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A study of machining parameters to optimize surface finish in metal cutting through CNC

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ABSTRACT

Title of Thesis: A study of machining parameters to optimize surface finish in metal cutting through CNC

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The purpose of this thesis is to find the relationship between surface finish and machining parameters. A series of experiments have been performed at shop floor of NJIT, on MAZAK(CNC turning center), using two different cutting tool materials(high speed steel and cemented carbide) and a workpiece of Aluminium. The results have been then evaluated and analyzed to see the effects of various combinations of cutting conditions, that is, feed, speed, and depth of cut. Recommendations have been made on the basis of analysis to estimate the minimum and maximum values of surface roughness with respect to the cutting conditions for Aluminium using HSS tool and Carbide tool for a specific surface finish.

A STUDY OF MACHINING PARAMETERS TO OPTIMIZE SURFACE FINISH IN METAL CUTTING THROUGH CNC

by

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Dedicated to my parents

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INTRODUCTION

In manufacturing products, it is important that the processes involved be efficient and capable of producing parts of acceptable surface finish quality.

Improved surface finish is one of the major objectives in metal cutting. For high quality products surface quality is commonly specified along with dimensions.

A precise dimension usually means a good surface. The quality of a surface often determines how well a part performs. It is very important that metal cutting principles be well understood in order to have application to produce parts of acceptable surface finish quality. The surface finish of a part depends on many factors such as feed, speed, and depth of cut which are known as cutting conditions in metal cutting. The choice of the proper tool, feed, speed, and depth of cut is a compromise, since the faster a machine is operated the higher the efficiency of both operator and machine. Unfortunately, however, such accelerated use greatly shortens the life of the tool. The objective of this thesis is to study surface finish characteristics in order to determine how surface finish is affected by cutting conditions.

For this study a series of experiments was performed on the shop floor of NJIT. By varying the cutting conditions, surface roughness data was recorded and then was analyzed.

After the analysis of data, recommendations are given for cutting conditions relevant to specified tools and work material. The focus is upon the estimation of the minimum and maximum values of surface roughness measurements as determined by feed, speed, and depth of cut.

CHAPTER 1

INTRODUCTION TO METAL CUTTING

1. INTRODUCTION

The objective of this chapter is an introduction to the basic concepts of metal cutting theory. The importance of metal cutting may be realized by considering the total cost associated with this activity, including tool cost, labour cost, and cost of capital investment.

Today metal cutting is a very large segment of industry. The automobile industry, electrical engineering, railways, shipbuilding, aircraft manufacture, production of domestic equipment and the machine tool industry itself have large scale application of metal cutting [19].

Metal cutting is a very major industrial activity, employing tens of millions of people throughout the world. The wastefulness of turning so much metal into low grade scrap has directed attention to the methods of reducing this loss. Much effort has been devoted to the development of ways of shaping components in which metal losses are reduced to a minimum.

Progress in the technology of machining is achieved by the ingenuity and experiment, the intuition, logical thought of many thousands of practitioners engaged in many-sided arts of metal cutting[19]. The worker operating the machine, the tool designer, the lubrication engineer, the metallurgist, are all constantly probing to find answers to new problems

in the form of limitations on the speed, feed, and depth of cut to produce parts of good surface finish quality[19].
It is what happens in a very small volume of metal around the cutting edge that determines the performance of tool, the machineability of metals and alloys and the qualities of machined surface.

1.1 METAL CUTTING

Metal cutting commonly called machining, is the removal of the unwanted material from a workpiece in the form of chips so as to obtain a finished product of desired size, shape and finish [1]. Over the past eighty years, the process has been the object of considerable research and experimentation, which has lead to improved understanding of the nature of both the process itself and the surfaces which are produced by it [1]. The problem of getting specified surface finish is complicated by tool geometry variations, wide variety of tool materials used in the process, temperature or heat problems, and the great variations in operating condition of the machines performing this process [9].
Most of the machining is done with cutting tools. A cutting tool is a hardened piece of metal or other material, with a cutting edge that cuts the metal. Four things determine the way a machine tool cuts the metal and produces a desired surface roughness [14].
1. The kind of material in the workpiece.

2. The kind of material in the cutting tool.
3. The shape of the cutting tool.
4. The action of the cutting tool on the material being cut.

The above factors determine the kind of chip that will be formed which is very important because The chips show that whether the cutting tool is correctly ground to shape and sharpness required for the job to obtain good surface finish.

1.2 OBJECTIVES IN METAL CUTTING

The purpose of machining by cutting is to give workpiece the desired shape and dimensions of necessary accuracy, as well as to ensure that the surface layer of the workpiece has the desired surface finish quality. This purpose should be achieved in a most economical way.

Therefore, the main objectives in the field of metal cutting are [12].

1. Reduction of material losses:

Reduction of material losses concerns both the machined material and the tools. In connection with this aim there arises the task of reducing the machining allowances to the limits of a theoretical minimum. Even minor improvements in productivity are of major importance in high volume production.

2. Improvement of the quality of the machined products:

This means in particular the attainment of the necessary accuracy of shape and dimensions, as well as the optimization of the cutting cycle time and to produce products of greater useful life with good surface finish quality.

3. Raising of output and reduction of the labour:

This means an increase in the rate of production and production of greater number and variety of products and improvement of work safety and comfort. In particular, the task of automation belongs here, especially use of program-controlled machining.

4. The widening of machining possibilities:

This requires the improvement of the machineability of materials and the development of new methods, ways and types of machining and improvement of the existing ones.

1.3 BASIC MACHINING DEFINITIONS AND CALCULATIONS

The three most widely used cutting operations are:

1.3.1 TURNING

This basic operation as shown in figure (1-a) is also the one most commonly employed in experimental work on metal cutting. The work material is held in the chuck of a lathe and rotated [8]. The tool is held rigidly in a tool post and moved at a constant rate along the axis of the bar, cutting away a layer of metal to form a cylinder or a surface of more complex profile.

1.3.2 DRILLING

Drilling produces a hole in an object by forcing a rotating drill against it as shown in figure (1-b). The same can be accomplished by holding the drill stationary and rotating the work, such as drilling on a lathe with the work held and rotated by a chuck [2].

1.3.3 MILLING

The milling operation as shown in figure (1-c) is a metal removal process using a tool with one or more teeth rotating about a fixed axis, each tooth removing material from work piece fed past the tool [2].

For each of the machining processes, there are certain parameters, called cutting conditions, that are used to control the process and to achieve the desired results. The parameters are called the speed, feed, and depth of cut and are shown in figure (1-d).

1.3.4 CUTTING SPEED

The cutting speed can be defined as the maximum linear speed between the tool and the work piece [1]. The cutting speed for drilling, and milling can be determined as a function of the work piece or tool diameter, D, and the rotational speed, N. It can be calculated by the following expression.

V = (Đ*D*N)/12

Where

V = Speed, feet per minute

D = Diameter, inches (of cutter)

N = Rotational speed, RPM

Also in machining operations involving rotation (of tool or workpiece), feed expressed in in/rev might have to be converted to feed rate in in/min. The feed rate can be calculated by the following expression

Fr = (N*f)

where

Fr = Feed rate in in/min

f = Feed in in/rev

1.3.5 DEPTH OF CUT

The depth of cut is determined by the width of the chip. During roughing operation, the depth of cut is usually much greater than for finishing operation. For turning operation, it is one half the difference between inner and outer diameter of the workpiece [2]. It can be calculated by the following expression.

A_p = (Do - Di)/2

where

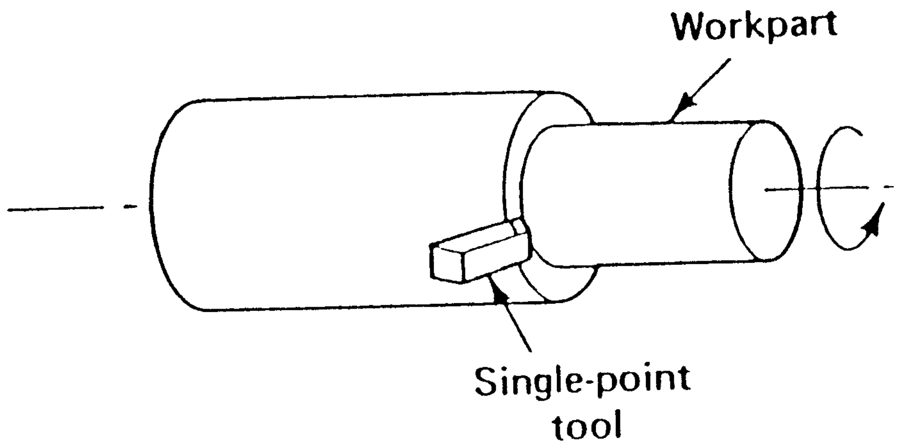
A_p = Depth of cut

Do = Outer diameter, inches

Di = Inner diameter, inches

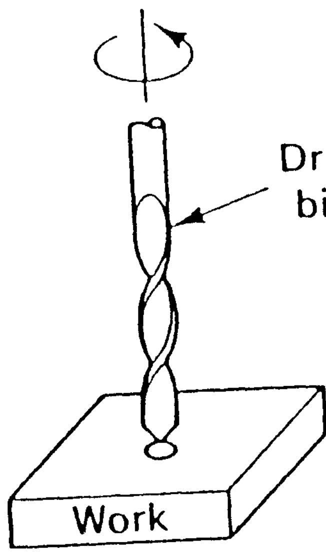
1.3.6 METAL REMOVAL RATE

It is a measurement of how fast material is removed from a workpiece. It can be calculated by multiplying the cross-sectional area of the chip by the feed rate [3]. A large MRR produces a short processing time, and a low MRR yields a long processing time. How ever MRR also affects the tool life of a cutter. Its unit is cubic inches per minute.



