the machining parameters (cutting speeds and feeds). For Numerical Control (NC) machining the part programmers make these decisions. In either case, the general decline of experience in these key planning positions results in lower productivity with respect to available machine tool capabilities.

Computer aided manufacturing (CAM) and Computer- aided process planning (CAPP) systems are being designed to automate the planning functions. However, the importance of machining experience cannot be overlooked. The experienced planners, machine operators, and manufacturing engineering personnel within any given facility unquestionably know the best cutting tools, methods and machining condi-

tions to be used for their production. Capturing this experience and merging it with the scientific models into a form that can conveniently provide required machining technology to CAM and CAPP systems is the central problem.

The estimation of surface finish resulting from a metal removal operation is of considerable interest in planning production. In many cases, the required surface finish may act as a constraint on the selection of cutting parameters such as cutting speed, feed rate and depth of cut. Process planners frequently must resort to trial and error methods in order to determine 'acceptable' machining conditions. These estimated machining conditions may sometimes lead to increased surface roughness, requiring the selection of more conservative cutting conditions, thereby leading to lower productivity. Reliable models should not only simplify manufacturing process planning and control, but also assist in optimizing the machinability of metals. A knowledge of the optimum combinations of machining conditions, would therefore achieve a predefined objective such as maximizing metal removal rate, minimizing production cost or maximizing production rate, without compromising surface finish.

One of the most common metal removal operations encountered in a manufacturing environment is the end milling process. End milling has become a crucial material removal operation for die sinking, pocketing and for the generation of sculptured surfaces on numerically controlled machines. The end mill is capable of removing material with the periphery of the tool and also with the end if it has bottom cutting features. The end mill is essentially a rotating cantilever, gripped by the machine tool spindle. End mills are available in a great variety of diameters, lengths and configurations.

The selection of machining parameters for a given end mill depends on the work-

piece material, cavity size and shape, accuracy and rigidity of the setup, and the machine tool. The selection involves a choice of climb or conventional mode, axial or radial depth of cut, speed, feed rate, and cutting fluid. Further, the selection of end mill diameter, flute length, and tooth edge geometry influences part dimensional accuracies and surface finish. Other important factors limiting the choice of end mill machining conditions include chatter and available power at the spindle. Chatter not only leads to poor surface finish but also to tooth chipping. Machining conditions (primarily speed and axial depth of cut) also influence chatter. Cutting speed generally has a greater effect on tool wear than does feed rate. It is advisable to select a reasonable cutting speed, depending on the workpiece material/endmill combination, then select the best combination of feed rate and radial depth of cut for a given axial depth of cut to obtain a high material removal rate. This combination should be such that it does not violate the part accuracy and surface finish requirements.

Given the complexity of the process, and the options available to the process planner, it is very difficult to arrive at optimal cutting conditions without violating the surface accuracy of the part. Mathematical models to predict surface finish of an end milled part would be very useful in selecting the most appropriate condition.

## 1.1 Research Goals

Very few attempts have been made to develop a model that will predict the surface finish resulting from the end milling operation based on the cutting parameters and material conditions. The overall objective of this research is to develop such a general purpose mathematical model that will predict surface finish in the end milling operation for Aluminum - 6061 based on the cutting speed, feed rate, depth of cut,

cutter diamter, number of teeth, and workpiece hardness. The specific goals of this research were:

1. to design an experiment that would adequately model the end milling process while minimizing the experimental trials needed,

2. to develop the experimental methodology that would include all the variables mentioned above and postulate the model,

3. to analyze the data using standard statistical techniques,

4. to study the effect of cutter diameter,number of teeth and the work piece hardness on the surface finish,

5. to study the surface finish produced by the peripheral and center cutting actions of the end mill and,

6. to validate the developed model and compare the predictive with the experimental values.

## 1.2 Thesis Organization

To identify the need for the present research and to understand prior work, a literature review was conducted. A summary of this review is provided in Chapter 2. Chapter 3 describes the statistical design of the experiment, and the Box and Behnken design used in this thesis is explained in detail. The experimental details and data are provided in Chapter 4. Chapter 5 deals with the analysis of data and results obtained. The conclusions and scope for future work are summarized in Chapter 6. /

## 2. REVIEW OF PAST WORK

The literature review is divided into two main sections. The first section is a review of recent efforts in turning research. This is explained to provide an appreciation of the efforts in single point tool research and the corresponding lack of attention towards end milling surface finish predictions. The second section is a review of previous investigations concerning end milling, classifying them as research pertaining to the prediction of cutting forces in end milling and the prediction of surface error in end milling.The final section details with the scope and need for the present research.

### 2.1 Turning Research

Surface finish resulting from single point turning operations has traditionally received considerable research attention. Single point turning is one of the oldest and most basic metal removal processes, and this has been the reason for such extensive focus. Surface finish in turning has been found to be influenced in varying amounts by a number of factors, such as feed rate, work material characteristics, workpiece hardness, built up edge, cutting speed, depth of cut, time of cut, tool nose radius, the side and end cutting edge angles of the tool, stability of the machine tool and workpiece set-up, use of cutting fluids etc.

One of the major goals of researchers in this area has been the development of

models that can predict the surface finish of a metal resulting from a variety of machining conditions dictated by the simultaneous variation of cutting factors: speed, feed, nose radius, and the like. Theoretical models to predict surface finish, while accounting for the effect of feed rate and nose radius of the cutting tool, have considered the effect of cutting speed to be insignificant (Grieve and Kaliszer 1968, Dickinson 1968, Fischer and Elrod 1971). However, cutting speed has been determined by other workers to be a significant factor (Chandiramani and Cook 1964, Shaw 1965, Boothroyd 1975, Sundaram and Lambert 1981, Miller et al. 1983). Some studies have concluded that surface finish improves with speed (Shaw 1965, Boothroyd 1975), while others have determined that speed has a mixed effect (Chandiramani and Cook 1964, Takeyama and Ono 1966). Mittal and Mehta (1988) summarized the major studies conducted in the area of surface finish for single point turning operation, and their literature review summary is presented in Table 2.1 for reference.

## 2.2  End Milling Research

End milling modeling research can be divided primarily into two areas. (1) Predicting cutting forces in end milling and (2) Predicting surface error in end milling.

### 2.2.1  Cutting Force Prediction In End Milling

Martellotti (1941) contributed to the fundamental understanding of the end milling process through studies of the cutting mechanisms and the force system in end milling. This author developed the mathematical equations for cutter path, and chip thickness for conventional and climb milling.

Table 2.1:  Factors affecting surface finish in turning and
major research efforts

| Investigations | Major factors Investigated | Material studied |
|---|---|---|
| Albrecht | Speed, feed, depth of cut, nose radius | Steel |
| Allen and Brewer | Chip size, tool condition, surface finish distribution | Steel |
| Ansell and Taylor | Tool material | Cast iron |
| Bhattacharya et al. | Speed, feed, nose radius workpiece hardness | Plain carbon steel |
| Boothroyd | Speed, feed | Mild steel |
| Chandiramani and Cook | Speed,cutting temperature | Resulphurized steel MXC |
| Dickinson | Feed, nose radius, cutting edge angles | Aluminum alloys 380 and 390 |
| Fischer and Elrod | Feed, nose radius,cutting edge angles | - |
| Grieve et al. | Feed, nose radius | Steel |
| Karmakar | Speed, feed, depth of cut | Steel C-45 |
| Lambert et al. | Speed, feed, depth of cut | Steel SAE 1018 |
| Lambert | Speed, feed, nose radius | Steel D6AC |
| Miller et al. | Speed, feed, tool condition cutting fluid grey cast iron | Aluminum alloys 380 and 390, |
| Olsen | Speed, feed, nose radius, workpiece hardness, surface roughness distribution | Steel SAE 45 |
| Petropoulos | Tool wear, surface finish distribution | Steel |
| Rasch et al. | Speed, feed | Carbon steel |
| Selvam and Radhakrishnan | Speed, built-up edge, workpiece strain hardening | Steel |
| Selvam | Vibrations, chatter speed | Steel |
| Shaw | Speed, cutting temperature | Steel |
| Sundaram and Lambert | Speed, feed, nose radius depth of cut, time of cut tool coating | Steel 4140 |
| Takeyama and Ono | Speed, depth of cut, nose radius | Steel |

.

DeVor and Kline (1980) developed a model for the force system in end milling, which merged the cutting geometry analysis of Martellotti (1941) with empirical force predicting equations to study the instantaneous force system characteritics. The equations of the model were used to study the force system characterstics when machining 4340 steel and Ti-6Al-4V. The variables in the model are radial depth of cut, axial depth of cut and feed.

Another model for the prediction of the cutting force system and surface error in end millling was provided by Kline et al. (1982). This model takes into account the effect of system deflections on the chip load, and solves for the chip load that balances the cutting forces and the resulting system deflection. The model predictions of cutting force and surface error are compared with measured values obtained from experiments performed on 390 casting aluminum alloy. The variables in the model were effective length of the cutter, radial depth of cut, axial depth of cut and the feed rate.

A mathematical model was developed by Sutherland and DeVor (1986), combining the models for cutting force system, cutter deflection and workpiece deflection so that surface error could be predicted from the machining conditions and the geometry and material properties of the cutter and workpiece. The model predictions were compared with experimental values obtained during the machining of Al-7075-T6 alloy. The variables in the model are radial and axial depths of cut.

## 2.2.2  Prediction Of Surface Error In End Milling

DeVor et al. (1983) developed a model to predict surface error in end milling by combining models for cutter and workpiece deflection with the model for the cutting

force system. This model was applied to the two pass end milling problem to predict the surface error. The variables included in the model are rough cut cutter radius, rough and finish cut feed rates, and radial depth of cut for roughing and finishing passes. The data obtained from force tests during the machining of Al-7075-T6 were used in this model.

A model to predict the topography of end milled surfaces was created by Babin et al. (1985). This model incorporates the effects of cutter run out and end mill deflection into basic tool path equations to predict resultant surface error. The predictions of the model were verified against the experimental values obtained on Al-7075-T6. The variables in the model are cutter radius, feed per tooth and cutter run out. The research efforts in end milling process modeling are summarized in Table 2.2.

Table 2.2:   Summary of research efforts in modeling of end milling

| Investigator | Year | Factors Modeled | Variables used | Material used |
|---|---|---|---|---|
| DeVor and Kline | 1980 | Cutting force | Depth of cut, feed | Steel 4340 |
| Kline et al. | 1982 | Cutting force | Depth of cut, cutter length, feed. | Al 390 |
| Sutherland and DeVor | 1986 | Surface error | Depth of cut | Al 7075-T6 |
| DeVor et al. | 1983 | Surface error | Depth of cut, cutter radius | Al 7075-T6 |
| Babin et al. | 1985 | Surface error | Cutter radius, cutter runout, feed per tooth | Al 7075-T6 |
| Ema and Davies | 1988 | Surface Finish | Cutting Speed, depth of cut, feed helix angle | En-9 |

## 2.3  Scope And Need For Present Research

All the studies conducted so far in end milling have concentrated on the effect of cutter imperfections, workpiece deflection and machine tool vibration on the accuracy of the milled surface. With the advent of computer controlled machine tools, most of these influences can be greatly reduced if not eliminated. The aerospace industry has been in the forefront in adopting computer aided manufacturing technology. A great deal of attention and time is devoted in this industry towards tool setting, tool grinding and workpiece clamping, thereby almost eliminating cutter and machine tool- induced inaccuracies in the end milling process. A model to predict surface finish as a function of the cutting parameters, cutter diameter, number of teeth and the workpiece hardness would be extremely useful to the aerospace industry. While developing a model useful to the aerospace industry, it is only logical to use the material widely used by this industry, namely Aluminum. Aluminum-6061 is used very extensively in aerospace structures and this material is used in the proposed study in the annealed (O), solution heat treated and naturally aged (T4), and solution heat treated and artificially aged (T6) conditions.

Under ideal conditions of no run-out, no cutter inaccuracy, no vibration, and no workpiece plastic deformation, the surface finish produced during end milling is influenced by the cutter diameter, number of teeth, workpiece hardness, and the cutting parameters such as cutting speed, feed rate and depth of cut. Not much attention has been given to the effect of cutter diameter, number of teeth and the workpiece hardness. All the studies mentioned previously and listed in Table 2.2, in the area of end milling surface error prediction, considered only the peripheral cutting action of the end mill. In many of the applications, such as pocketing, the material

is removed not only by the peripheral cutting action, but also by the center cutting action of the end mill. Ema and Davies (1988) studied this aspect of end milling while conducting a study on the cutting performance of end mills having different helix angles. Their studies concluded that the surface finish on the bottom portion of the workpiece (a result of the center cutting action of the end mill), was influenced by the cutting parameters. It was further observed that peripheral cutting action had little influence on end surface finish. It was one of the objectives of this study to examine the peripheral cutting action of end milling in greater detail, to confirm and validate results obtained by these authors.

Based on the already existing research work in end milling, to the best of our knowledge we understand that:

1. general-purpose surface finish prediction models for end milling considering cutting speed, feed, depth of cut, cutter diameter, number of teeth and workpiece hardness as the variables for a center cutting end mill do not exist

2. the effect of cutter diameter, number of teeth and the work piece hardness on the surface finish in end milling has not been studied, and

3. the surface finish obtained as a result of the peripheral and center cutting actions of the end mill has not been researched.

These topics form the main objectives of this research work.

# 3.  EXPERIMENTAL DESIGN

/ An experiment consists of a carefully considered and executed plan for data collection and analysis. A good experimental design furnishes the required information with the minimum of experimental effort. A correct choice of experimental method must be made and the general pattern of experiments (i.e., the number, spacing, and inter-relation of the individual observations), must be correctly chosen. The statistical theory of experimental design deals with this general pattern comprising the number and inter-relation of the individual items in a set of observations. Using mathematical theory it is possible to obtain measures of the quantity of information provided by an experimental arrangement, which can then be used to compare different arrangements to assess their suitability for any given problem./

An important function of statistics is to provide a rational basis for deciding the number of observations to be made. Since all measurements are usually subject to random errors to some degree, it is frequently necessary to combine the results of a number of observations in order to obtain the required information with sufficient precision. In industrial work these random errors may be appreciable, and in an investigation designed for a given purpose a certain minimum number of observations is required to give the necessary precision. If more observations than this are made, experimental effort which might otherwise be employed on other work will be wasted.