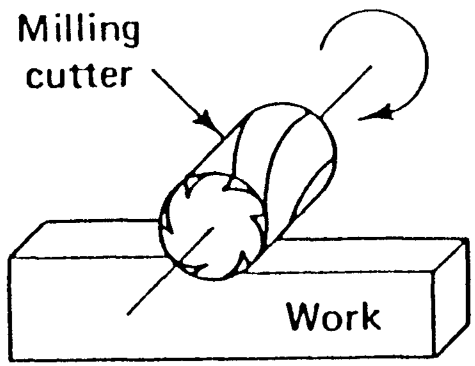
Turning Operation

Fig.1-a



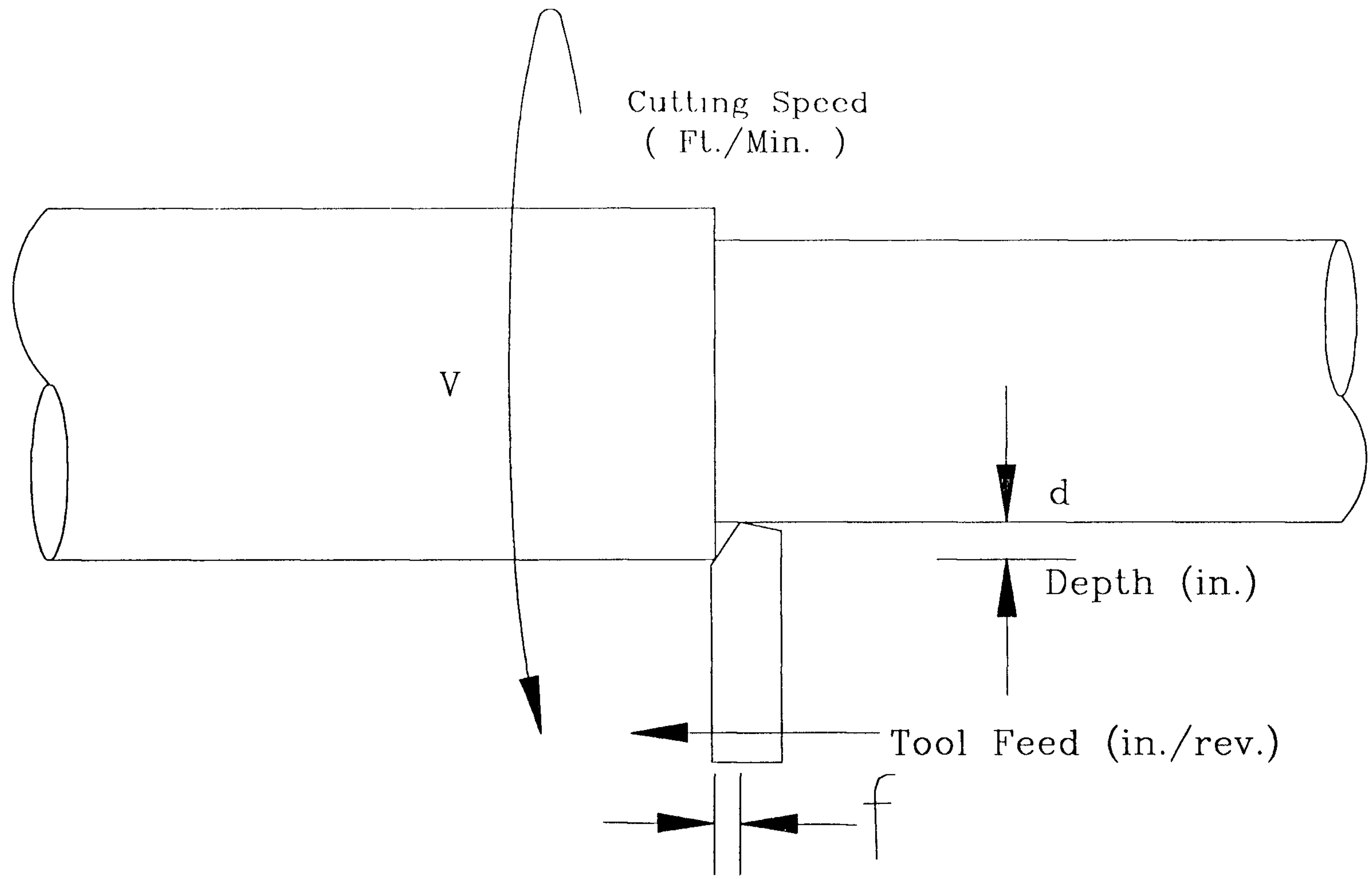
Drilling Operation

Fig.1-b



Milling Operation

Fig.1-c



Cutting Conditions for a Cutting Operation

Fig.1-d

For drilling the cross-sectional **area** of the chip is

(Đ*D^2)/4

therefore,

MRR = (Đ*D^2/4)*(Fr)

Where D = Drill diameter

Fr= Feed rate, in/min

Since

Fr = (f*N) and

N = (12*V)/(Đ*D) So

MRR = (Đ*D^2/4)*(f*N) = (Đ*D^2/4)*(f)*(12*V/Đ*D) =(3*D*f*V)

For turning chip width is (Do - Di)/2

the cross-sectional area is (Đ/4)*(Do^2-Di^2), so

MRR = 6(Do-Di)*(f*V)

1.3.7 MACHINING TIME

It is the total amount of time it takes to finish a workpiece. Machining time is a function of workpiece size, depth of cut, feed and speed. It can be calculated by dividing the tool path length by the feed rate. The tool path length is determined by the length of the workpiece, overtravel of tool for clearance, and number of passes required to clear the volume. For drilling, one pass turning and milling [3].

Tm = (L+l)/Fr

Where

Tm = Machining time, minutes

L = Hole depth, inches

l = Clearance height or over travel, inches

Fr= Feed rate, in/min

1.4 FUTURE TRENDS IN METAL CUTTING

With dramatic change on both factory floor and in purchasing, its a new challenge out there for distributors and manufacturers of metal cutting tools in metal cutting industry to produce parts of good surface finish quality[6]. The rush to automate and improve surface finish quality has pressed manufacturers to produce higher quality tools. This coupled with the trend in purchasing to reduce vendors, has led customers to sign on only with those manufacturers who have the technical expertise to excel in this new environment [6]. Manufacturers who can meet the technical demands of metal cutting industry have a tremendous opportunity ahead of them.

1.5 ROLE OF TECHNOLOGY

Without question, technology is driving change in the metal cutting industry. The new CNC machine tools turn out increased production runs with more uniform surface finish quality, and these machines need better, more efficient cutting tools to achieve their potential and justify much higher purchase prices. CNC machining now allows automatic machining of parts. This leads to unmanned machine in a factory environment [4]. Under these circumstances, the metal cutting tools must be reliable and of consistent quality and dimensions, be able to run at higher speeds, feeds and depth of cut while giving good surface finish quality.

CHAPTER 2

CUTTING TOOL MATERIALS

2. INTRODUCTION

In nearly all machining operations, cutting speed and feed are limited by the capability of the tool material. Chip formation involves high local stresses, sliding friction and abrasion, and considerable heat generation [1]. Speed and feed must be kept low enough to provide for a minimum acceptable tool life. If not, the time lost changing tools may cause a decrease in the productivity gains due to increased cutting speed. Today's machining centers have evolved into the most versatile and flexible of all metal cutting machines and the push to speed production cycles has also affected basic machine design [5]. Modern machines are moving toward ever higher spindle speeds and axis feed rates which require the cutting tools to be more reliable and perform well in a wide range of cutting conditions.

There are several characteristic that a satisfactory tool material must possess. These include:

2.1 HOT HARDNESS

The hardness of a material is a measure of its resistance to indentation, and is one of the most significant properties [11]. The hardness of the tool must be appreciably greater than that of the workpiece material to enable the tool to maintain its ability at the high temperatures developed at the tool/chip interface [12]. This item becomes increasingly important as the speed of the cutting operation is raised. Cutting tool material must be able to penetrate other materials.

2.2 WEAR RESISTANCE

The welding and strain hardening characteristics of the tool relative to those of the metal cut must be such that excessive wear does not occur in the operating range of the speed.

2.3 LOW FRICTION

The co-efficient of friction between the chip and the tool should be as low as possible in the operating range of the feed and speed [8]. This consideration is important not only from the standpoint of tool wear, but particularly with regard to surface finish.