This is equivalent to what is termed as over-design, and it can be very expensive. If however, the experiment is under designed, so that too few observations are made, false conclusions may be drawn. The combined effect of design, and of the use of the right number of observations leads to substantial economies in the amount of experimental work required for a problem. These economies far outweigh the extra time and thought required in planning the experiments. Since the main expense in any investigation is nearly always the expense due to experimental work, a reduction in this is immediately reflected in the cost of the work as a whole.

The experimental design options available to a researcher are very many and it becomes very difficult sometimes to make a correct choice. Three of the more widely used designs, the factorial design, the randomized block design, and the incomplete factorial design are discussed here briefly and their merits and demerits are highlighted.

## 3.1 Factorial Designs

In scientific investigations, particularly where an empirical approach has to be adopted, problems arise in which the effects of a number of different factors on some property or process must be evaluated. Such problems can usually be most economically investigated by arranging the experiments according to an ordered plan in which all the factors are varied in a regular way,

The term factor is used in a general sense to denote any feature of the experimental conditions which may be deliberately varied from trial to trial. The various values of a factor examined in an experiment are known as levels. The set of levels of all factors employed in a given trial is called the treatment, or treatment combina-

tion. The numerical result of a trial based on a given treatment is called the response corresponding to that treatment. The effect of a factor is the change in response produced by a change in the level of the factor.

Provided the plan has been chosen correctly, it is possible to determine not only the effect of each individual factor but also the way in which each effect depends on the other factors (i.e., interactions). This allows a more complete picture to be obtained of what is happening than would be obtained by varying each of the factors one at a time while keeping the others constant. Designs of this sort, lend themselves well to statistical analysis and can, if required, provide their own estimates of experimental error.

The advantages of factorial design are:

1. when there are no interactions the factorial design gives the maximum efficiency in the estimation of the effects.

2. when interactions exist, their nature being unknown, a factorial design is necessary to avoid misleading conclusions.

3. in the factorial design, the effect of a factor is estimated at several levels of the other factors, and the conclusions hold over a wide range of conditions.

In spite of all the advantages mentioned above, an experimental design may be very time consuming and expensive if the number of factors and/or the number of levels is large. For example, if a factorial design is to be adopted for the study, where the number of factors is six and each factor is at three levels, the total number of experiments that need to be performed would be $3^6 = 729$ which is a very large

number. Especially, in metal cutting studies, this number of experiments would cost a great deal of money and time. Hence, a design such as this is not very well suited for the task at hand.

## 3.2 Randomized Block Design

When several experimental treatments are to be compared, it is desirable that all other conditions should be kept as nearly constant as is practicable. Random variations will occur and appear as experimental error, and some replication under similar conditions will be required to compare the treatments with sufficient reliability. Such replication also supplies the information to estimate the experimental error, and this is required to assess the reliability. The number of repeat tests required may be too great for all to be carried out under similar conditions, but is frequently possible to carry out one complete set of tests at a time under uniform conditions, these conditions being different from set to set. The precision of the experiment can be increased by dividing it into blocks, within each of which the random variations are likely to be smaller than in the experiment as a whole.

In statistics a block means, in general, a set of observations in which the error variation (i.e., the variation not associated with any deliberate variation in the experimental conditions) is expected to be less than in the whole series of observations. As a precaution against systematic variation from one trial to another within a block, it is desirable to arrange the treatments within each block in random order, and when this has been done, the result is a randomized block design. The size of the block in this design is not restricted, except by the consideration that the larger the block the greater the variation within it is likely to be, and therefore the less the gain from

dividing the material into blocks.

When using a randomized block design it is generally assumed that while the general level of the results may be different in the different blocks, the relative effects of the treatments are the same in all blocks apart from the experimental error. In other words there is no interaction between treatments and blocks.

The advantages of the randomized block design are considerable. The experiment is made more precise by eliminating from the error term sources of variance associated with the blocking factor. Additionally, the design allows an assessment of possible interactions between treatment effects and blocks. If such an interaction is significant, then it will be known that the effects of the treatments do not generalize the variables represented in the experiment. If these interactions are not significant, then a certain degree of generality is achieved in the results.

## 3.3   Incomplete Factorial Design

It has been pointed out earlier, that within the scale of the experiment and within the limits set by the experimental error, the factorial designs:

1. enable the main effects of every factor to be estimated independently of one another,

2. enable the dependence of the effect of every factor upon the levels of the others (the interactions) to be determined,

3. enable the effects to be determined with maximum precision, and,

4. supply an estimate of the experimental error for the purpose of assessing the significance of the effects, and enable the confidence limits to be determined.

However, when the number of factors is large, the extent of the trials required may become prohibitive. Thus an investigation of six factors each at three levels will entail $3^6 = 729$ observations, each under a different set of experimental conditions. This number of experiments may be excessive, even after consideration of the advantages of factorial design mentioned above. In many cases, the experiment may not require the high degree of accuracy in the estimates of the effects given by the complete factorial design. Since the fullest possible information would be obtained from a complete factorial design, it is worthwhile to consider the economies resulting from the investigation of a portion only of the composite design, called the fractional factorial design or incomplete factorial design.

The object of these latter designs is to obtain information concerning the main effects and as many of the interactions as seems necessary with a smaller number of observations than is required by the complete design. The design used in the present study is an incomplete factorial design, originally proposed by Box-Behnken (1960).

## 3.4 Box-Behnken Design

A symmetrical factorial design is an experimental arrangement in which a small integral number, $p$, of levels is chosen for each of k factors (i.e., variables) and all $p^k$ combinations of these levels are run. Classes of these designs which have proved to be of popular interest are those in which two or three levels are used for each of the k variables. These are called respectively $2^k$ and $3^k$ factorials. If not all the factorial combinations are employed, but merely a selected subset, the design is called an incomplete factorial design.

When a design involving N runs is employed to separately estimate L constants,

the ratio $R = N/L$ is defined as the redundancy factor for the design. This factor is not always less than unity. The redundancy factors for complete factorials are very large. For example, regarded as a first order design, the two level factorial in five factors requires $2^5 = 32$ runs to estimate the 6 constants of the first degree polynomial. It therefore, has a redundancy factor of $32/6 = 5.33$. Similarly, regarded as a second order design the three level factorial in five factors requires $3^5 = 243$ runs to estimate the 21 constants for the second degree polynomial. It therefore has a redundancy factor of $243/21 = 11.6$.

In situations in which the experimental error variance is not so large as to require large numbers of observations to obtain necessary precision, designs having small redundancy factors are desirable. Small redundancy factors may sometimes be obtained by using incomplete rather than complete factorial design. The Box-Behnken design selects a part of the $3^k$ factorial which allows efficient estimation of a second degree graduating polynomial, and generates a second order rotatable design. A second order rotatable design is one in which the variance is constant for all points equidistant from the center of the design. The requirement of rotatability is introduced to ensure a symmetric generation of information in the space of the variables defined and scaled in a manner currently thought most appropriate by the experimenter. The designs are formed by combining two-level factorial designs with incomplete block designs in a particular manner. The exact method of arriving at the design is illustrated in the paper by Box and Behnken [1960].

The present experiment employs 6 variables each of three levels . The variables are coded for ease of calculation, and the coding of cutting speed is illustrated as follows:

| Speed | ln 306.25 | ln 350 | ln400 |
|-------|-----------|--------|-------|
| code  | -1        | 0      | +1    |

The code for the cutting speed is,

$$X_1 = \frac{lnV - ln350}{ln400 - ln350}$$

The other variables included in the model are coded as follows:

Feed rate,

$$X_2 = \frac{lnf - ln0.0015}{ln0.002 - ln0.0015}$$

Depth of cut,

$$X_3 = \frac{lnd - ln0.15}{ln0.225 - ln0.15}$$

Number of teeth,

$$X_4 = \frac{2(lnN - ln4)}{ln4 - ln2} + 1$$

Cutter diameter,

$$X_5 = \frac{2(lnD - ln1)}{ln1 - ln0.75} + 1$$

Workpiece Hardness,

$$X_6 = \frac{2(\ln H - \ln 95)}{\ln 95 - \ln 35} + 1$$

The variables, the levels, and the values associated with them are tabulated below:

Table 3.1:   Experimental variables and levels

| Level | Speed fpm (m/min) | Feed in/tooth (mm/tooth) | Depth in (mm) | Cutter dia in (mm) | Flutes | Hardness BHN | Code |
|-------|------|------|------|------|------|------|------|
| High | 400 (122) | .002 (.05) | .225 (5.7) | 1 (25) | 4 | 95 | 1 |
| Med | 350 (106) | .0015 (.038) | .15 (3.8) | .75 (18.75) | 3 | 65 | 0 |
| Low | 306 (93.5) | .00112 (.025) | .1 (2.5) | .5 (12.5) | 2 | 35 | -1 |

Following, the Box-Behnken design, 54 trials in two blocks each of 27 need to be performed. The trials in both the blocks are listed in Tables 3.1 and 3.2 respectively.

Table 3.2: Experimental
Conditions: Block 1

| No. | $X_1$ | $X_2$ | $X_3$ | $X_4$ | $X_5$ | $X_6$ |
|-----|-------|-------|-------|-------|-------|-------|
| 1   | 1     | 1     | 0     | 1     | 0     | 0     |
| 4   | 1     | -1    | 0     | -1    | 0     | 0     |
| 6   | -1    | 1     | 0     | -1    | 0     | 0     |
| 7   | -1    | -1    | 0     | 1     | 0     | 0     |
| 9   | 0     | 1     | 1     | 0     | 1     | 0     |
| 12  | 0     | 1     | -1    | 0     | -1    | 0     |
| 14  | 0     | -1    | 1     | 0     | -1    | 0     |
| 15  | 0     | -1    | -1    | 0     | 1     | 0     |
| 17  | 0     | 0     | 1     | 1     | 0     | 1     |
| 20  | 0     | 0     | 1     | -1    | 0     | -1    |
| 22  | 0     | 0     | -1    | 1     | 0     | -1    |
| 23  | 0     | 0     | -1    | -1    | 0     | 1     |
| 25  | 1     | 0     | 0     | 1     | 1     | 0     |
| 28  | 1     | 0     | 0     | -1    | -1    | 0     |
| 30  | -1    | 0     | 0     | 1     | -1    | 0     |
| 31  | -1    | 0     | 0     | -1    | 1     | 0     |
| 33  | 0     | 1     | 0     | 0     | 1     | 1     |
| 36  | 0     | 1     | 0     | 0     | -1    | -1    |
| 38  | 0     | -1    | 0     | 0     | 1     | -1    |
| 39  | 0     | -1    | 0     | 0     | -1    | 1     |
| 41  | 1     | 0     | 1     | 0     | 0     | 1     |
| 44  | 1     | 0     | -1    | 0     | 0     | -1    |
| 46  | -1    | 0     | 1     | 0     | 0     | -1    |
| 47  | -1    | 0     | -1    | 0     | 0     | 1     |
| 49  | 0     | 0     | 0     | 0     | 0     | 0     |
| 50  | 0     | 0     | 0     | 0     | 0     | 0     |
| 51  | 0     | 0     | 0     | 0     | 0     | 0     |

Table 3.3: Experimental
Conditions: Block 2

| No. | $X_1$ | $X_2$ | $X_3$ | $X_4$ | $X_5$ | $X_6$ |
|---|---|---|---|---|---|---|
| 2 | 1 | 1 | 0 | -1 | 0 | 0 |
| 3 | 1 | -1 | 0 | 1 | 0 | 0 |
| 5 | -1 | 1 | 0 | 1 | 0 | 0 |
| 8 | -1 | -1 | 0 | -1 | 0 | 0 |
| 10 | 0 | 1 | 1 | 0 | -1 | 0 |
| 11 | 0 | 1 | -1 | 0 | 1 | 0 |
| 13 | 0 | -1 | 1 | 0 | 1 | 0 |
| 16 | 0 | -1 | -1 | 0 | -1 | 0 |
| 18 | 0 | 0 | 1 | 1 | 0 | -1 |
| 19 | 0 | 0 | 1 | -1 | 0 | 1 |
| 21 | 0 | 0 | -1 | 1 | 0 | 1 |
| 24 | 0 | 0 | -1 | -1 | 0 | -1 |
| 26 | 1 | 0 | 0 | 1 | -1 | 0 |
| 27 | 1 | 0 | 0 | -1 | 1 | 0 |
| 29 | -1 | 0 | 0 | 1 | 1 | 0 |
| 32 | -1 | 0 | 0 | -1 | -1 | 0 |
| 34 | 0 | 1 | 0 | 0 | 1 | -1 |
| 35 | 0 | 1 | 0 | 0 | -1 | 1 |
| 37 | 0 | -1 | 0 | 0 | 1 | 1 |
| 40 | 0 | -1 | 0 | 0 | -1 | -1 |
| 42 | 1 | 0 | 1 | 0 | 0 | -1 |
| 43 | 1 | 0 | -1 | 0 | 0 | 1 |
| 45 | -1 | 0 | 1 | 0 | 0 | 1 |
| 48 | -1 | 0 | -1 | 0 | 0 | -1 |
| 52 | 0 | 0 | 0 | 0 | 0 | 0 |
| 53 | 0 | 0 | 0 | 0 | 0 | 0 |
| 54 | 0 | 0 | 0 | 0 | 0 | 0 |

.

# 4. EXPERIMENTAL DETAILS AND RESULTS

This chapter is divided into four sections. The first section explains the importance of surface finish, the various ways of specifying surface finish and the measurement of surface finish. The second section details the model development. The experimental procedure and the equipment used are presented in the third section. The last section deals with the presentation of results.

## 4.1 Surface Finish Specification

The terms surface finish and surface roughness are used very widely in industry and are generally used to quantify the smoothness of a surface. However, surface finish alone does not describe the deviation of a surface from the theoretical surface. Surface texture defined as the repetitive or random deviation from the nominal surface that forms the three dimensional topography of the surface, accounts for most of the surface deviations. Many terms such as roughness, waviness, lay, flaws, profile, peak, valley, are used in the context of surface finish, and these terms as defined by ASTM are listed below.

**Roughness:** Roughness consists of the finer irregularities of the surface texture, usually including those irregularities that result from the inherent action of the production process. These are considered to include traverse feed marks and other

irregularities within the limits of the roughness sampling length.

**Waviness:** Waviness is the more widely spaced component of surface texture. Unless otherwise noted, waviness should include all irregularities whose spacing is greater than the roughness sampling length and less than the waviness sampling length. Waviness may result from such factors as machine or work deflections, vibration, chatter, heat treatment, or warping strains. Roughness may be considered as superimposed on a wavy surface.

**Lay:** Lay is the direction of the predominant surface pattern, ordinarily determined by the production method used.

**Flaws:** Unintentional, unexpected, and unwanted interruptions in the topography typical of a part surface are defined as flaws.

**Profile:** The profile is the contour of the surface in a plane perpendicular to the surface, unless some other angle is specified.

**Peak:** A peak is the point of maximum height on that portion of a profile that lies above the center line and between two intersections of the profile with the center line.

**Valley:** A valley is the point of maximum depth on that portion of a profile that lies below the centerline and between the two intersections of the profile with the centerline.

**Roughness Sampling Length:** The roughness sampling length is the sampling length within which the roughness average is determined. This length is chosen, or specified, to separate the profile irregularities which are designated as roughness from those irregularities designated as waviness.

**Cutoff:** The cutoff is the electrical response characteristic of the roughness measuring instrument which is selected to limit the spacing of the surface irregularities to be included in the assessment of roughness average. The cutoff is rated in millimeters.

Surface finish could be specified in many different ways such as Center Line Average (CLA, $R_a$, or AA), Root Mean-square (rms) $R_q$, Maximum Peak-to-Valley Roughness Height $R_y$ or $R_{max}$, Ten-Point Height $R_z$, Average Peak-to-Valley Roughness R and others. some of the popular methods of surface finish specification as defined by the ASME (ANSI/ASTM B 46.1) are described below.

### 4.1.1 Roughness Average $R_a$, AA, or CLA

The arithmetic average deviation from the center line is

$$R_a = \frac{1}{L} \int_{x=L}^{x=0} Y \, dx$$

where

$R_a$ = arithmetic average deviation from the center line

L = sampling length

y = ordinate of the curve of the profile

An approximation of the average roughness $R_a$ may be obtained by adding the y increments, without regard to sign and dividing the sum by the number of increments:

$$R_a(approx.) = \frac{y_1 + y_2 + y_3 \cdots + y_N}{N}$$

## 4.1.2 Root-Mean-Square (rms) Roughness $R_q$

The root-mean-square deviation from the center line is

$$R_q = \sqrt{(\frac{1}{L} \int_{x=L}^{x=0} y^2\, dx)}$$

or approximately

$$R_q = \sqrt{\frac{y_1^2 + y_2^2 + y_3^2 + ...y_N^2}{N}}$$

## 4.1.3 Maximum Peak-to-Valley Roughness Height $R_y$ or $R_{max}$

This is the distance between two lines parallel to the mean line that contacts the extreme upper and lower points on the profile within the roughness sampling length.

## 4.1.4 Ten-point Height $R_z$

This is the average distance between the five highest peaks and the five deepest valleys within the sampling length measured from a line parallel to the mean line and not crossing the profile.

The CLA or AA value is the most widely used in industry and this method is used to specify the surface finish in the present study.

## 4.2 Methods of Surface Finish Measurement

Several instruments capable of measuring the surface finish to a very high accuracy are available commercially in the market. The choice of the instrument for any

application should consider several factors such as capital outlay involved, simplicity of operation, surface finish assessment in a readily understood form, and the environment in which the instrument will function. Some of the important techniques available for surface finish measurement are (1) Optical Instruments (2) Stylus Tracer Instruments and (3) use of surface replicas. These techniques are discussed briefly here.

### 4.2.1 Optical Instruments

Optical instruments make no contact with the surface, which is a great advantage for surfaces of exotic materials subject to damage. A minor advantage is elimination of stylus radius. All the optical instruments lend themselves to three dimensional coverage, and with some instruments multiple profiles may be obtained. Optical instruments can be further classified based on the principles involved in the surface finish assessment, such as simple microscope, comparison microscope, surface reflectance, interferometric, and scattering methods.

### 4.2.2 Stylus Tracer Methods

The tracer type instrument consists of a sharply pointed stylus, the excursions of which, as it traverses across the surface, are magnified and recorded on a strip chart or displayed on a meter. The requirements of the magnifying technique are high magnification (up to $10^5$ times) and a very light operating force. Several magnifying techniques such as mechanical, pneumatic, optical and electronic are available. Of these, electronic magnification is the most popular since an electronic signal can be easily manipulated to give different measures of roughness and to be fed to other

recording equipment. Stylus instruments are used widely in industry, and a pro-filometer with stylus was used in the present study to measure surface finish on the experimental samples.

### 4.2.3 Use of Replicas

Replicas of the surfaces are used for examination purposes, if the surface of a material is soft and liable to surface damage if stylus instruments are used, and where size or inaccessibility prevents direct optical examination. Plastic replicas are generally used for the assessment of surfaces.

## 4.3 Model Development

The model proposed to be established is of the form

$$R = v^p f^q d^r n^s D^t H^u \tag{4.1}$$

where

R = Arithmetic Average surface finish values in $\mu$m

v = cutting speed in meters per minute

f = feed rate in millimeters per tooth

d = depth of cut in millimeters

n = number of flutes

D = diameter of the cutter in mm

H = Brinell hardness of the workpiece

The model when logarithmically transformed becomes:

$$\ln R = p\ln v + q\ln f + r\ln d + s\ln n + t\ln D + u\ln H \qquad (4.2)$$

If the error term $\epsilon$ is included, the model can be written as

$$\ln y = \epsilon + p\ln v + q\ln f + r\ln d + s\ln n + t\ln D + u\ln H \qquad (4.3)$$

where y is the logarithmic transformation of the AA surface finish value and $\epsilon$ is the experimental error.

Due to the experimental error, the true response is $y - \epsilon$, where y is the logarithmic transformation of the measured surface finish value and $\epsilon$ is the experimental error.

The equation (4.3) can be rewritten as.

$$Y = b_0 + b_1 x_1 + b_2 X_2 + b_3 X_3 + b_4 X_4 + b_5 X_5 + b_6 X_6 \qquad (4.4)$$

where Y is the estimated (predicted) surface roughness value after logarithmic transformation, $X_1$, $X_2$, $X_3$, $X_4$, $X_5$ and $X_6$ are the logarithmic transformations of cutting speed, feed rate, depth of cut, number of flutes, cutter diameter and the workpiece hardness respectively, and $b_0, b_1, b_2, b_3, b_4, b_5, b_6$ are the estimates of the quantities p, q, r, s, t and u respectively.

The model in the present study was developed on the assumption that the relationship between surface finish and the variables involved could best be described by a second degree polynomial of the form;

$$
\begin{aligned}
Y = \ & b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_4 X_4 + b_5 X_5 + b_6 X_6 \\
& + b_{11} X_1^2 + b_{22} X_2^2 + b_{33} X_3^2 + b_{44} X_4^2 + b_{55} X_5^2 + b_{66} X_6^2 \\
& + b_{12} X_1 X_2 + b_{13} X_1 X_3 + b_{14} X_1 X_4 + b_{15} X_1 X_5 + b_{16} X_1 X_6 \\
& + b_{23} X_2 X_3 + b_{24} X_2 X_4 + b_{25} X_2 X_5 + b_{26} X_2 X_6 + b_{34} X_3 X_4 \\
& + b_{35} X_3 X_5 + b_{36} X_3 X_6 + b_{45} X_4 X_5 + b_{46} X_4 X_6 + b_{56} X_5 X_6 \quad (4.5)
\end{aligned}
$$

A second order mathematical model is required when the true response function is curvilinear or unknown.

## 4.4   Experimental Details

The workpiece material used was 6061-Aluminum alloy of 50 x 25 mm cross-section. This alloy in the T6 condition was annealed (to BHN 35), by heating at $775^{o}$F for two hours and then cooling slowly to ambient temperature. Other samples of the same material were heated at $900^{o}$F for two hours, followed by water quenching and natural ageing for four days, to obtain the T4 condition.

The machine tool used for conducting the experiments was a Hitachi-Seiki VM40 machining center of 7.5 Kw spindle power and a table size of 500 x 500 mm.

Milling cutters used were standard Putnam High Speed Steel end mills with 2, 3 and 4 flutes of diameters 12.5 mm, 18.75 mm and 25 mm (1/2 in, 3/4 in and 1

in). The cutters used in this study were all of 75 mm length (3 in). This eliminates any variation due to cutter deflection and chatter. The workpiece used in the study was of dimension 50 x 25 x 25 mm. One slot of width equal to the cutter diameter was cut across the thickness of the workpiece and the surface finish obtained was measured on the bottom surface of the slot. The workpiece dimensions are shown in Figure 4.1

Surface finish measurements were obtained as the arithmetic average in micrometers using a profilometer with a cut-off level of 0.8 mm. For each unique cutting condition, six AA measurements were recorded at random locations around the bottom surface of the slot. These six measurements were averaged to obtain a single mean AA value for each experiment. All the tests were carried out in the presence of Prime-cut, a water soluble cutting fluid (30:1 concentration).

The surface finish values obtained on the experimental specimens are listed in Tables 4.1 and 4.2.
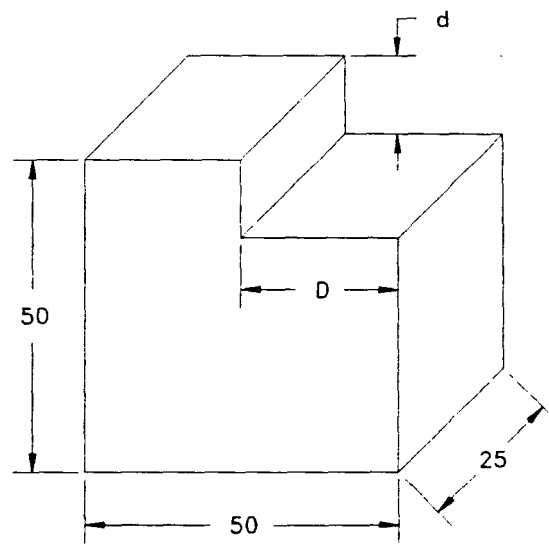
d: depth of cut    D: cutter diameter    All dimensions are in mm

Figure 4.1:   Workpiece Dimensions

Table 4.1:   Surface Finish Values obtained in Block 1

| No. | $X_1$ | $X_2$ | $X_3$ | $X_4$ | $X_5$ | $X_6$ | side finish $\mu$m | bottom finish $\mu$m |
|-----|-------|-------|-------|-------|-------|-------|-----------|-------------|
| 1 | 1 | 1 | 0 | 1 | 0 | 0 | 0.787 | 0.635 |
| 4 | 1 | -1 | 0 | -1 | 0 | 0 | 0.17 | 0.635 |
| 6 | -1 | 1 | 0 | -1 | 0 | 0 | 0.279 | 0.617 |
| 7 | -1 | -1 | 0 | 1 | 0 | 0 | 0.584 | 0.533 |
| 9 | 0 | 1 | 1 | 0 | 1 | 0 | 0.279 | 1.14 |
| 12 | 0 | 1 | -1 | 0 | -1 | 0 | 0.685 | 1.075 |
| 14 | 0 | -1 | 1 | 0 | -1 | 0 | 0.279 | 0.465 |
| 15 | 0 | -1 | -1 | 0 | 1 | 0 | 0.177 | 0.736 |
| 17 | 0 | 0 | 1 | 1 | 0 | 1 | 0.787 | 0.567 |
| 20 | 0 | 0 | 1 | -1 | 0 | -1 | 0.482 | 0.414 |
| 22 | 0 | 0 | -1 | 1 | 0 | -1 | 0.482 | 0.584 |
| 23 | 0 | 0 | -1 | -1 | 0 | 1 | 0.762 | 0.685 |
| 25 | 1 | 0 | 0 | 1 | 1 | 0 | 0.279 | 0.973 |
| 28 | 1 | 0 | 0 | -1 | -1 | 0 | 0.889 | 0.871 |
| 30 | -1 | 0 | 0 | 1 | -1 | 0 | 0.279 | 0.228 |
| 31 | -1 | 0 | 0 | -1 | 1 | 0 | 0.279 | 0.465 |
| 33 | 0 | 1 | 0 | 0 | 1 | 1 | 0.482 | 1.3 |
| 36 | 0 | 1 | 0 | 0 | -1 | -1 | 0.66 | 1.06 |
| 38 | 0 | -1 | 0 | 0 | 1 | -1 | 0.584 | 0.804 |
| 39 | 0 | -1 | 0 | 0 | -1 | 1 | 0.177 | 0.516 |
| 41 | 1 | 0 | 1 | 0 | 0 | 1 | 0.381 | 1.524 |
| 44 | 1 | 0 | -1 | 0 | 0 | -1 | 0.482 | 1.79 |
| 46 | -1 | 0 | 1 | 0 | 0 | -1 | 0.889 | 1.53 |
| 47 | -1 | 0 | -1 | 0 | 0 | 1 | 0.177 | 1.89 |
| 49 | 0 | 0 | 0 | 0 | 0 | 0 | 0.381 | 0.71 |
| 50 | 0 | 0 | 0 | 0 | 0 | 0 | 1.09 | 0.668 |
| 51 | 0 | 0 | 0 | 0 | 0 | 0 | 0.685 | 0.448 |

Table 4.2: Surface Finish Values obtained in Block 2

| No. | $X_1$ | $X_2$ | $X_3$ | $X_4$ | $X_5$ | $X_6$ | side finish $\mu$m | bottom finish $\mu$m |
|---|---|---|---|---|---|---|---|---|
| 2 | 1 | 1 | 0 | -1 | 0 | 0 | 0.381 | 0.39 |
| 3 | 1 | -1 | 0 | 1 | 0 | 0 | 0.685 | 0.448 |
| 5 | -1 | 1 | 0 | 1 | 0 | 0 | 0.889 | 0.55 |
| 8 | -1 | -1 | 0 | -1 | 0 | 0 | 0.482 | 0.3 |
| 10 | 0 | 1 | 1 | 0 | -1 | 0 | 0.177 | 0.668 |
| 11 | 0 | 1 | -1 | 0 | 1 | 0 | 0.279 | 1.21 |
| 13 | 0 | -1 | 1 | 0 | 1 | 0 | 0.279 | 0.668 |
| 16 | 0 | -1 | -1 | 0 | -1 | 0 | 0.414 | 0.567 |
| 18 | 0 | 0 | 1 | 1 | 0 | -1 | 0.99 | 0.567 |
| 19 | 0 | 0 | 1 | -1 | 0 | 1 | 0.279 | 0.346 |
| 21 | 0 | 0 | -1 | 1 | 0 | 1 | 0.584 | 0.465 |
| 24 | 0 | 0 | -1 | -1 | 0 | -1 | 0.685 | 0.262 |
| 26 | 1 | 0 | 0 | 1 | -1 | 0 | 0.431 | 0.228 |
| 27 | 1 | 0 | 0 | -1 | 1 | 0 | 0.381 | 0.482 |
| 29 | -1 | 0 | 0 | 1 | 1 | 0 | 0.279 | 0.889 |
| 32 | -1 | 0 | 0 | -1 | -1 | 0 | 0.787 | 0.445 |
| 34 | 0 | 1 | 0 | 0 | 1 | -1 | 0.381 | 1.159 |
| 35 | 0 | 1 | 0 | 0 | -1 | 1 | 0.177 | 0.7 |
| 37 | 0 | -1 | 0 | 0 | 1 | 1 | 0.279 | 0.66 |
| 40 | 0 | -1 | 0 | 0 | -1 | -1 | 0.279 | 0.414 |
| 42 | 1 | 0 | 1 | 0 | 0 | -1 | 1.143 | 1.502 |
| 43 | 1 | 0 | -1 | 0 | 0 | 1 | 0.177 | 0.668 |
| 45 | -1 | 0 | 1 | 0 | 0 | 1 | 0.279 | 0.651 |
| 48 | -1 | 0 | -1 | 0 | 0 | -1 | 0.787 | 1.104 |
| 52 | 0 | 0 | 0 | 0 | 0 | 0 | 0.482 | 0.584 |
| 53 | 0 | 0 | 0 | 0 | 0 | 0 | 0.381 | 0.397 |
| 54 | 0 | 0 | 0 | 0 | 0 | 0 | 0.381 | 0.346 |

# 5. RESULTS AND DISCUSSION

In the first section, the experimental data obtained in the study are analyzed in the form of an analysis of variance table. The general conclusions of the present study are detailed in section two and the effects of each of the experimental variables on the surface finish are discussed in section three.