2.4 TOUGHNESS

Toughness is also desirable to withstand shocks and resist fracture. Cutting tools must work upon many kinds of metals and under a variety of conditions. There is no single tool material which is best with regard to all of these considerations. The relative importance of each item will shift with [9]:

The nature of the product machined, the volume of production, type of machining operation (roughing or finishing, high or low speed etc.) the tool design details(cutting and clearance angles etc.), and physical characteristics of work material.

present day production or metal cutting demands on the machine tool. To accomplish the many conditions imposed upon them, a wide variety of tool materials have been developed. The best material to use for a certain job is the one that will produce the machined part at the lowest cost with desirable or less machine cycle tome. The principal materials used in metal cutting are as follows.

1. Carbon steels(or tool steels)
2. High speed steels
3. Cast tool alloys
4. Cemented carbides
5. Ceramics
6. Diamond

The cutting tool materials used in the experiments are high speed steel and cemented carbide. Therefore high speed steel and carbide are discussed below.

2.5 CARBIDE TOOLS

The evolution of cutting tool materials from one family to another has, with each succeeding development, made it possible to perform metal removal operations on harder workpiece materials at increasing speed. An advancement in metal cutting was introduced with the development of cemented carbides, also called sintered carbides or carbides which, again, made higher speeds possible and improved cutting efficiency [10]. Carbides are composed of very hard particles held together by a metallic bond. The primary ingredient is tungsten carbide in most commercial tools, but it is often mixed with various amounts of tantalum, titanium, and columbium carbides to improve resistance to abrasion and lower the co-efficient of friction [1]. Cemented carbides have an initial high cost but are economical for machining parts in large quantities. Carbides are made in number of grades by varying the size and proportion of the carbide particles and the amount of binder. Carbides are classified by machining applications as C-1 through C-8 as shown in table 2-1 [10].

Table 2-1

Abrasion Resistant Grades	**Crater and Deformation Resistant Grades**
C-1 roughing	C-5 roughing
C-2 general purpose	C-6 general purpose
C-3 finishing	C-7 finishing
C-4 precision finishing	C-8 precision finishing

Machining Applications of Cemented Carbides

The grade used in the experiments is C-3. Previously, most cutting tool materials, depended largely upon heat treatment for their properties which could be destroyed by further heat treatment. At higher speeds, and consequently high temperatures, these products failed [10].

However, cemented carbide cutting tool materials have different(and inherent) hardness properties. Carbide is harder than most other tool materials at room temperatures and can retain its hardness at higher temperatures so that faster cutting speed can be withstood [1]. Higher operating speed is probably the most dramatic contribution of the cemented carbides to a machining operation, but they also allow machining of harder materials. Because of these desirable characteristics, the carbides have assumed an important role in the metal cutting industry.

2.5.1 TUNGSTEN CARBIDES

The term "tungsten carbide" describes a comprehensive family of hard carbide compositions used for metal cutting tools. In general, these materials are composed of the carbides of tungsten, titanium, or tantalum(or some combination of these), sintered or cemented in a matrix binder, usually Cobalt. As cutting tool materials, the tungsten carbide base materials can be separated into two types. First, and most common, is the simple two-phase type consisting of tungsten carbide with a cobalt binder (WC-Co) which falls into the C-1 through C-4 categories [10]. If the metal removal operation causes tool wear primarily by abrasion, the two-phase type is most effective because it is characterized by extreme hardness and excellent resistance to abrasive wear. On the other hand, if the workpiece material causes tool wear primarily by cratering the rake face, the alloyed grades C-5 through C-8 must be used [10]. In these grades, WC-Co is alloyed with additional carbide, usually tantalum carbide (TaC), titanium carbide (TiC), or both. This additional alloying delays crater development on the top face of the tool. The effects of composition on the properties of cemented carbides may be summarized as follows [10]:

1) Increasing Co content contributes to lower wear resistance, lower hot hardness, lower thermal deformation, and lower crater resistance. Higher Co content does, however, increase strength.

2) TiC increases the wear resistance, hot hardness, resistance to thermal resistance, but decreases the strength.

3) TaC increases the hot hardness, resistance to thermal deformation, and crater resistance. however, it decreases wear resistance and strength.

Other properties of cemented carbides are

2.5.2 IMPACT STRENGTH

Imact strength values for cemented carbides are another indication of their resistance to mechanical shocks. Almost a linear relationship exists between impact strength and Co content; the greater the Co content, the greater the impact strength [1].

2.5.3 MODULAS OF ELASTICITY

The modulas of elasticity (or resistance to bending under load) of cemented carbide alloys is extremely high, two to three times that of steel [11]. This property is of prime importance which contribute to the success of WC-Co as a cutting tool material. Because of its high elastic modulas, deflection under cutting loads is minimized. This property makes carbide useful in tool shanks or tool holders.

2.5.4 COMPRESSIVE STRENGTH

The carbides are characterized by extremely high compressive strength values. As with other properties, this property is influenced most by cobalt content, and increases with increasing Co content in the lower ranges to a maximum at approximately 4 percent cobalt by weight, then decreases with additional amounts of cobalt [8].

2.5.5 THERMAL CONDUCTIVITY

The thermal conductivity of cemented carbides is high, two or three times that of high speed steel

2.6 HIGH SPEED STEEL TOOL

The introduction of high speed steel made possible, a significant increase in machining speeds, which accounts for its name. However, today high speed steel is general material for use in machining operations. The chief characteristics of these steels is superior hot hardness and wear resistance [9]. The first tool steel that would hold its cutting edge to almost a red heat was developed by Fred

W. Taylor and white in 1900 [12]. This was accomplished by adding 18% tungsten and 5.5% chromium to steel as the principal alloying elements [12]. Present-day practice in manufacturing high-speed steels still uses these two elements in nearly the same percentage. Other alloying elements are vanadium, molybdenum, and cobalt [10]. The high speed steel used in the experiments is super high speed steel which has cobalt added to high speed steel in amounts ranging from 2 to 15 percent, since this element increases the cutting efficiency, especially at high temperatures.

2.7 FUTURE TECHNOLOGY

The cutting tool materials in use today are the result of significant advances in materials technology. Within a period of less than 50 years, commercial cutting tools have evolved from carbon tool steels through high speed steels, cast cobalt-base alloys, and cemented carbides to ceramics [23]. The materials in each of these categories have been steadily improved by modifying compositions and by optimizing processing techniques. Improvements of these commercial products continue, and research and development groups are exploring entirely new classes of tool materials at an accelerated pace.

Several factors are responsible for the development of advanced tool systems [10]:

1. Good surface finish quality is being used as a marketing strategy nowadays, which has resulted in the customer

becoming more conscious of quality. Most of the companies realize that one of the keys to a high quality is good surface finish. Quality is so important to the customer today that product sales can be hurt on the basis of customer's perception of quality alone. Even the best machine tools can not alone make every unit exactly the same. Better surface finishes can be followed by new cutting tools offering lower cost, better performance, or both. Thus the luxury of improved surface quality soon becomes the necessity which has become one of the major business advantage.

2. The increasing widespread use of the automated machine tools and systems which require a high degree of reliability and longer tool life.

2.8 HI-TECH CUTTING TOOL REQUIREMENTS

Research activities on the next generation of tool materials are guided by knowledge of the extreme conditions of stress and temperature produced at the tool/workpiece interface. Pressure in excess of 100,000 psi and temperatures above $2000^{o}F$ are generated during the more severe cutting operations [10]. Tool wear proceeds by one or more complex mechanisms which include abrasive wear, mechanical chipping of the cutting edge, thermal cracking, plastic deformation, oxidation, and indiffusion between tool and workpiece. Since most of these wearing processes are greatly accelerated by increased temperatures, the more obvious requirements for new tool materials are improvements in physical, mechanical, and chemical properties at elevated temperatures [12]. Today's cutting tool materials encompass a wide range of properties. The high speed steels possess bend strengths in excess of 600,000 psi., but they become very soft at temperatures above 1200^{o}F [10]. Ceramic tools retain useful hardness at temperatures above 1700^{o}F but their bend strength (at room temperature) is less than 100,000 psi [10]. In order to develop tools capable of withstanding more severe rough cuts, the tougher types of tool materials(high speed steels) must have considerably greater hot hardness with loss of strength at elevated temperatures. The harder types of tool alloys(cemented carbides and ceramics) will require greatly increased toughness, or a significant improvement in mechanical properties at elevated temperatures, to increase effectively the cutting efficiency. It appears that such improvements can not be obtained by minor modifications of tool alloy compositions. Instead, major changes in alloy chemistry and entirely new compositions along with nonconventional processing methods are being explored in order to achieve a major breakthrough.