## 5.1 Analysis of Variance

### 5.1.1 Bottom surface finish

The surface roughness model was developed by assuming that surface roughness could be predicted as a function of the variables listed previously, via a second order polynomial, i.e.,

$$
\begin{aligned}
Y \; = \; & b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_4 X_4 + b_5 X_5 + b_6 X_6 \\
& + b_{11} X_1^2 + b_{22} X_2^2 + b_{33} X_3^2 + b_{44} X_4^2 + b_{55} X_5^2 + b_{66} X_6^2 \\
& + b_{12} X_1 X_2 + b_{13} X_1 X_3 + b_{14} X_1 X_4 + b_{15} X_1 X_5 + b_{16} X_1 X_6 \\
& + b_{23} X_2 X_3 + b_{24} X_2 X_4 + b_{25} X_2 X_5 + b_{26} X_2 X_6 + b_{34} X_3 X_4 \\
& + b_{35} X_3 X_5 + b_{36} X_3 X_6 + b_{45} X_4 X_5 + b_{46} X_4 X_6 + b_{56} X_5 X_6 \quad (5.1)
\end{aligned}
$$

The b's in the equation (1) were estimated and the resulting surface finish model is represented by the following equation:

$$\begin{aligned}
Y = {} & 3.143 - 0.024X_1 + 0.26X_2 - 0.027X_3 + 0.106X_4 \\
& +0.245X_5 + 0.024X_6 + 0.137X_1^2 - 0.036X_2^2 + 0.167X_3^2 \\
& -0.513X_4^2 + 0.14X_5^2 + 0.26X_6^2 + 0.132X_1X_2 + 0.173X_1X_3 \\
& +0.061X_1X_4 - 0.068X_1X_5 - 0.081X_1X_6 - 0.068X_2X_3 \\
& -0.16X_2X_4 - 0.057X_2X_5 - 0.09X_2X_6 + 0.048X_3X_4 \\
& +0.025X_3X_5 - 0.08X_3X_6 + 0.419X_4X_5 - 0.126X_4X_6 \\
& +0.068X_5X_6
\end{aligned} \tag{5.2}$$

The analysis of variance for the surface roughness model is shown in Table 5.1.

Table 5.1: Analysis of variance for bottom surface finish

| Sources of variation | Sum of squares | Degrees of freedom | Mean squares | F ratio |
|---|---|---|---|---|
| Regression | 10.095 | 27 | 0.3738 | $F_1^* = 2.7$ |
| Residual | | | | |
| Lack fit | 3.047 | 21 | 0.145 | |
| pure error | 0.417 | 5 | 0.0835 | $F_2^* = 1.7365$ |

The value of $F_{0.95,27,25}$ from F-tables is 1.92.

Since $F_1^* > F_{0.95,27,25}$ regression is found to be significant

The value of $F_{0.95,21,5}$ from F-tables is 2.59.

Since $F_2^* < F_{0.95,21,5}$ no lack of fit is indicated.

## 5.1.2 Side surface finish

The b's in the equation (1) were estimated and the resulting surface finish model
is represented by the following equation:

$$
\begin{aligned}
Y = {} & 3.042 + 0.0606X_1 + 0.109X_2 + 0.094X_3 + 0.0521X_4 \\
& -0.008X_5 - 0.308X_6 - 0.103X_1^2 - 0.12X_2^2 - 0.244X_3^2 \\
& +0.253X_4^2 - 0.437X_5^2 + 0.122X_6^2 + 0.017X_1X_2 + 0.131X_1X_3 \\
& -0.027X_1X_4 - 0.03X_1X_5 + 0.068X_1X_6 - 0.0387X_2X_3 \\
& +0.198X_2X_4 - 0.131X_2X_5 - 0.004X_2X_6 + 0.2965X_3X_4 \\
& +0.062X_3X_5 - 0.052X_3X_6 + 0.419X_4X_5 + 0.05X_4X_6 \\
& +0.068X_5X_6
\end{aligned}
\tag{5.3}
$$

The analysis of variance for the surface roughness model is shown in Table 5.2.

Table 5.2: Analysis of variance for side surface finish

| Sources of variation | Sum of squares | Degrees of freedom | Mean squares | F ratio |
|---|---|---|---|---|
| Regression | 11.511 | 27 | 0.388 | $F_1^* = 1.64$ |
| Residual | | | | |
| Lack fit | 5.859 | 21 | 0.2790 | |
| pure error | 0.923 | 5 | 0.1846 | $F_2^* = 1.512$ |

The value of $F_{0.95,27,25}$ from F-tables is 1.92.

Since $F_1^* < F_{0.95,27,25}$ regression is found to be insignificant

The value of $F_{0.95,21,5}$ from F-tables is 2.59.

Since $F_2^* < F_{0.95,21,5}$ no lack of fit is indicated.

It is a little difficult to analyze the effects of different variables on the resulting surface finish from the regression coefficients as the variables are statistically coded. However an analysis based on the experimental data has been made. Because of the change in levels of the other variables, it is highly difficult to analyze the effect of one variable alone on the resulting surface roughness with the experimental data. A detailed study is required to analyze the effects of these variables on the resulting surface roughness. The interpretation of the regression equation is presented in the next section.

## 5.2   Results

### 5.2.1   Bottom surface finish

Although the experimental results are represented adequately by the functional equation 1, certain trends are clearly evident from an examination of the data shown plotted in Figures 5.1 thru 5.15.

Referring to Figures 5.8, 5.9, and 5.10, it can be seen that rougher surfaces are produced by cutters with larger diameters. The unexpected result shown in Figures 5.4, 5.5, 5.6, and 5.7 indicates that three-flute cutters yield rougher surfaces. In all cases, surface finish deteriorates for larger feed rates (not unexpectedly). These results are further supported by the results shown plotted in Figures 5.10 thru 5.15. Here it is seen that material with intermediate workpiece hardness provides better finish than softer or harder material.

The effect of change in axial depth of cut is not pronounced (Figures 5.2, 5.3) but the trends would seem to indicate the existence of an optimal value equal to 4.3 mm. Small changes in surface cutting speed in the range 93-120 m/min, have little effect on surface roughness values (Figures 5.1, 5.2). A detailed analysis of the effect of each of the parameters is carried out in the following section.

## 5.2.2   side surface finish

Ema and Davies (1988) investigated the cutting performance of end mills in slotting operation. The surface finish measured on the bottom surface of the slots were in conformance with the predicted values, and the effect of variation of different cutting parameters was easily observed and explained. However, the surface finish achieved on the side surfaces of the slot had an erratic behavior. The authors concluded that the side surface finish in slotting was unaffected by the variation of the cutting parameters.

The surface finish values measured on the side surfces of the slot in the present study are tabulated in tables 4.1 and 4.2. The erratic behaviour of the values could be observed. Also, the regression equation behaves poorly, with an $R^2$ value of 0.64, and hence accounts for only 64 percent of the variation in the process. This study validates the findings of Ema and Davies (1988) and it can be concluded that side surface finish is unaffected by the cutting parameters.

## 5.3 Discussion

### 5.3.1 Cutting speed

It is observed from the results, that an increase in cutting speed reduces the surface roughness and results in better finish. However, this is true for speeds up to 350 fpm. Beyond this, any further increase in speed results in a rougher surface [Figures 5.1, 5.2]. Chandiramani and Cook (1964) in their investigation on the response of surface roughness to the change in cutting speed stated that the surface roughness decreased with an increase in cuting speed in the low speed region, deteriorated in the intermediate speed region, and decreased gradually to a limiting value in the high speed region. The deterioration of surface roughness in the intermediate region was explained to be the result of built-up edge formation.

Sundaram and Lambert (1981) observed that surface finish improved with increase in cutting speed. The improvement is reported to be rapid up to some critical speed due to a continuous reduction in the size of the built-up edge. Further increase in speed resulted in negligible improvement in the surface finish. However, Nakayama et al. (1966) observed an improvement in the surface finish with an increase in the cutting speed. Over the range of the experimental values, it can therefore be concluded that an increase in the speed improves the surface finish up to a certain point, and a further increase in speed deteriorates the surface finish.

### 5.3.2 Effect of feed rate

The observations of this study indicate that an increase in feed rate deteriorates the surface finish. The deterioration is continuous over the range of experimental
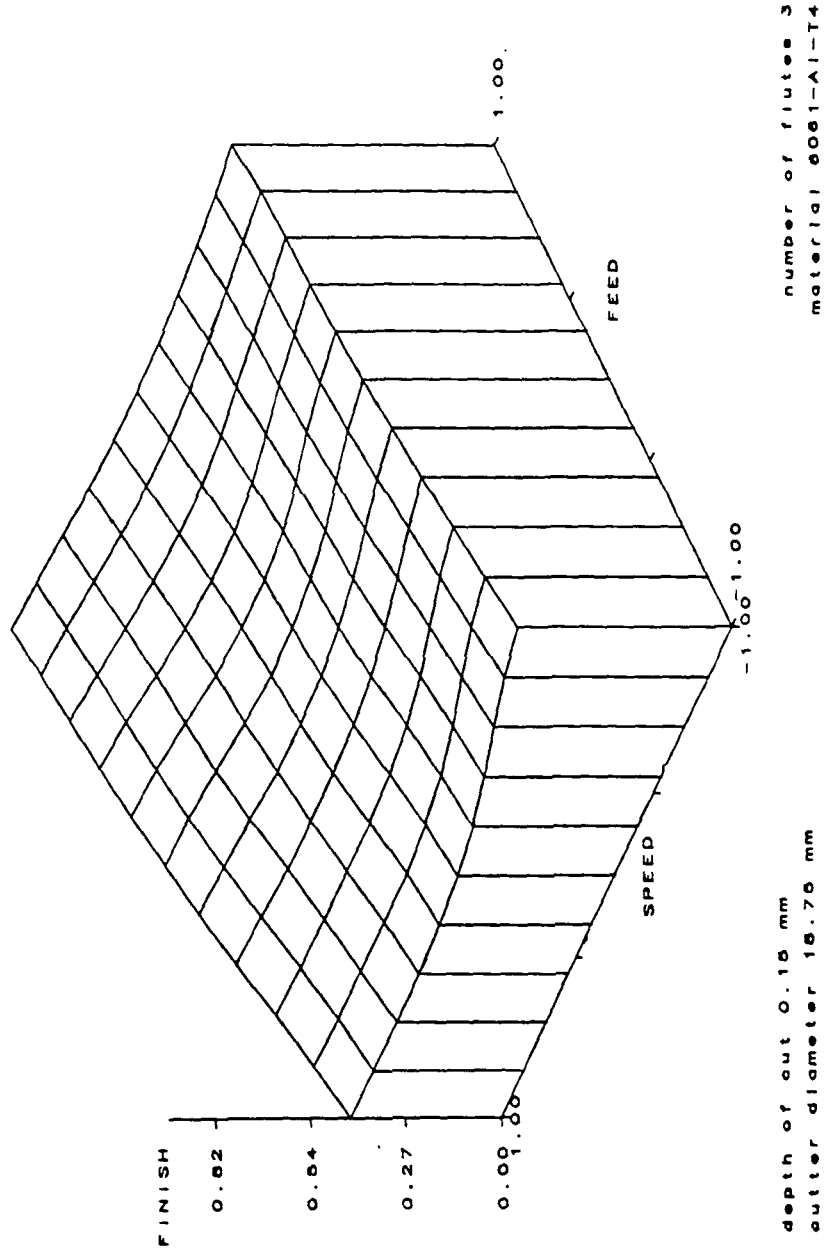
Figure 5.1: Variation of Surface Finish With cutting Speed and Feed Rate
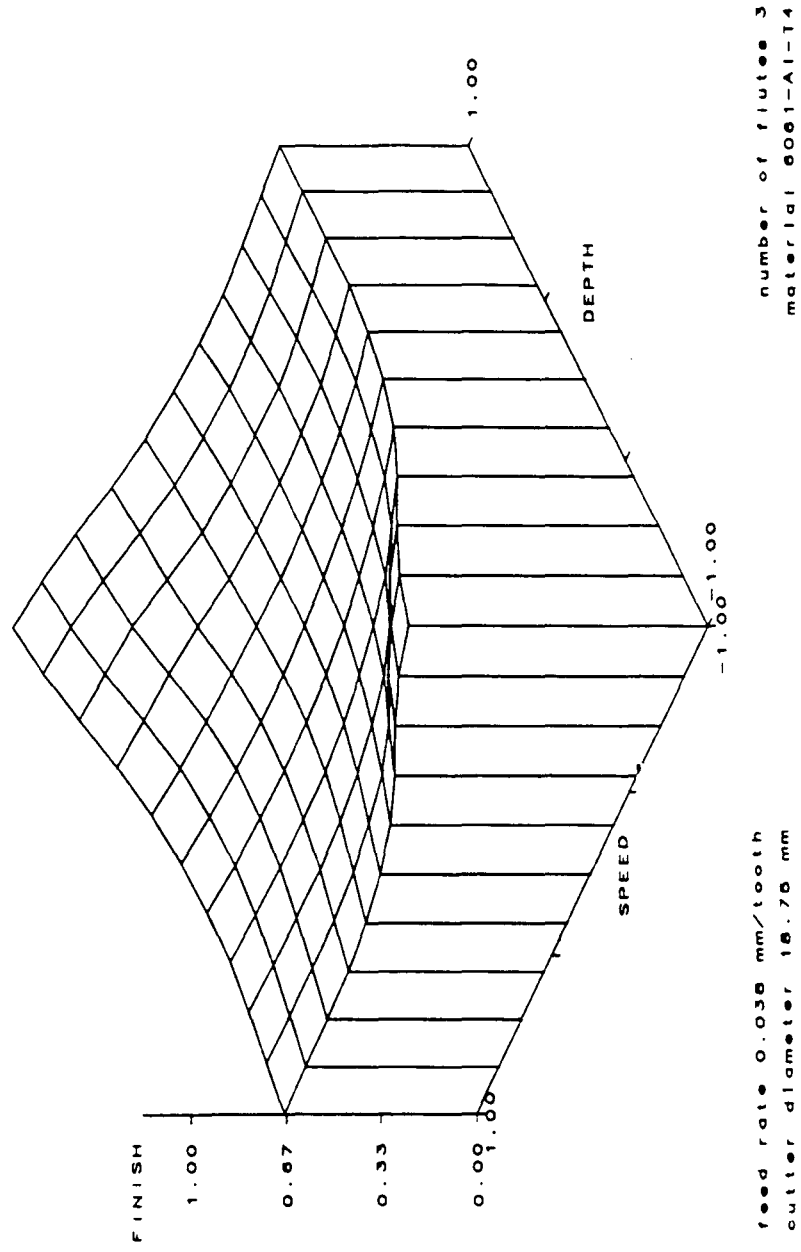
Figure 5.2:   Variation of Surface Finish With Cutting Speed and Depth of Cut

feed rate values.

Martellotti (1941) in his study of the milling process derived the following expression for the peak-to-valley roughness ($R_t$) in a milling operation

$$R_t = \frac{f^2}{8[r + \frac{fn}{\pi}]}$$  (5.4)

where f is the feed per tooth, r is the cutter radius, and n is the number of teeth in the cutter. The + sign pertains to upmilling where as the - sign is for down milling. This equation was found by Martellotti to be in good agreement with the measured values. According to this equation, the surface roughness is directly proportional to the square of the feed rate, which explains the feed rate influences on surface finish observed in the present study [see Figure 5.3]. Similar conclusions have been arrived at by Shaw (1965), Mittal and Mehta (1988), Sundaram and Lambert (1981) in turning and by Wong and Middleton (1984) in milling.

### 5.3.3   Effect of Depth of cut

Increase in the depth of cut for small values of this parameter (up to 3 mm) improved the surface finish, but a further increase in the depth of cut produced rougher surfaces. Depth of cut influences the metal removal rate in milling. In finish milling, the goal is to decrease the surface roughness rather than to increase the metal removal rate. Hence it is not uncommon to use only very small levels of depth of cut in finish milling [ see Figure 5.2 ].

Karmar (1970) in turning C-45 steels found the surface roughness to decrease with increased depth of cut. He also found that increased depth of cut has no influence on surface roughness beyond a certain level of depth of cut. Shaw et (1965) observed

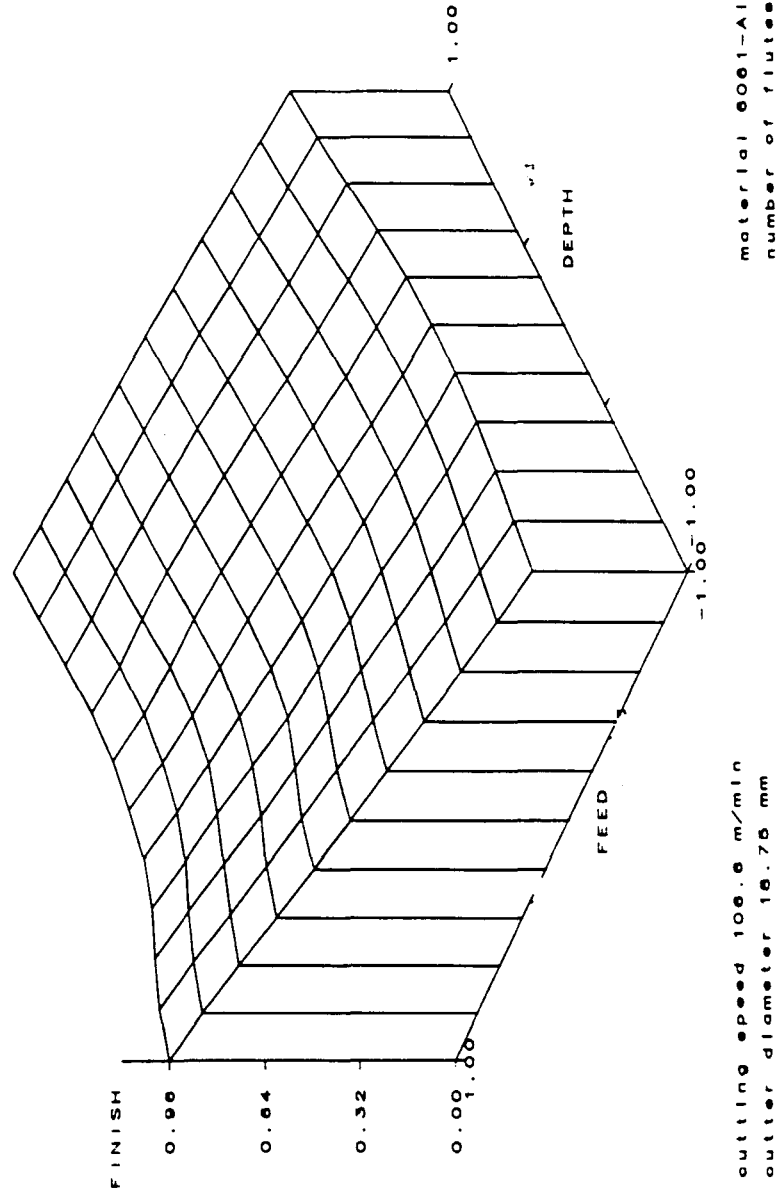FEED RATE AND DEPTH OF CUT INTERACTION



Figure 5.3: Variation of Surface Finish With Feed Rate and Depth of Cut

that surface finish improved with an increase in depth of cuts for small depths, and at higher values of depth of cut, the surface finish deteriorated. Wong and Middleton (1984) while studying the milling operation, concluded surface finish to be inversely proportional to the depth of cut. The findings of the current study are consistent with some of the above conclusions.

### 5.3.4 Effect of Number of Flutes

Very smooth surfaces were produced by two flute cuttters, while the finish deteriorated for four flute cutters. Three flute end mills produced the roughest surfaces. [see Figures 5.4, 5.5, 5.6, 5.7]. This is a very surprising outcome. According to the equation developed by Martellotti (1941) [Equation 5.3], surface roughness is inversely proportional to the number of teeth. Therefore, four flute end mills should have produced the smoothest surfaces and two flute end mills, very rough surfaces. Three flute end mills shoud have produced surfaces with roughness values between those produced by two and four flute end mills. The findings of this study are quite contrary to what Martellotti predicted.

Martellotti analyzed the peripheral cutting action of a slab milling cutter, and concluded that surface finish improves with increasing number of teeth. The cusp height generated decreases with an increase in the number of teeth in peripheral cutting. However, for a center cutting end mill, the surface roughness is influenced by other geometric factors like the helix angles and rake angles. The applicability of the Martellotti approach to the center cutting end mills needs to be studied further.
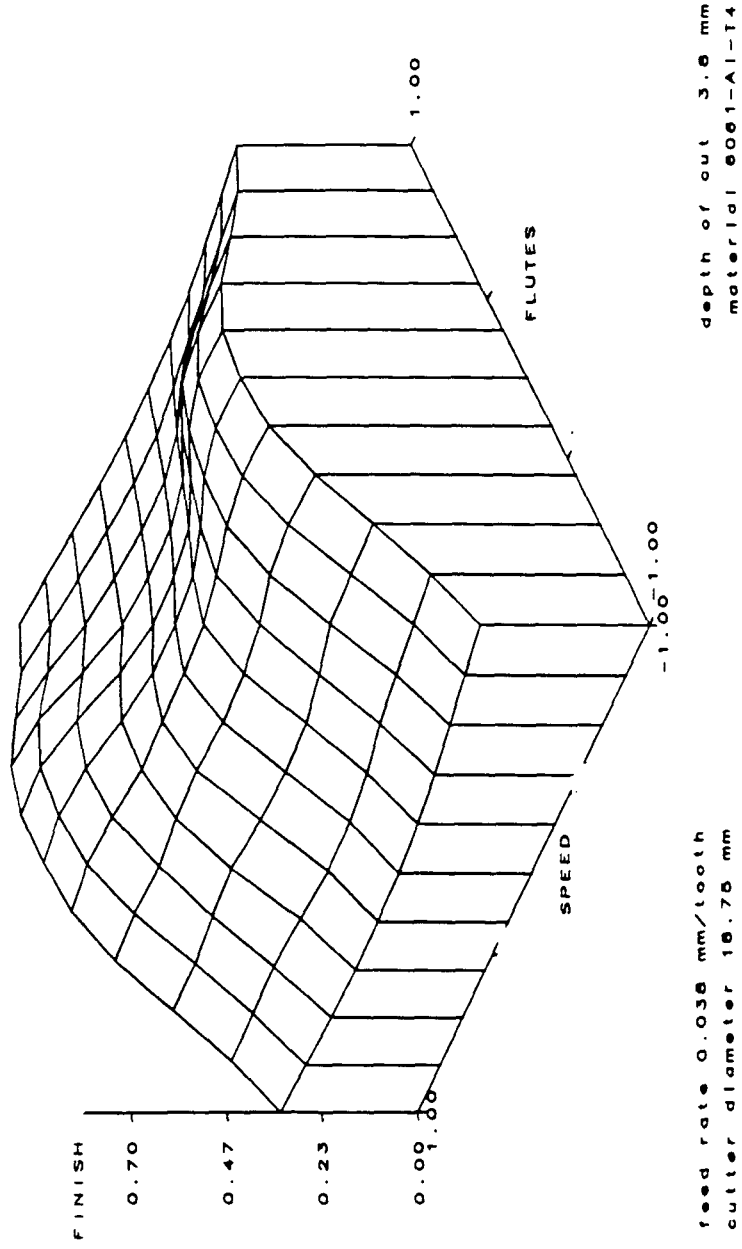
CUTTING SPEED AND NUMBER OF FLUTES INTERACTION