CHAPTER 3

SURFACE FINISH

3. INTRODUCTION

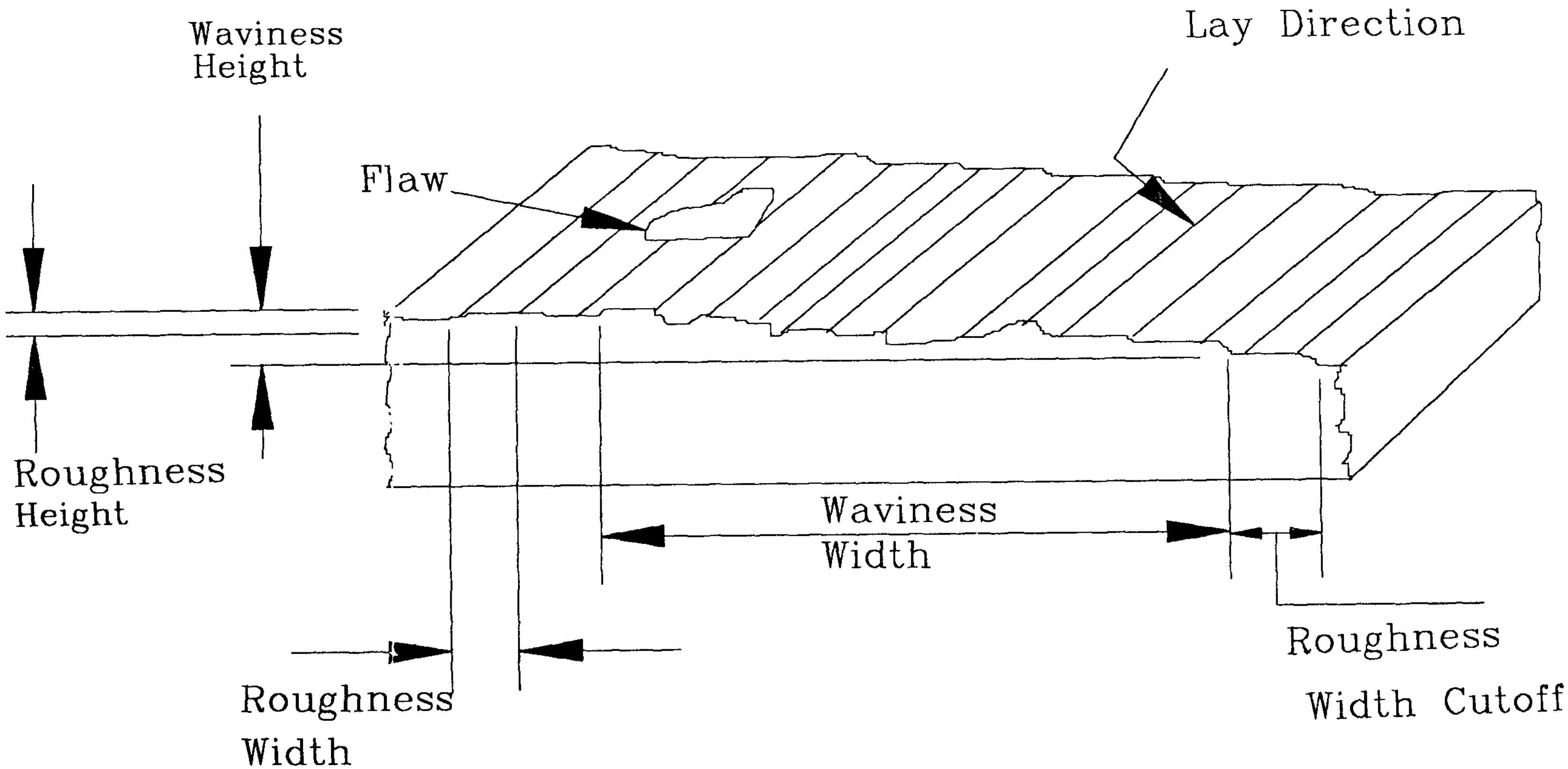
Table 3-1 shows a turning operation from the point of view of a system. Here a number of inputs are listed together with important internal items and outputs. The outputs are most important since they represent the end goal of the operation. The integrity of the machined surface is frequently one of the most important outputs [8]. Surface integrity is a term that involves surface roughness which is very important for machining operations. The growing influence of surface roughness can be traced to dramatic changes in manufacturing specifications and tolerances over the past few decades. The ability to measure and control surface roughness is assuming ever-greater importance in today's machining operations, not only in terms of part quality but in many other aspects as well. Surface finish affects how a part fits and wears, how it reflects light, transmits heat, distribute a lubricant or accepts a coating [13]. On mating parts, all surface irregularities have significant and prolonged effect on wear and performance. The classic case is the piston and cylinder in which imperfect surfaces can cause the mating parts to heat up, bind and freeze, possibly even explode [13]. Where a surface finish is important, a finishing operation is usually involved. In addition to surface roughness, other kinds of deviations from a perfectly smooth surface can occur. These deviations are called surface flaws and waviness as shown in figure (3-a). Surface flaws are widely separated irregularities that occur at random over the surface. They may be scratches, cracks, or similar flaws. Waviness is a form of regular deviation where the wavelength is greater than a specified magnitude(usually about 1mm) [8].

Roughness is a finer irregularity than waviness. A further term used in surface measurement is lay. The lay of a surface is the direction of the predominant surface pattern and is usually determined by the machining method used to produce the surface. Measurements of a surface are made at right angles to the lay.

TABLE 3-1

INPUTS	MACHINE	OUTPUTS
Workpiece	Force	Parts/Cost
Tools	Energy	Parts/Time
Motions	Temperatures	Required Geometry
Control	Wear	Surface Integrity
Fluids	Vibration	

Inputs, Outputs, and internal items in the machining system when metal are cut.



Surface Flaws and Waviness

Fig.3-a

3.1 SURFACE ROUGHNESS

The surface roughness obtained during a practical machining operation may be considered as the sum of two independent effects [22].

1. The " Ideal " surface roughness, which is the result of the geometry of the tool and feed or speed.

2. The " Natural" surface roughness, which is a result of the irregularities in the cutting operation.

3.1.1 IDEAL SURFACE ROUGHNESS

The ideal surface roughness represents the best possible finish which may be obtained for a given tool shape, feed, speed and depth of cut and can only be approached if built-up edge, inaccuracies in machine tool movement etc. are eliminated.

3.1.2 NATURAL SURFACE ROUGHNESS

Natural surface roughness forms a large portion of the actual roughness. One of the main factors contributing to natural surface roughness is the occurrence of a built-up edge [22]. The built-up edge may be continuously building-up and breaking down, the fractured particles being carried away on the under-surface of the chip and on the new workpiece surface. Thus it would be expected that the larger the buildup edge, the rougher would be the surface produced, and factors tending to reduce chip tool friction and to eliminate or reduce the build-up edge would give improved surface finish. Such factors would therefore be, the application of the correct cutting fluid, a change from HSS tool material to cemented carbide etc.

Other factors which commonly contribute to natural surface roughness in practice are [20]:

1. Vibration of the machine tool.
2. Irregularities in the feed mechanism.
3. Defects in the structure of the workpiece material.
4. Discontinuous chip formation when machining brittle materials.
5. Surface damage caused by chip flow etc.

Thus a good surface finish is affected by many variables in turning which are type of chip formation, friction, cutting fluids, vibrations, tool geometry, round nose tools, and most important are the cutting conditions, that is speeds, feeds, and depth of cut. The above factors are discussed below:

3.2 TYPES OF CHIP FORMATION

Before discussing the affect of type of chip formation on surface roughness it is necessary to describe the kinds of chips and what build-up edge is.

3.2.1 CHIPS

Chips are a waste product of the cutting process. The surface finish in machining operations will depend on the type of chip formation also, therefore the types of chips have been discussed ahead.

The main objective of machining is the shaping of new work surface. Therefore, much attention is paid to the formation of chip. The consumption of energy occurs mainly in the formation and movement of chip, and for this reason, the main practical problems concerned with rate of metal removal and tool performance, can be understood only by studying the behavior of the work material as it is formed into the chip and moves over the tool [1]. Chip features characterize the machineability of the materials and determine the difficulty involved in their removal. Therefore it is better to understand also that what machineability is, which has been discussed later in this chapter.

3.2.2 CHIPS CLASSIFICATION

The chips resulted from metal cutting as shown in figure (3-b) are of three kinds:

3.2.2.1 DISCONTINUOUS(BROKEN) CHIPS

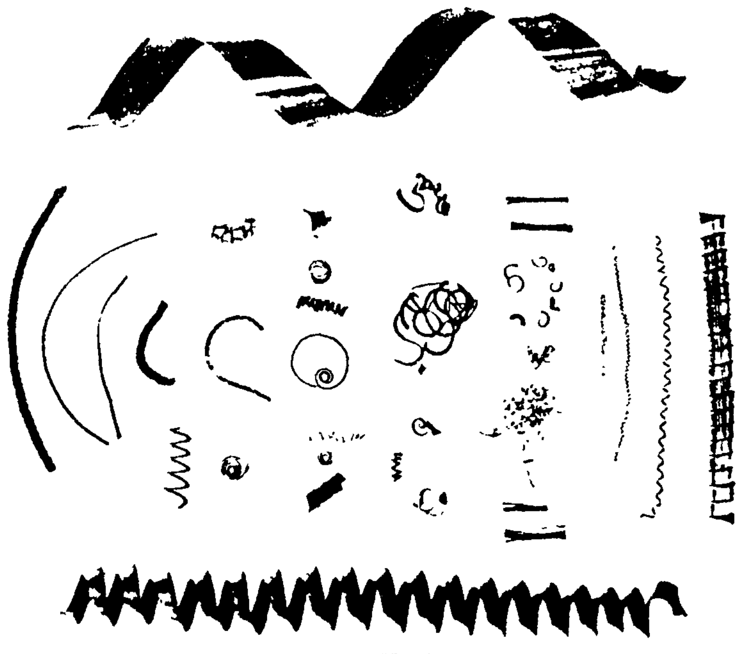
These are also called splintering chips. Brittle metal like iron or hard bronze produces small chips, each one separate from the previous one. The metal compresses in front of the cutting edge of the tool until it breaks away and the chip leaves the face of the tool [18]. This happens over and over again as long as the cutting goes on. Discontinuous chip formation can cause cracks to extend into the finished work surface and create force fluctuations which deflect the tool, forming ridges on the machined surface [21]. This type of chip formation can also cause vibrations which affect the surface finish.