Figure 5.4:  Variation of Surface Finish with Number of Flutes and Cutting Speed

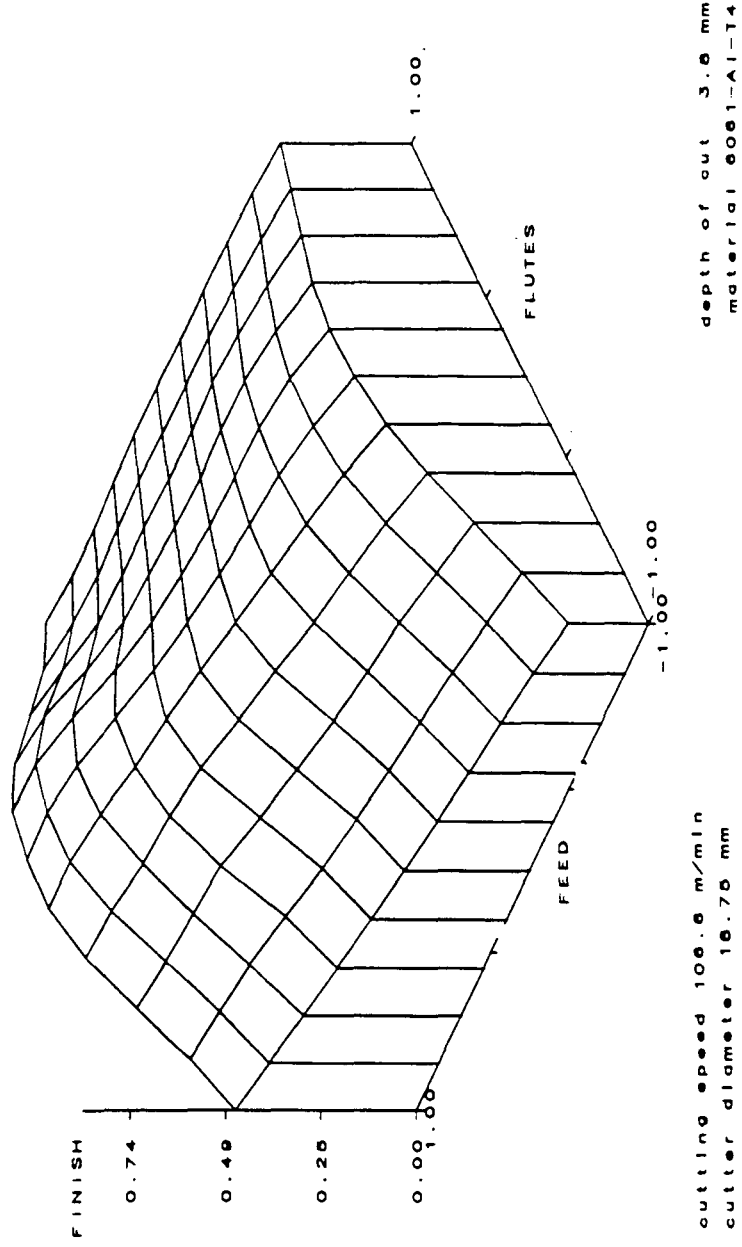FEED RATE AND NUMBER OF FLUTES INTERACTION



Figure 5.5:   Variation of Surface Finish with Number of Flutes and Feed Rate

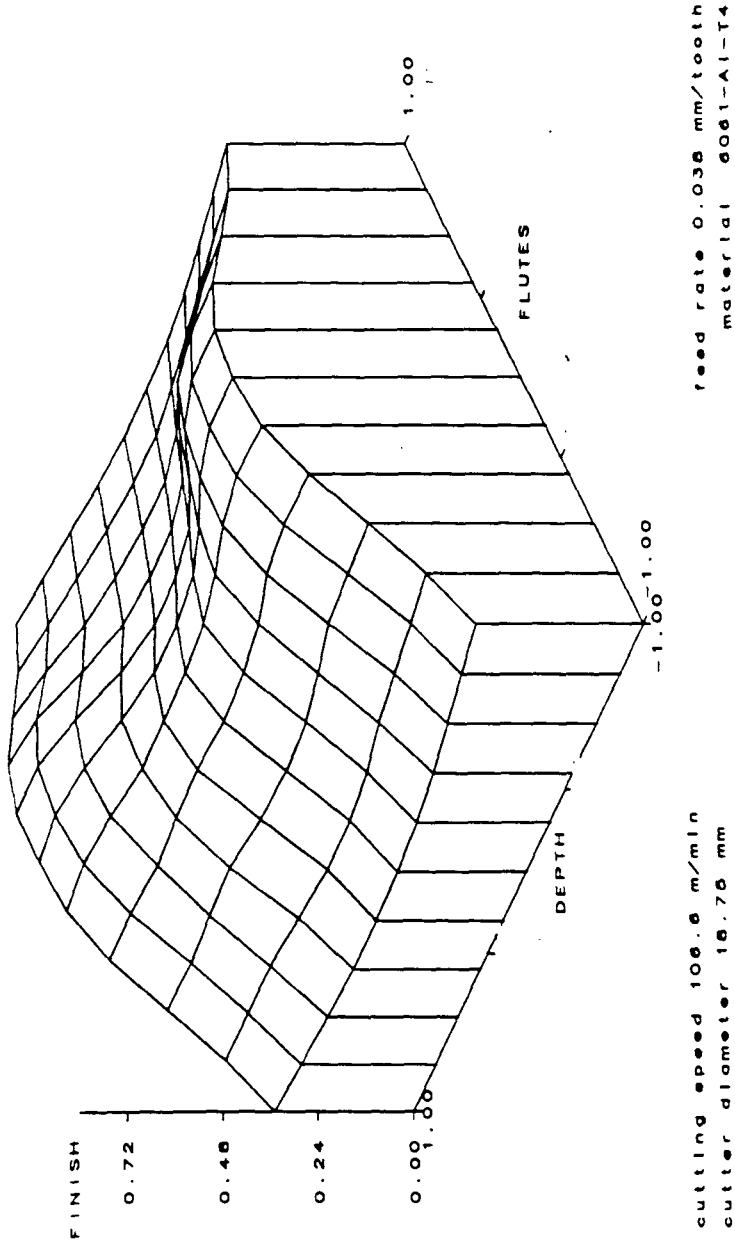DEPTH OF CUT AND NUMBER OF FLUTES INTERACTION



Figure 5.6:   Variation of Surface Finish with Number of Flutes and Depth of Cut
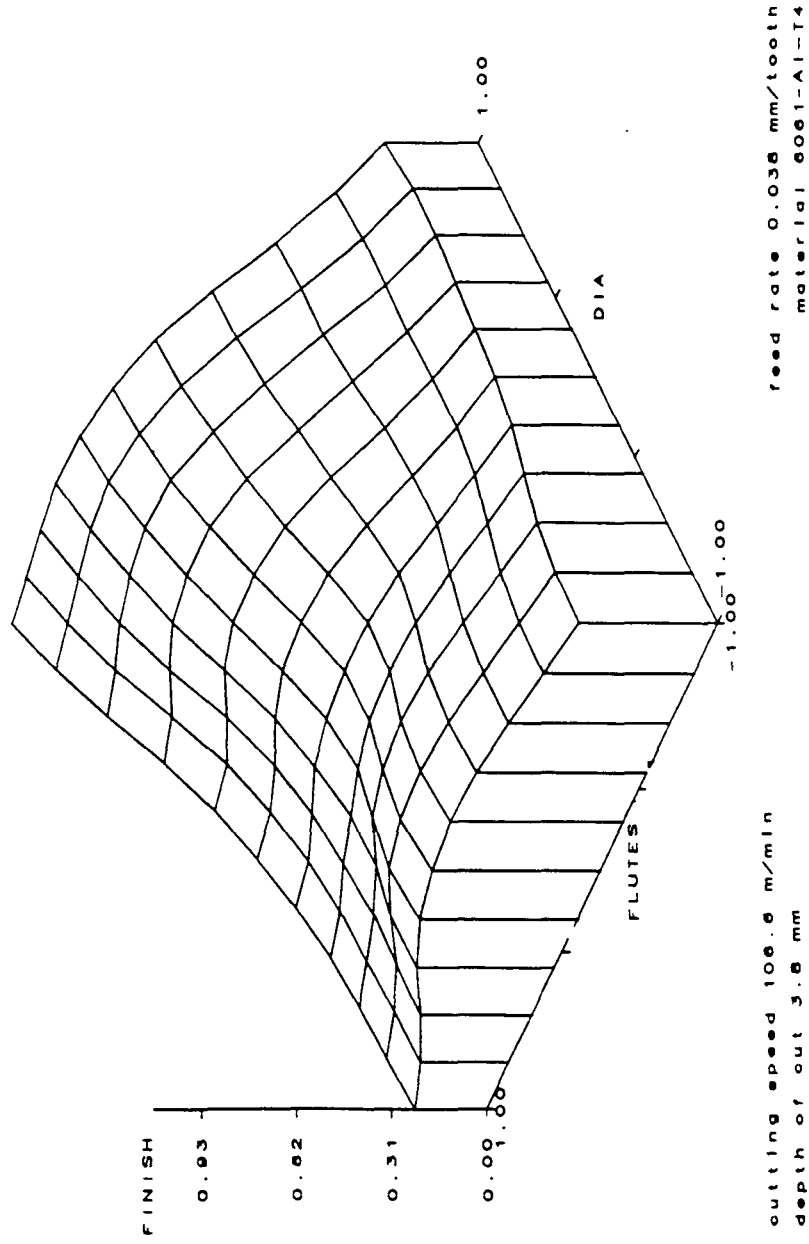
NUMBER OF FLUTES AND CUTTER DIAMETER INTERACTION



cutting speed 100.6 m/min
depth of cut 3.8 mm

feed rate 0.038 mm/tooth
material 6061-Al-T4

Figure 5.7: Variation of Surface Finish with Number of Flutes and Cutter Diameter

## 5.3.5  Effect of Cutter Diameter

In the present study it was found that surface finish deteriorated with increasing cutter diameter. Cutters with diameter 25 mm produced very rough surfaces, the 12.5 mm diameter cutters generated very smooth surfaces, while the 18.75 mm cutters gave intermediate values [see Figure 5.8, 5.9, 5.10].

It is known from theory, pertaining to peripheral milling that larger cutter diameters generate smoother surfaces, and as the cutter diameter is decreased, the surface roughness increases. Also, the part of the work piece which was machined was of the same width as that of the cutter and the cross-sectional area of the machined surface remained constant for all the cutters. In the present study, as the cutter diameter varied, the area machined also varied ( since the slot width was equal to the cutter diameter). With cutting speed, feed rate and depth of cut constant, increasing the cutter diameter results in larger cutting forces, leading to possible vibration and chatter. The increased cutting force could lead to deflection of the workpiece. The effect of cutter diameter should be investigated making use of a larger workpiece to eliminate deflections.

## 5.3.6  Effect of Workpiece Hardness

In the present work, surface roughness was found to be inversely proportional to the workpiece hardness. The 6061-Al-O (annealed) produced rougher surfaces, while 6061-Al-T6 (solution treated to 95 BHN) and 6061-Al-T4 (solution treated to 65 BHN) generated smooth surfaces in that order[See Figure 5.11, 5.12, 5.13, 5.14, 5.15]. This result is not unexpected, and could be attributed to the influence of the built-up edge. As the cutting speed is increased, the friction between the chip and
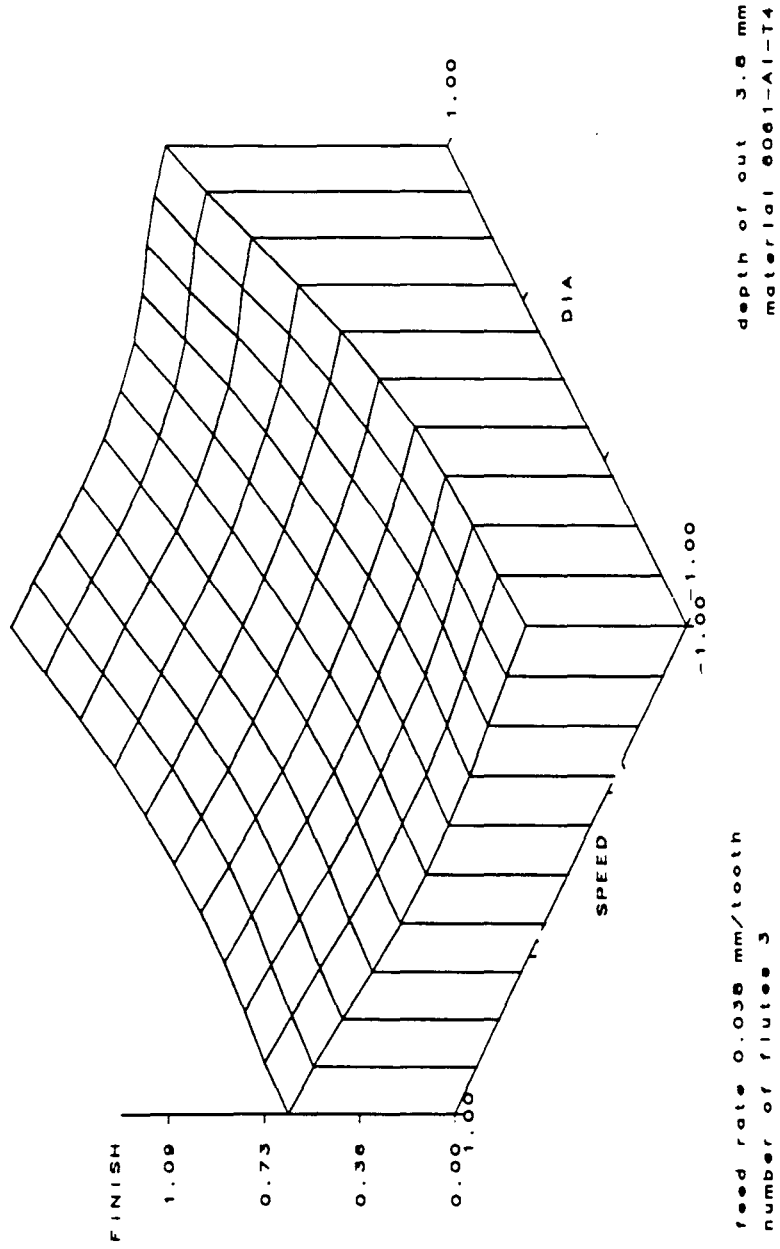
Figure 5.8: Variation of Surface Finish with Cutter Diameter and Cutting Speed
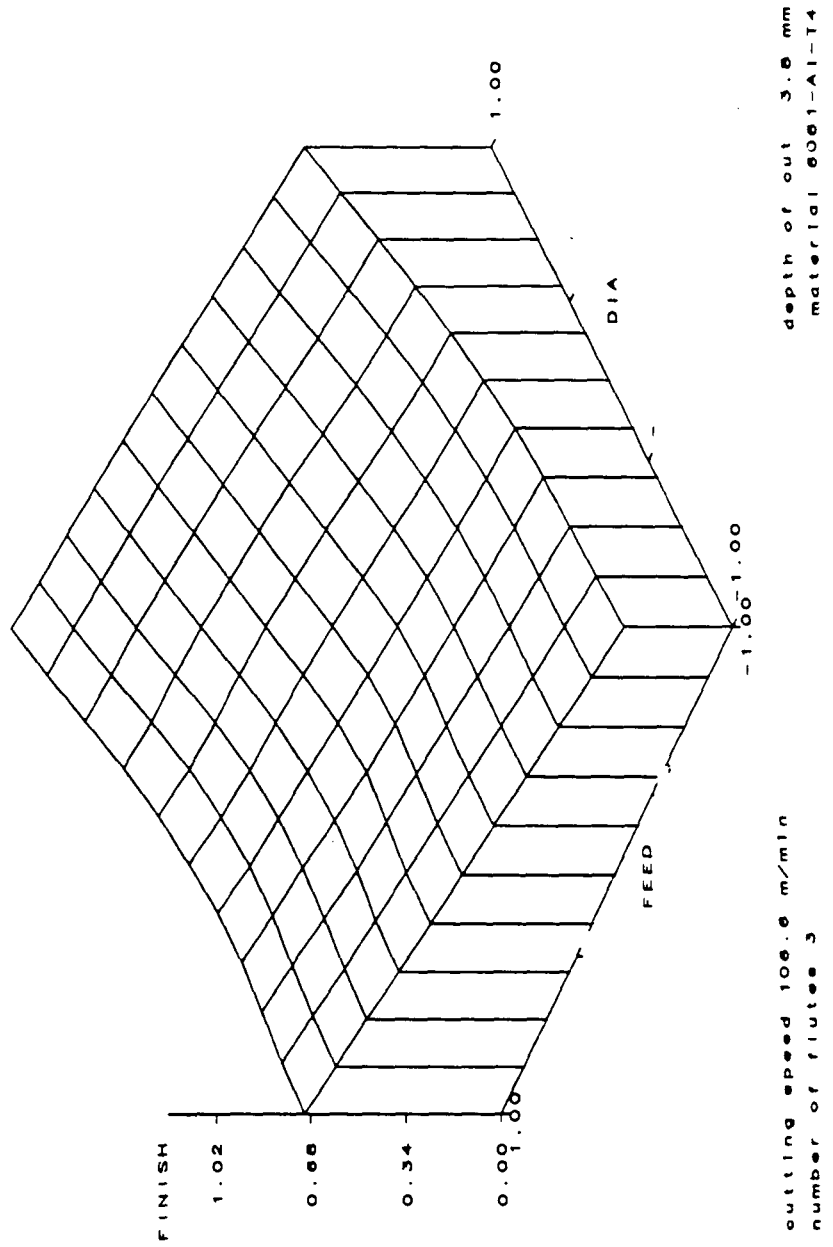
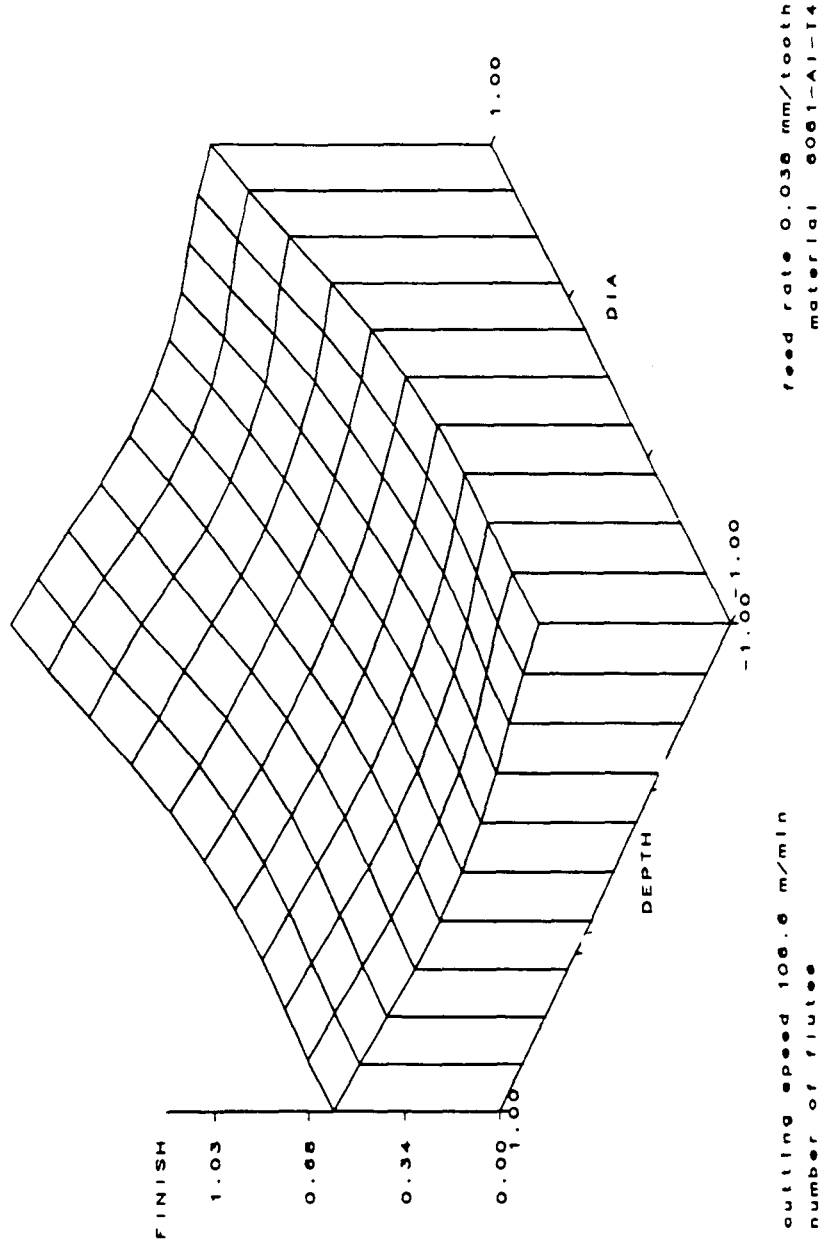Figure 5.9:   Variation of Surface Finish with Cutter Diameter and Feed Rate