3.2.2.2 CONTINUOUS CHIPS

These are also called ribbon chips or uniform chips. Metal is compressed in front of cutting edge. Then the metal begins to escape as a continuous (unbroken) chip. There is no build-up in front of the cutting edge. This is the ideal chip on ductile materials. In general continuous chips is the most desirable, since steady cutting conditions prevail, with little or no force fluctuations and their associated difficulties [18]. To a certain extent the Discontinuous chip can be changed to continuous chip by increasing the rake angle or using cutting fluids [12].

3.2.2.3 CONTINUOUS CHIP WITH BUILT- UP EDGE

Next to the tool face, first, the metal directly in front of the cutting tool becomes compressed. Soon the chip begins to form and flow away. Then small particles of metal from the workpiece anchor or lodge on the very point of the cutting tool. AS the compressed metal on the cutting edge builds up, this edge becomes larger and larger. Thus a build up edge is produced [14]. Finally this edge breaks away from the cutting tool. The fragments from the build up edge are torn off and escape with both the chip and the workpiece. This type of chip leads to similar problems as that faced by discontinuous chip since some of the fragments attach themselves to the workpiece itself, the surface becomes rough. This action goes on all the time while the cutting takes place. Soft or mild steel usually forms a continuous



Different Kinds of Chips

Fig.3-b

chip with build up edge when machined with high speed cutting tools [9].

3.3 FRICTION

Friction is the resisting force one surface experiences when it slides over another. The friction between chip, face of the cutting tool, and lubrication of this interface is of considerable importance in metal cutting. The surface finish of a machined surface is improved when the co-efficient of friction is decreased. This is due to decreased tendency to form a build-up edge as the cutting forces and the strain in the chip are decreased, both of which result when the co-efficient of friction is decreased [12]. In general friction may be reduced by:

1. Improved tool finish and sharpness of the cutting edge
2. Use of the low friction work or tool materials
3. Improved tool geometry
4. Use of cutting fluid

3.4 CUTTING FLUIDS

Liquids and Gases that are used in cutting operations are broadly referred to as cutting fluids. Cutting fluids, usually in the form of a liquid, are applied to the chip formation zone to improve the cutting conditions. The two most important ways in which a fluid can act are as a coolant and as a lubricant. Most practical cutting fluids have a mineral or vegetable-oil base, mineral oil being the more widely used. Some of these oils are made to be applied as an emulsion with water(water miscible cutting fluids), the remainder are used neat(undiluted with water) either plain or having various additives such sulphur, chlorine, or phosphorus [21]. In general the oil-and-water emulsions are used where the cooling action is most important requirement because these emulsions have a much larger heat conducting capacity than neat oils [22]. Neat oils are used when the lubrication action is most important consideration(at low speed cutting operations).

3.4.1 LUBRICATION IN METAL CUTTING

Under certain conditions the application of a lubricant to the cutting process can result in a reduction in friction on the tool face; this reduction of friction on the tool face can cause a reduction in power consumption, an increase in tool life, and, most important, an improvement in the surface finish of the machined component by reducing the build-up edge [12].

To be useful, a cutting fluid must assist in achieving these objectives [19]:

1. Increasing tool life
2. Improving the surface finish
3. Reducing the cutting forces
4. Reducing the distortion due to temperature rise in the workpiece
5. Facilitating the removal of chips

Usually the first two are considered the major reasons for applying the cutting fluid. The other three factors are not as important as the first two, how ever, in certain operations any one of these latter three can be of prime importance. For example, the finish on a component may be ruined because the chips are jamming around the tool. By driving these away with a jet of fluid, the finish may be made acceptable. The fluid used in the experiments is heavy duty water soluble oil WS5050. WS5050 is a multi purpose heavy duty, soluble oil formulated for the machining of all metals, especially high nickle alloys, Zinc, Aluminium, and stainless steel. Its ingredient are

1. Mineral oil
2. Emulsifier
3. Extreme pressure additives
4. Rust inhibitors
5. Anti foam agent
6. Bacteriacide
7. Fragrance and dye

3.5 VIBRATIONS

An important practical problem in metal cutting is vibration or "chatter." Chatter has three main adverse effects [18]:

1. It may produce imperfections on the work surface
2. It may increase the rate of wear of the tool
3. It may cause a high frequency sound at best is unpleasant and can be physically harmful to nearby personnel.

The principal causes of vibration are [20]:

1. Improper gear meshing.
2. Dynamic unbalance of rotating parts.
3. Bearing imperfections.
4. Faulty electrical or hydraulic controls.
5. looseness in slides and screws.
6. lack of rigidity.

Analysis of vibration in machining is not a simple matter. The machine tool, the cutting tool, and the workpiece form a complex system [17]. The vibration will involve the relative movement of the tool and the workpiece. Workpiece can move in almost any direction relative to the tool. Under vibrating conditions there may be fluctuations in

1. The cutting speed
2. Feed
3. Depth of cut
4. The inclination of the tool face to the workpiece surface(i.e fluctuations in the rake angles, clearance angles, cutting edge angles are possible).

The fluctuations in above parameters can cause a change in surface finish quality.

3.6 TOOL GEOMETRY

The role that a side and end cutting angles have upon the theoretical surface finish of a machined surface is shown in figure (3-c). Here, the maximum amplitude of surface roughness (h) is seen to be a function of feed, and the angles Cs and Ce as follows [17]

$h = f/\tan Cs + \cot Ce$

Where Cs and Ce are side and end cutting edge angles respectively. Thus theoretical surface finish increases linearly with feed and decreases with increased Cs or decreased Ce.

3.7 ROUND NOSE TOOLS

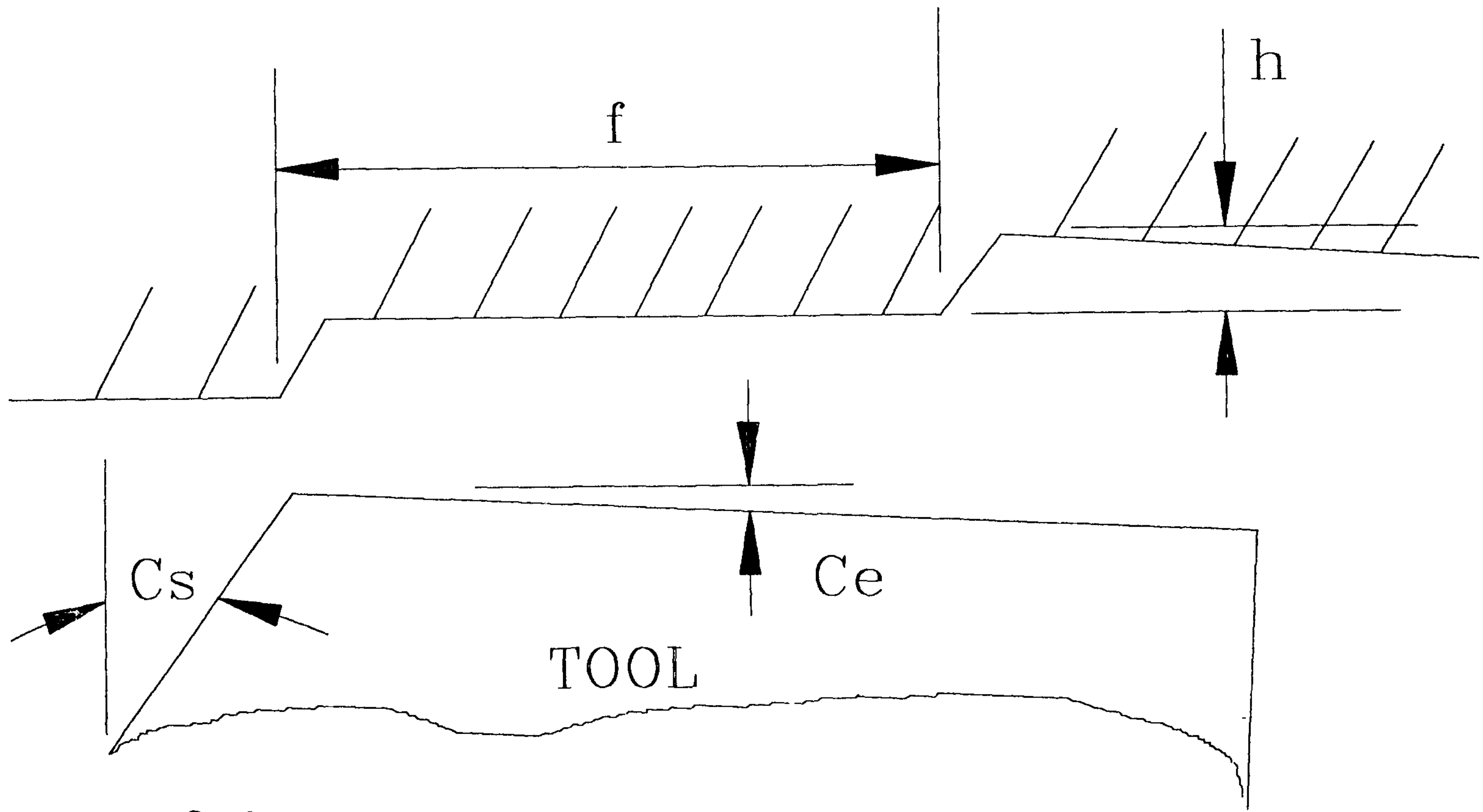
Nose radius of the cutting tool also affect the surface finish. When a large nose radius is present, it will influence the surface roughness. In figure (3-d) a tool is shown with such a large nose radius that all cutting occurs on the curved surface. For this case we have to a good approximation [18].

$$h = f^2/8r$$

for center line average(CLA), the roughness in this case is

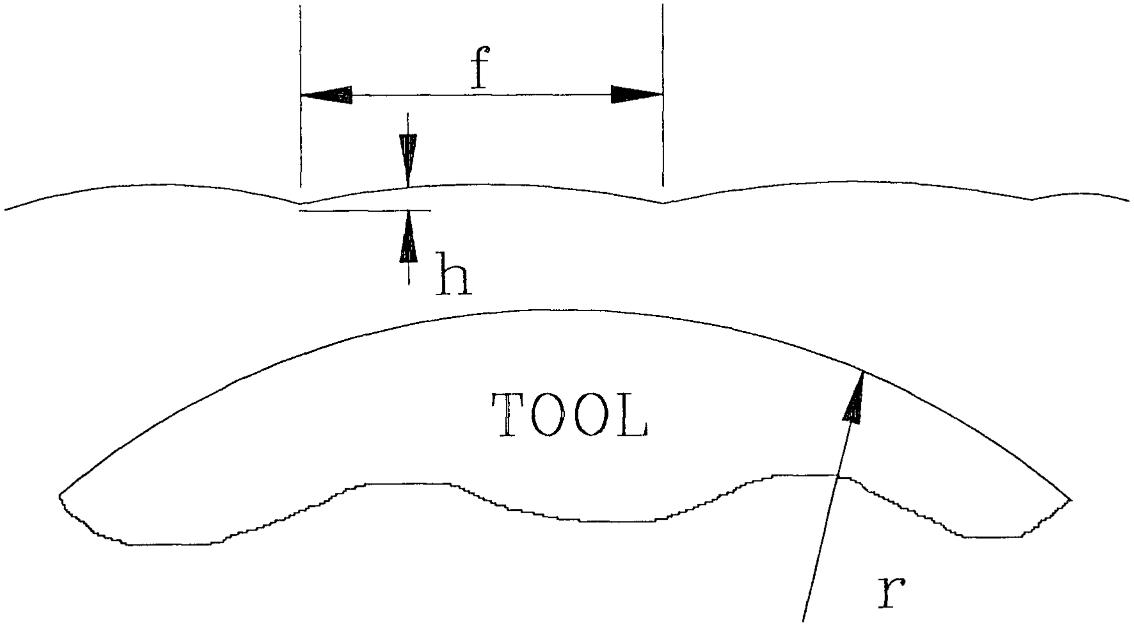
$$h = f^2/(31.177*r)$$

This above expression clearly shows that for a given feed, the surface imperfections decrease with increased nose radius. Thus nose radius play an important role in controlling the surface finish. The above expression gives the ideal surface finish values which can only occur when satisfactory cutting conditions are achieved. A nose radius is needed in all tools to strengthen the tool point. It is considered good practice to increase the radius as the depth of cut is increased, and a nose radius that is about 10% of depth of cut conforms to accepted practice [12].



Surface Produced by Lathe tool Without Nose Radius

Fig.3-c



Surface Produced by Lathe Tool Having Circular Plan

Fig.3-d

3.8 MACHINEABILITY

Machineability is a term that is often used and seldom fully explained. Initially it was thought that machineability was a property of the work material which in turn depended on other physical properties such as the hardness. The search for this material property which would indicate how machinable a material is, has eluded investigators for years. Therefore, a simple and accurate definition of this property has not evolved, and a unit of machineability is not available [15]. It is generally accepted that machineability is mainly concerned with assessing work materials. A material has good machineability if the tool wear is low or the tool life is long, the surface finish produced is good and the cutting forces are low. Further more, ease of chip disposal and good dimensional accuracy are also considered important. Hence, basically machineability is measured in three ways [20]:

1. Tool life
2. Surface quality of finished work
3. The cutting power required

The above are the machineability factors, and while machineability is not a mathematical equation, it is thought of as the combined result of these three factors.

Improvement of machining conditions and machineability requires analysis and understanding of the elements which enter into machining process. While machineability is divided into three measurable factors, the machining process, too, can be analyzed in terms of three major elements [19].

1. The behavior of the work material in cutting, that is, the ease or difficulty with which the chip is removed from the workpiece.
2. Operating characteristic of the machine tool.
3. The performance of the cutting tool itself, that is, the amount of wear on the cutting edge of the tool during cutting.

The workpiece material used in the experiments is Aluminium and its machineability characteristics are discussed below:

3.8.1 MACHINEABILITY OF ALUMINIUM

Alloys of Aluminium in general also rate highly in the machineability table by most of the criteria. In general, tool forces when cutting Aluminium alloys are low, and tend to decrease slightly as the cutting speed is raised, high forces occur, how ever, when cutting commercially pure Aluminium, particularly at low speeds. In general most Aluminium alloys, both cast and wrought, are easier to machine than pure Aluminium, inspite of its low shear strength [19]

A build-up edge is not present when cutting commercially pure Aluminium, but the surface finish tends to be poor except at very high cutting speed. The main machineability problems with Aluminium are in controlling the chips. Extensive plastic deformation before fracture occurs more readily with Aluminium [15]. The excellent machineability of Aluminium alloys in general makes them ideal work materials to be shaped in automated machine tools [23]. Completely automated production of certain classes of shapes can be introduced with confidence because long tool life and consistent performance can be guaranteed even at high rates of metal removal [19].

CHAPTER 4

DESIGN OF EXPERIMENTS

4. INTRODUCTION

Experimental studies have provided the momentum that has resulted in most of the major scientific developments throughout history. The efforts to determine the effect of cutting conditions on surface finish have been done with the help of data obtained after the experiments. The data obtained has been used to generate equations with the help of which optimization of surface finish measurements has been done as determined by feed, speed, and depth of cut.

In this age of multimillion-dollars space probes, the value of the experimental development has been adequately demonstrated. Therefore most engineering graduates become involved with experimental programs in their positions with industry. Thus, the importance of a complete understanding of experimental analysis can not be over-emphasized. All of the technological knowledge gained by experiments performed at shop floor of NJIT is profitable because it has resulted a workable product, that is, knowledge of surface roughness values estimation.

4.1 EXPERIMENTAL ANALYSIS

Experimental analysis is a program in which physical phenomena are evaluated. It is advantageous to consider experimental analysis in three parts [25].

1. Design and execution of the experiment
2. Design of the measurement system
3. Analysis of the data obtained

The design of the experiment was the first step for experimental analysis of experiments performed at shop floor of NJIT, because, the attainment of experimental goal was possible only if a well-thought-out initial design of experiments was developed. To be effective in any situation the problem being considered was clearly defined. Time spent in this effort was never wasted, If I had been uninformed I would have not been able to make contribution to the solution of the problem not understood. Once the problem was well defined, a complete search of the technical literature was made to develop a good technical background in the problem area. Finally the program parameters or variables, to be controlled, were considered.

4.2 PROBLEM STATEMENT

The problem or the objective of this thesis is the study of the effects of various combinations of cutting conditions on surface finish. An incomplete problem statement almost always results in an unsatisfactory solution.Therefore the overall problem was explicit, that is, the estimation of surface roughness values. The problem should define the ultimate goal sought and understanding the overall problem was essential if maximum effort towards its solution was to be realized. Any work without an ultimate goal is usually wasted. The ultimate goal of the experiments performed is the estimatiom of surface roughness measurements as determined by different cutting conditions.

4.3 ASSIMILATION OF TECHNICAL KNOWLEDGE

It was possible to solve the problem more easily and rapidly after the technical knowledge in the area of the problem had been developed. Most research began with a review of the literature associated with the problem being studied. Since I did not have a broad enough background on metal cutting to work on the problem, I had to search through lot of literature. This helped to develop my background in this area.

4.4 SELECTING THE CONTROL PARAMETERS

In any experimental program, all variables or parameters affecting the experiment should be listed. Then, the variables can be divided into classes of those that are to be maintained constant for a particular test and those that may vary [25]. In selecting the parameters to be controlled, it is important to include all variables that significantly affect the test being performed. The factors which affect the surface roughness are:

1. Speed 2. Feed 3. Depth of cut
4. Cutting fluid 5. Tool geometry 6. Workpiece material
7. Tool material

The first three variables are very important and they affect the surface finish significantly and can be controlled with very short time lost in change overs on "MAZAK" (CNC turning center). The other variables are also important but they are small factors and need time for changeovers which can result a reduction in production rate. Therefore these variables were kept constant. The three values, selected for each of the independent variables, that is, cutting conditions, were chosen to be extreme values so that the effect of these values is noticeable.