Figure 5.10:   Variation of Surface Finish with Cutter Diameter and Depth of Cut

tool interface increases, and when this becomes large enough to cause shear fracture in the vicinity of the tool edge, a built-up edge is formed. The built-up edge forms very easily as the material becomes more ductile. Nakayama et al. (1966) studied the built-up edge extensively, and gave the following ways of eliminating or reducing the size. (1) Increase the cutting speed (2) Make materials less ductile, since brittle materials do not form a built-up edge and (3) Use cutting fluid. For a material such as Aluminum, which is a good conductor of heat, the tool-chip interface temperature could be very crucial in the formation of a built-up edge and could also have an effect on the surface finish of the workpiece. This matter needs to be studied further.

### 5.3.7 Variable Interactions

It was observed in the present work that high speeds and low feed rates resulted in very good surface finish as indicated in Figure 5.2. The cutting speed and depth of cut interaction is interesting. Rough surfaces are produced at low cutting speeds and depths of cut as well as at high cutting speeds and depths of cut. Very smooth surfaces are produced at intermediate values of speed and depth of cut as in Figure 5.3. The choice of depth of cut is a trade off between the metal removal rate and the surface finish.

As the feed rate and the depth of cut reach their extreme values, the surfaces become rougher. At low values of feed rate and intermediate values of depth of cut, the surface finish obtained is very high. For any given depth of cut, surfaces become rougher with an increase in feed rate as in Figure 5.3. Likewise, for any given feed rate, extreme values of depth of cut generate rougher surfaces, and intermediate values of depth of cut produce a good surface finish. The influence of the number

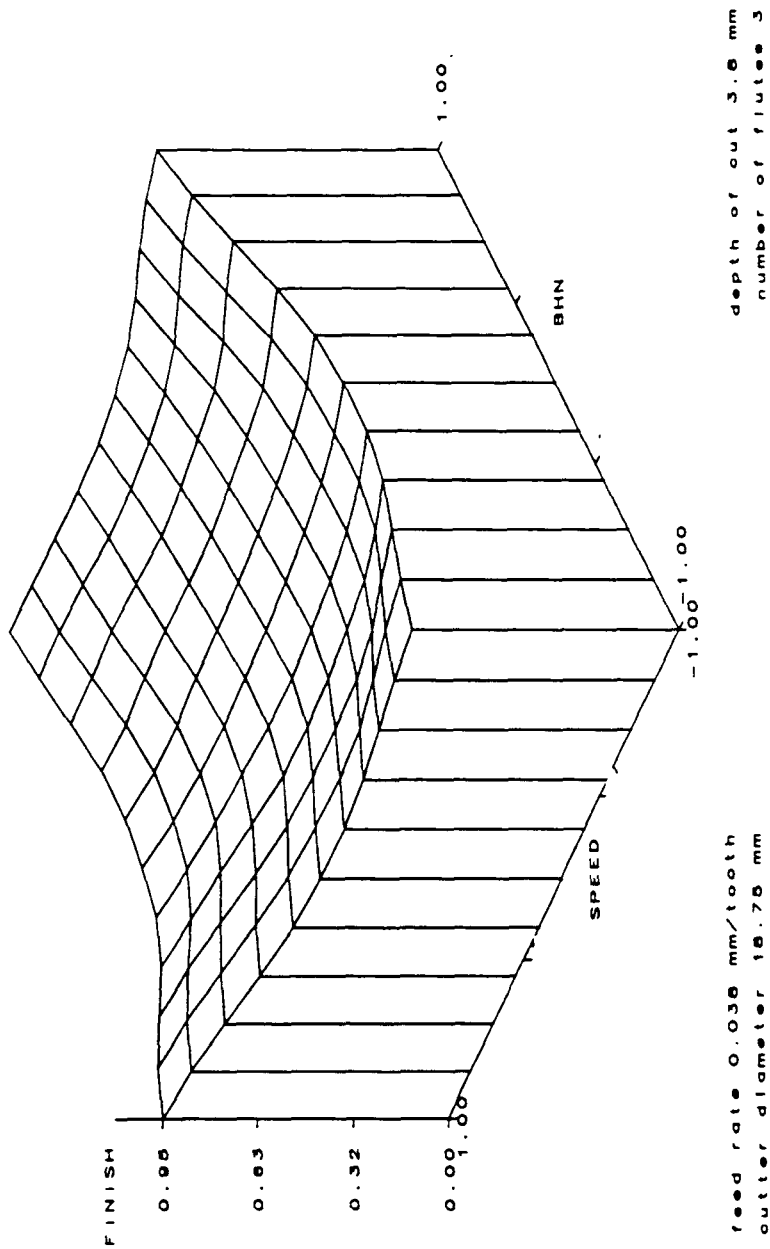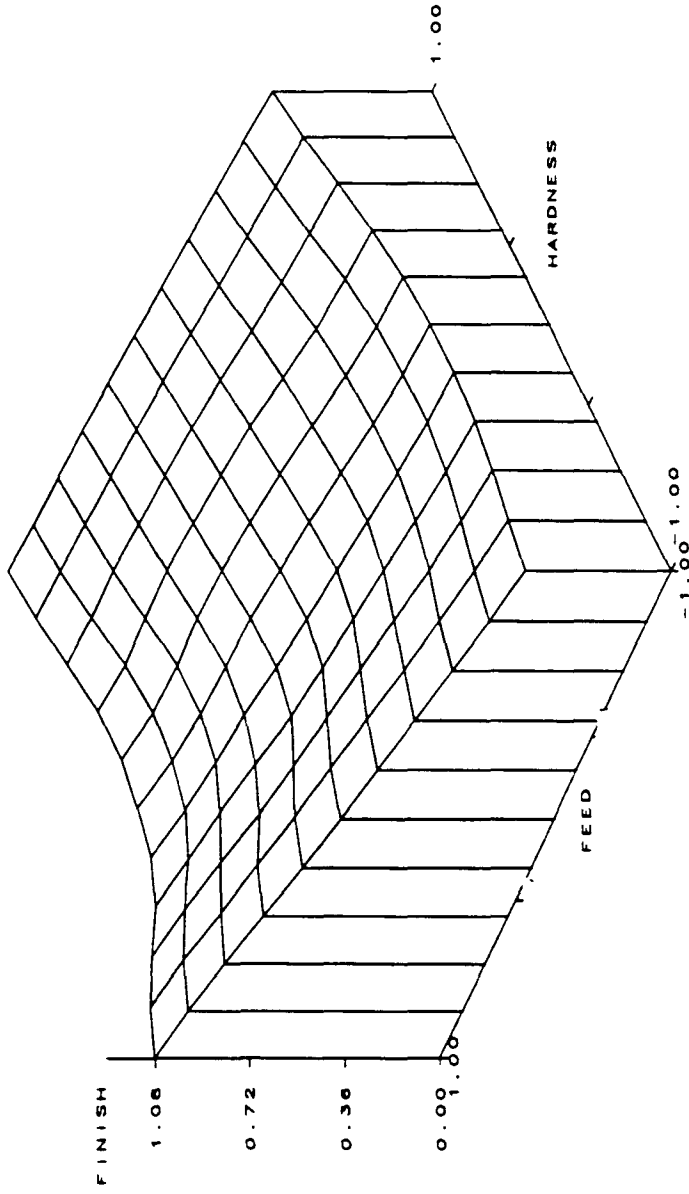CUTTING SPEED AND HARDNESS INTERACTION



Figure 5.11: Variation of Surface Finish with Workpiece Hardness and Cutting Speed

FEED RATE AND WORK PIECE HARDNESS INTERACTION



cutting speed 106.6 m/min
number of flutes 3

depth of cut 3.8 mm
cutter diameter 15.76 mm

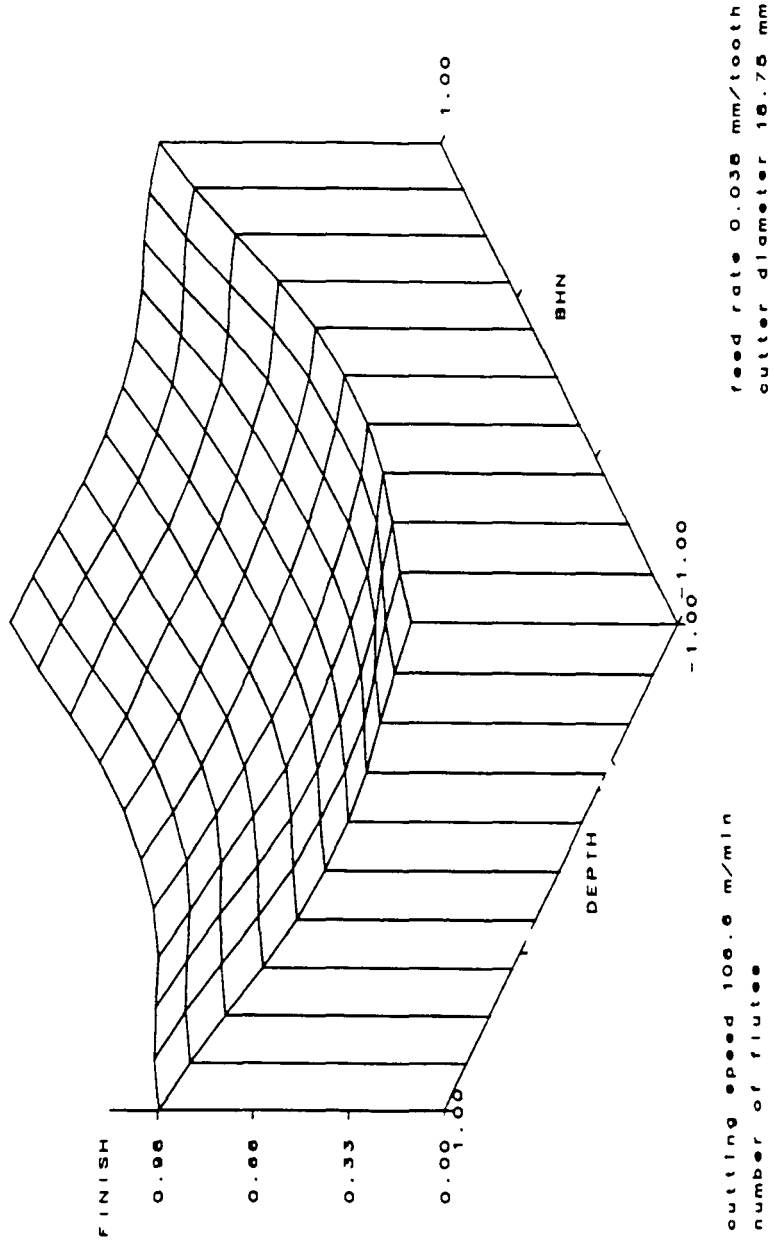DEPTH OF CUT AND WORK PIECE HARDNESS INTERACTION



Figure 5.13:  Variation of Surface Finish with Workpiece Hardness and Depth of Cut
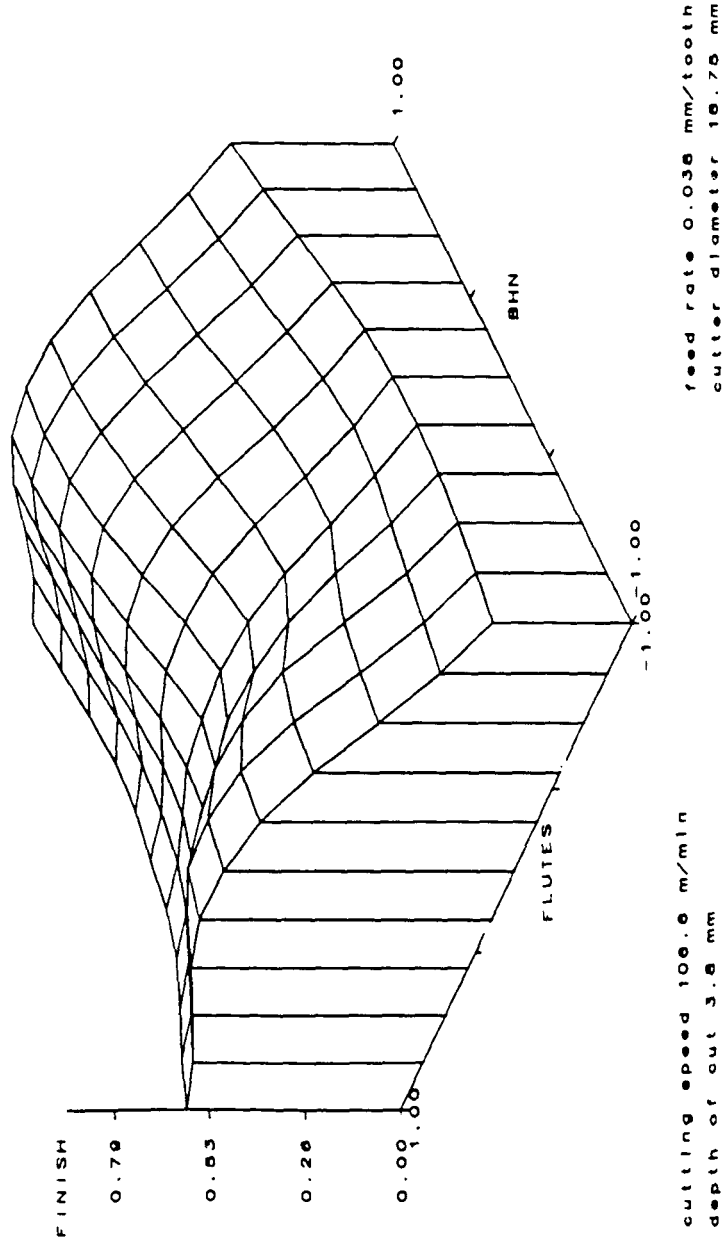
NUMBER OF FLUTES AND WORK PIECE HARDNESS INTERACTION



cutting speed 100.0 m/min
depth of cut 3.8 mm

feed rate 0.038 mm/tooth
cutter diameter 18.75 mm

Figure 5.14:  Variation of Surface Finish with Workpiece Hardness and Number of Flutes

CUTTER DIAMETER AND WORK PIECE HARDNESS INTERACTION



cutting speed 106.6 m/min          feed rate 0.036 mm/tooth
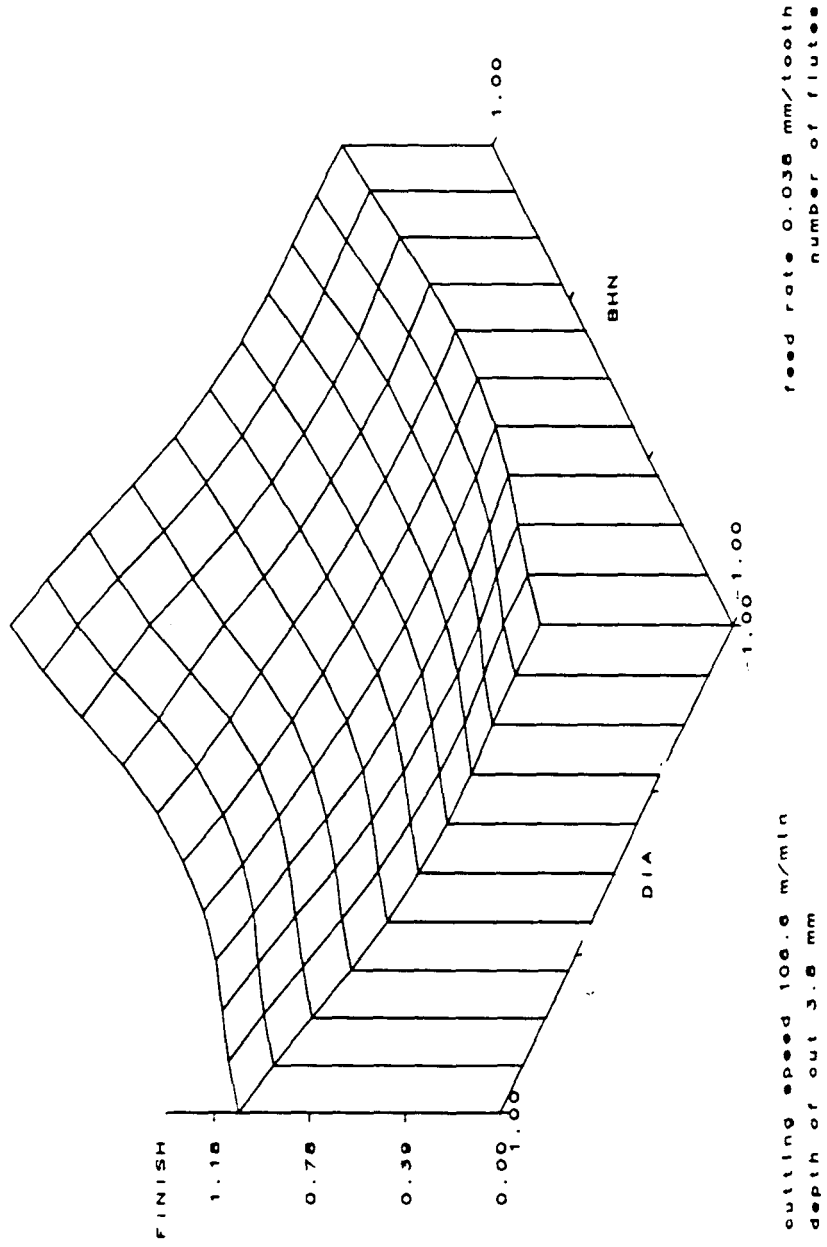depth of cut 3.8 mm                 number of flutes

Figure 5.15: Variation of Surface Finish with Workpiece Hardness and Cutter Diameter

of flutes is consistent, irrespective of the feed rate, depth of cut, and the material hardness. Two flute end mills produce the smoothest surfaces, followed by four flute and three flute end mills. At higher feed rates, the surface finish values obtained by two flute and four flute end mills tend to become equal as in Figures 5.4 thru 5.7.

Larger cutter diameters produce rougher surface finish regardless of the other cutting parameters and the work piece hardness as indicated in Figures 5.8 thru 5.10. Similarly annealed workpieces have rougher finishes as shown in Figures 5.10 thru 5.15.

# 6. CONCLUSIONS

The major objective of this research was to develop a model that would predict the surface finish of end milling on Aluminum 6061, and compare the predicted values to validate the model. This chapter summarizes the result as related to the objectives set and proposes recommendations for future research.

## 6.1 Summary of Conclusions

The effect of parameters: cutting speed, feed, depth of cut, cutter diameter, number of flutes, and workpiece hardness on the surface finish of Aluminum 6061 was studied. A vertical Machining center was used to perform the experiments and a stylus tracer instrument was used to measure the surface finish. The number of experiments were arrived at using the Box and Behnken (1960) of experiments. The data obtained were analyzed for the variance and lack of fit and a second order polynomial was fit. The interactions of various parameters were studied and certain important trends observed. The important conclusions drawn from this research are:

1. It is possible ofpredict the bottom surface finish obtained in a slot milling operation by center cutting end mills. A second order polynomial sufficiently predicts the surface finish for a six variable, three level experiment.

2. The equation developed has a high regression coefficient and passed the lack of fit test. This adequately describes the effect of speed, feed rate, depth of cut, cutter diameter, number of flutes, and workpiece hardness on the surface finish of Aluminum.

3. Surface finish improves with an increase in the cutting speed and is consistent with other research efforts. Over the speed range of data for Aluminum, surface finish improves to a certain speed and further increase deteriorates surface finish.

4. Surface finish deteriorates with an increase in feed rate and is inversely proportional to the square of the feed rate.

5. Surface finish is inversely proportional to the workpiece hardness for Aluminum. The main reason is attributed to the formation of built-up edge.

6. Surface finish improves for a small increase in depth of cut but beyond a critical value, the surface finish deteriorates.

7. Results for three flute end mill surface finish is not consistent with published results. Three flute end mills generate rougher surfaces while two/four flute end mills produce better surface finish.

8. Larger diameter cutters produce rougher surfaces.

## 6.2   Recommendation for Future Work

The mathematical model developed to predict the surface finish in end milling operation is for a specific material: Aluminum. The model sufficiently described the

behaviour and interaction of various parameters. However, this effort is only a beginning and further research is needed to develop an overall mathematical model that includes different materials, and varied operating ranges for the cutting parameters. It is suggested here that future research could focus on the following areas:

1. Different workpiece materials such as carbon steel, alloy steel, and Ti-6Al-4V could be used to study the effect of cutting parameters on the surface finish. A general purpose mathematical model can be developed to take into consideration, the cutting parameters, material characteristics, tool geometries, and others. This could lead to a better understanding of what interaction is important and may describe the end milling process more precisely.

2. Surface finish can be affected by varied factors. Cross feed of the cutter between passes may contribute to the overall surface finish. The effect of programmed high frequency changes in cross feed as well as axial feed could yield important information. Further experimentation introducing these superimposition can be attempted.

3. The current problem of not being able to reason the poor surface finish of a three flute end mill in comparison to a two/four flute end mill can be investigated. A carefully designed experiment incorporating all the geometric parameters of the cutting tool and the forces on the workpiece/cutting tool can lead to a good mathematical model. This model can help explain the results obtained in this research.

4. If and when a general purpose model is developed, we could utilize the model to predict surface finish for new materials and also study the concept of " inverse

engineering " - that of obtaining cutting parameters given the surface finish. One of our long term goals is to research inverse engineering further and this effort will hopefully act as a precursor.

# 7. REFERENCES

American Society of Mechanical Engineers. 1985. Surface Texture (Surface roughness, waviness, and lay). *ANSI/ASME B 46.1.*

Babin, T. S., J. M. Lee, J. W. Sutherland, and S. G. Kapoor. 1985. A model for End Milled Surface Topography. pp 362-368. *Proceedings of the North American Manufacturing Research Conference.* Dearborn, Michigan: Society of Manufacturing Engineers.

Boothryod, G. 1975. Fundamentals of Metal Machining and Machine Tools. New York: *McGraw-Hill Publishers.*

Box, G. E. P., and D. W. Behnken. 1960. Some New Three Level Designs for the Study of Quantitative Variables. *Technometrics,* 2: no.1:455-475.

Chandiramani, K. L., and N. H. Cook. 1964. Investigation on the Nature of Surface Finish and its Variation with Cutting Speed. *Journal of Engineering for Industry,* 86: 134-140.

DeVor, R. E., and W. A. Kline. 1980. A Mechanistic Model for the Force System in End Milling with Application to Machining Airframe Structures. pp 297-303. *Proceedings of the North American Manufacturing Research Conference.* Dearborn, Michigan: Society of Manufacturing Engineers.

DeVor, R. E., J. W. Sutherland, and W. A. Kline. 1983. Control of Surface Error in End Milling. pp 356-362. *Proceedings of the North American Manufacturing Research Conference.* Dearborn, Michigan: Society of Manufacturing Engineers.

Dickinson, G. R. 1968. A Survey of Factors Affecting Surface Finish. *Proceedings of Conference on Properties and Metrology of Surfaces.* pp 135-147. Dearborn,

Michigan: Society of Manufacturing Engineers.

Ema, S., and R. Davies. 1988. Cutting Performance of End Mills with Different Helix Angles. *International Journal of Machine Tools Manufacturing*, 29: 217-227.

Fischer, H. L., and J. T. Elrod. 1971. Surface Finish as a Function of Tool Geometry and Feed - a Thereotical Approach. *Microtechnic*, 25: 175-178.

Grieve, D. J., and H. Kaliszer. 1968. The Effects of Cutting Conditions on Bearing Area Parameters. *Proceedings of the IX International Machine Tool Design and Research Conference.* pp 989-1004. Fairfield, NewJersey: American Society of Mechanical Engineers.

Karmar, A. 1970. Factors Influencing Surface Finish During Fine Turning. *Proceedings of IV All India Machine Tool Design and Research Conference.* pp 123-128. Calcutta, India: Institution of Engineers.

Kline, W. A., R. E. Devor, and I. A. Shareef. 1982. The Prediction of Surface Accuracy in End Milling. *Transactions of the American Society of Mechanical Engineers*, 104: 272-278.

Martellotti, M. 1941. An Analysis of the Milling Process. *Transactions of the American Society of Mechanical Engineers*, 63: 677-700.

Miller, J. C., R. E. DeVor, and J. W. Sutherland. 1983. Surface Roughness Characterstics for Turning 380 and 390 Aluminum Casting Alloys. pp 282-288. *Proceedings of the North American Manufacturing Research Conference.* Dearborn, Michigan: Society of Manufacturing Engineers.

Mittal, Anil., and Mehta, Manish. 1988. Surface Finish Prediction Models for Fine Turning. *International Journal of Production Research*, 26: 1861-1876.

Nakayama, K., M. C. Shaw, and R. C. Brewer. 1966. *Annals of CIRP*, 14: 211.

Shaw, M. C. 1965. Optimum Selection of Machine Tool Speeds and Feeds. *International Journal of Machine Tool Design and Research*, 5: 25-34.

Sundaram, R. M., and B. K. Lambert. 1981. Mathematical Models to Predict Surface Finish in Fine Turning of Steel, Parts I and II. *International Journal of Production Research*, 19: 547-564.

Sutherland, J. W., and R. E. DeVor. 1986. An Improved Method for Cutting Force and Surface Error Prediction in Flexible End Milling Systems. *Journal of Engineering for Industry*, 108: 269-279.

Takeyama, M., and T. Ono. 1966. Study on Roughness of Turned Surfaces. *Bulletin of Japan Society of Precision Engineering*, 1: 274-279.

Wong, W. C., and Middleton, D. 1984. On the Estimation of Parameters for a Nonlinear Model of a Milling Process. *International Journal of Production Research*, 22: 247-252.