4.5 DESIGN OF EXPERIMENTS

The three independent variables selected are feed, speed, and depth of cut and the dependent variable is surface finish. By changing the independent variables, that is, feed, speed, and depth of cut, an Aluminium workpiece was turned on "MAZAK" (CNC turning center) at shop floor of NJIT and the corresponding surface roughness was measured. The three values selected for each independent variables are given below.

N1 = 500 RPM which gives S1 = 392.50 SFPM
N2 = 2000 RPM which gives S2 = 1570.80 SFPM
N3 = 3500 RPM which gives S3 = 2748.89 SFPM

feed = f1 = 0.001 in/rev
feed = f2 = 0.0025 in/rev
feed = f3 = 0.004 in/rev

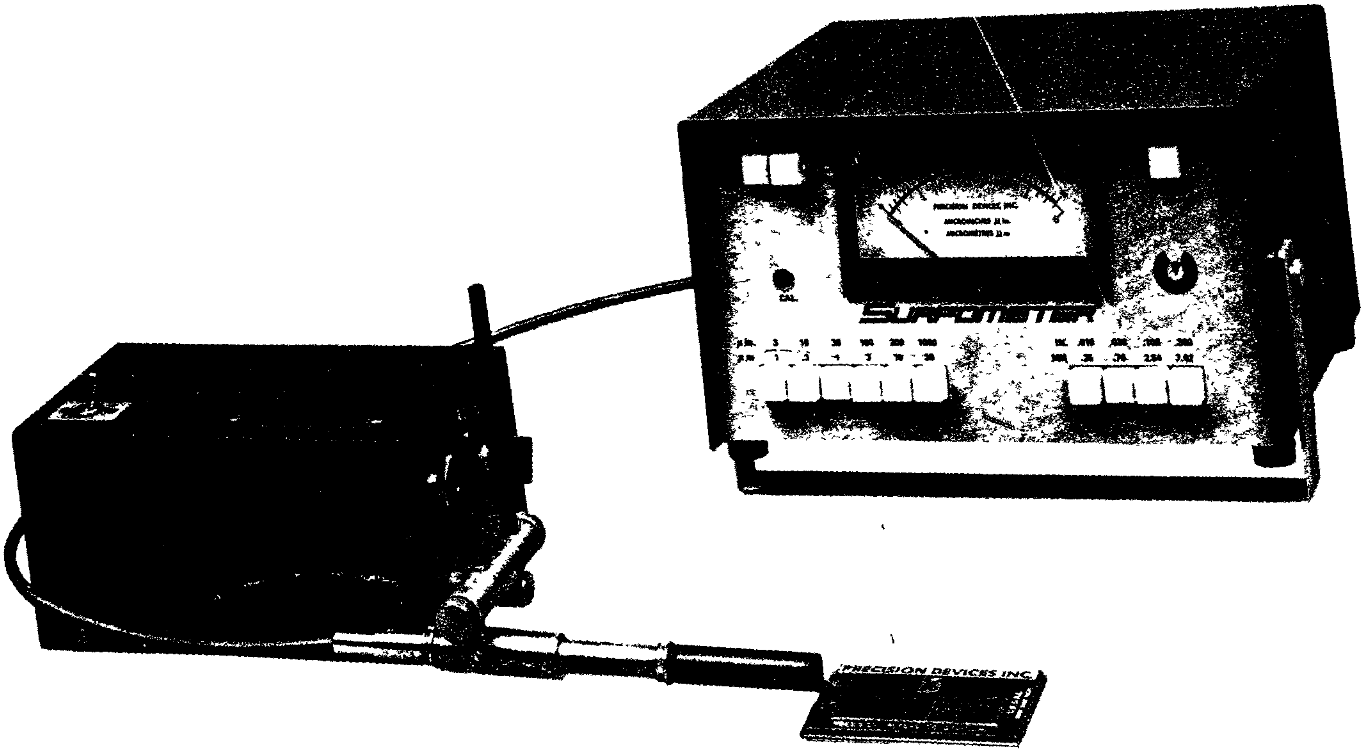
Depth of cut = A1 = 0.002 in
Depth of cut = A2 = 0.025 in
Depth of cut = A3 = 0.048 in

The number of experiments performed were (3*3*3) since the number of independent variables is three and each independent variable has three values. The twenty seven combinations for the above independent variables with their measured average surfaced roughness have been tabulated in reduced form in table 4-B. The sample size for each experiment is five which means (27*5=135) measurements were done using one type of tool material and one workpiece material that is, high speed steel and Aluminium which have been tabulated in table 4-A. The same experiments were conducted again with same cutting conditions except that the cutting tool material was changed to cemented carbide and the resulting data was tabulated in tables 4-C and in reduced form in table 4-D. Table 4-E shows the comparison of surface roughness obtained, with 27 combinations, using high speed steel and Carbide tool. The data to be analyzed have been tabulated in 54 tables from 1 to 54 which are enclosed in appendix for reference.

4.6 MEASUREMENT SYSTEM

The measurement system used for measuring the surface roughness after performing the experiments was Surfometer (available in material and processing lab of NJIT) which is a direct reading instrument for measuring the surface roughness. It is basically a stylus instrument that traverses a surface to be measured with a diamond stylus,

SURFOMETER



SURFACE MEASURING SYSTEMS

using the transducers to convert the vertical motion of the stylus into recorded traces. It includes a PDA amplifier, a model PDD motor drive, model PDK tracer with SMT skidmount, and a type PDL linkarm.

1. The PDA amplifier digital meter indicates the Ra average roughness height in microinches or micrometers. Ra or arithmetic average(AA) roughness is obtained by measuring the mean deviation of the peaks from the center line of a trace, the center line being established as the line above and below which there is an equal area between the center line and the surface trace.
2. The Pdd motor drive moves the tracer across the surface at the constant 0.3 in/sec. tracing speed.
3. The PDK tracer, with a 0.0004 inch diamond stylus, follow the surface irregularities and converts the vertical motion of the stylus to an electrical signal which is processed by a PDA amplifier.
4. The PDL linkarm connects the tracer to the PDD motor drive and is used to adjust the vertical height with respect to the surface being measured.

4.6.1 SET-UP AND OPERATION

Proper set-up procedure for the Surfometer is just as important as a working knowledge of its operation. There are certain steps which, if followed in proper sequence, make it easy to obtain accurate surface measurement readings [29].

1. Place the Surfometer equipment on a workbench isolated as much as possible from vibrating machinery and away from strong magnetic field(transformers, generators etc.)
2. Remove all accessories from storage compartment in rear of amplifier.
3. Install post in threaded hole at end of the motor drive ram and tighten with small, flat open end wrench.
4. Place PDL linkarm on post to approximately half way position and tighten locking thumbscrew.
5. Install tracer on linkarm and tighten threaded locking ring.
6. Attach tracer cord to linkarm and in proper receptacle at rear of PDA amplifier. Plug the amplifier and motor drive into A.C outlet.
7. Push amplifier power switch on. This completes the basic set-up.

4.6.2 AMPLIFIER CONTROLS

Before actually operating the Surfometer, it is necessary to be familiarized with pushbutton selections [29].

1. There are four range selections: 200 & 2000 microinch and 2 & 20 micrometer.
2. There are three cutoff selections: 0.010 inch, 0.03 inch, and 0.1 inch (0.25, 0.76, & 2.54 milimeters). The ANSI standard states that 0.03 inch cutoff is assumed unless otherwise specified.

3. The set-up/read switch: In the set-up position the digits are constantly changing as the roughness average changes. In the read position the average roughness value computed over one inch of length is displayed for a minimum of 2.5 seconds and then the meter blanks out for four seconds.

4.6.3 PUSHBUTTON SELECTION & READING THE METER

1. When reading the roughness values greater than 100 microinches it is recommended that the 2000 range is used.
2. When reading roughness values greater than 1.5 micrometers, use the 20 range.
3. Always use the 0.03 in cutoff unless otherwise specified.
4. The set-up/read switch should be in the set-up position when initial set-up is performed. After the PDD motor drive has been turned on, switch to read position.
5. Averaging starts at the beginning of the forward stroke. When the motor drive is turned off during the forward stroke, the reading will be reset to zero within 9 seconds. When it is shut off during the backward stroke, The reading will be retained until the next measurement is taken.

4.7 EXECUTION OF THE EXPERIMENTS

After all the planning of the experimental program was completed, the measurement system was selected, that is Surfometer as explained above. Then the experiments were performed on "MAZAK" (CNC turning center) at shop floor of NJIT and the resulting data was evaluated. The selection of the measurement system included all considerations necessary to establish an accurate value for the parameter to be measured. Measured values are meaningful only when they are properly collected and evaluated and it is always important to keep the measurement system as simple as possible while still accomplishing the required job.

HIGH SPEED STEEL TOOL

TABLE 4-A

R = Roughness, Y = Average Roughness
D = Standard Deviation, Unit = Micro inches

Sample Number	1	2	3	4	5	6	7
R1	11.8	9.70	11.6	8.8	13.2	13.4	12.4
R2	12.2	9.20	12.1	12.7	13.8	11.2	15.2
R3	12.0	10.70	11.8	12.5	13.9	11.7	12.6
R4	10.7	10.60	11.7	9.6	14.0	15.0	10.7
R5	9.2	8.40	9.2	9.0	13.7	12.4	9.6
Y	11.2	9.72	11.3	10.3	13.72	12.74	12.1
D	1.145	0.968	1.178	1.66	0.311	1.509	2.131

Sample Number	8	9	10	11	12	13	14
R1	29.2	28.3	9.3	7.6	10.9	13.4	12.8
R2	25.3	24.7	10.6	11.3	11.2	11.2	13.9
R3	27.0	24.3	9.8	10.5	11.6	10.5	13.2
R4	25.76	29.2	9.4	8.4	13.0	9.8	13.5
R5	25.5	23.5	8.1	11.7	9.8	10.7	13.1
Y	26.55	26.0	9.44	9.9	11.3	11.12	13.3
D	1.621	2.567	0.907	1.81	1.162	1.369	0.418

Sample Number	15	16	17	18	19	20	21
R1	12.9	11.2	24.4	27.7	11.5	10.7	13.9
R2	13.3	12.7	24.1	26.6	10.1	12.9	12.6
R3	12.2	14.2	23.1	26.2	9.8	11.9	10.9
R4	13.5	10.6	21.0	28.4	9.3	10.0	13.1
R5	12.8	9.8	21.36	27.1	11.9	12.4	11.2
Y	12.94	11.7	22.79	27.2	10.52	11.58	12.34
D	0.503	1.755	1.553	0.875	1.123	1.203	1.27

Sample Number	22	23	24	25	26	27
R1	11.4	15.2	16.2	10.7	23.6	28.3
R2	9.6	17.0	16.6	12.0	23.7	26.4
R3	10.0	15.76	16.3	13.8	25.8	27.6
R4	8.8	12.2	17.5	10.9	21.9	27.0
R5	12.4	12.6	15.1	12.4	23.9	25.6
Y	10.44	14.55	16.34	11.96	23.78	26.98
D	1.445	2.074	0.862	1.254	1.385	1.045

HIGH SPEED STEEL TOOL

TABLE 4-B

Exp. #	Speed(S) sfpm	Feed(f) in/rev	Depth of cut (A) inches	Average Roughness micro in
1	392.5	0.001	0.002	11.2
2	392.5	0.001	0.025	9.72
3	392.5	0.001	0.048	11.3
4	392.5	0.0025	0.002	10.3
5	392.5	0.0025	0.025	13.72
6	392.5	0.0025	0.048	12.74
7	392.5	0.004	0.002	12.1
8	392.5	0.004	0.025	26.55
9	392.5	0.004	0.048	26.0
10	1570.8	0.001	0.002	9.44
11	1570.8	0.001	0.025	9.90
12	1570.8	0.001	0.048	11.3
13	1570.8	0.0025	0.002	11.12
14	1570.8	0.0025	0.025	13.3
15	1570.8	0.0025	0.048	12.94
16	1570.8	0.004	0.002	11.7
17	1570.8	0.004	0.025	22.79
18	1570.8	0.004	0.048	27.2
19	2748.89	0.001	0.002	10.52
20	2748.89	0.001	0.025	11.58
21	2748.89	0.001	0.048	12.34
22	2748.89	0.0025	0.002	10.44
23	2748.89	0.0025	0.025	14.55
24	2748.89	0.0025	0.048	16.34
25	2748.89	0.004	0.002	11.96
26	2748.89	0.004	0.025	23.78
27	2748.89	0.004	0.048	26.98

* Note that the combination of independent variables in tenth measurement gives the best surface finish that is least surface roughness using HSS tool and Aluminium as the work piece material.

CARBIDE TOOL

TABLE 4-C

R = Roughness, Y = Average Roughness
D = Standard Deviation, Unit = Micro inches

Sample Number	1	2	3	4	5	6	7
R1	5.33	9.06	10.46	7.12	9.66	7.9	19.23
R2	5.60	7.40	7.46	6.76	5.20	8.0	17.03
R3	6.16	6.86	8.36	7.83	8.60	7.3	18.13
R4	5.46	5.40	6.76	6.83	6.50	8.9	18.66
R5	5.76	5.06	5.70	6.83	9.23	9.9	18.66
Y	5.66	6.76	7.75	7.08	7.84	8.39	18.35
D	0.323	1.617	1.803	0.444	1.912	1.92	0.83

Sample Number	8	9	10	11	12	13	14
R1	16.83	18.66	7.13	6.26	9.20	8.4	8.93
R2	16.20	16.13	6.63	6.63	4.70	8.5	7.86
R3	16.46	16.46	8.60	8.16	8.03	7.93	9.06
R4	15.56	15.83	6.66	7.30	5.70	7.93	9.90
R5	15.43	16.23	8.13	7.60	8.13	7.96	9.33
Y	16.10	16.66	7.43	7.19	7.15	8.14	9.02
D	0.594	1.141	0.89	0.758	1.874	0.28	0.744

Sample Number	15	16	17	18	19	20	21
R1	9.40	19.33	15.63	17.06	8.56	7.00	7.63
R2	6.13	17.90	17.0	16.36	8.33	7.76	6.50
R3	8.80	15.60	17.36	15.66	9.46	7.46	6.00
R4	6.16	16.93	17.03	15.80	8.50	5.80	7.36
R5	6.63	18.96	15.26	14.83	9.26	7.23	5.73
Y	7.42	17.74	16.46	15.94	8.82	7.05	6.64
D	1.555	1.52	0.942	0.832	0.505	0.756	0.831

Sample Number	22	23	24	25	26	27
R1	10.23	7.50	9.96	20.00	16.23	16.03
R2	9.86	8.70	6.86	18.96	15.80	15.06
R3	9.70	9.53	8.26	16.40	15.56	15.26
R4	10.23	7.93	7.56	18.83	15.06	15.20
R5	9.00	7.70	7.33	16.73	15.30	15.13
Y	9.81	8.27	7.99	18.18	15.59	15.34
D	0.507	0.838	1.210	1.550	0.452	0.395

CARBIDE TOOL

TABLE 4-D

Exp. #	Speed(S) sfpm	Feed(f) in/rev	Depth of cut (A) inches	Average Roughness micro in
1	392.5	0.001	0.002	5.66
2	392.5	0.001	0.025	6.76
3	392.5	0.001	0.048	7.75
4	392.5	0.0025	0.002	7.08
5	392.5	0.0025	0.025	7.84
6	392.5	0.0025	0.048	8.39
7	392.5	0.004	0.002	18.35
8	392.5	0.004	0.025	16.1
9	392.5	0.004	0.048	16.66
10	1570.8	0.001	0.002	7.43
11	1570.8	0.001	0.025	7.19
12	1570.8	0.001	0.048	7.15
13	1570.8	0.0025	0.002	8.14
14	1570.8	0.0025	0.025	9.02
15	1570.8	0.0025	0.048	7.42
16	1570.8	0.004	0.002	17.74
17	1570.8	0.004	0.025	16.46
18	1570.8	0.004	0.048	15.94
19	2748.89	0.001	0.002	8.82
20	2748.89	0.001	0.025	7.05
21	2748.89	0.001	0.048	6.64
22	2748.89	0.0025	0.002	9.81
23	2748.89	0.0025	0.025	8.27
24	2748.89	0.0025	0.048	7.99
25	2748.89	0.004	0.002	18.18
26	2748.89	0.004	0.025	15.59
27	2748.89	0.004	0.048	15.34

* Note that the combination of independent variables in tenth measurement gives the better surface finish with same metal removal rate than using HSS tool and Aluminium as the work piece material.

TABLE 4-E

R1 = Average surface roughness using high speed tool
R2 = Average surface roughness using carbide tool
MRR = Metal Removal Rate (in^3/min)
Unit of average surface roughness = micro inches

Experiment Number	R1	R2
1	11.20	5.66
2	9.72	6.76
3	11.30	7.75
4	10.30	7.08
5	13.72	7.84
6	12.74	8.39
7	12.10	18.35
8	26.55	16.10
9	26.00	16.66
10	9.44	7.43
11	9.90	7.19
12	11.30	7.15
13	11.12	8.14
14	13.30	9.02
15	12.94	7.42
16	11.70	17.74
17	22.79	16.46
18	27.2	15.94
19	10.52	8.82
20	11.58	7.05
21	12.34	6.64
22	10.44	9.81
23	14.55	8.27
24	16.34	7.99
25	11.96	18.18
26	23.78	15.59
27	26.98	15.34

Comparison of average surface roughness obtained corresponding to same cutting conditions using HSS tool and

Carbide tool.

4.8 DATA ANALYSIS

Data analysis is the basic vehicle by which the experimental program has been evaluated. This evaluation is necessary to determine if the complete analytical process of the total experiment results in a correct decision-making process. Our conclusions are based on the final analysis of the data with the help of a multivariate regression model, implemented through a software package, namely, Statistical Analysis for Engineers, a Computer-Based Approach (SAE).

4.8.1 MULTIVARIATE REGRESSION MODEL

Since a single independent variable is inadequate to describe the behavior of dependent variable, that is, surface roughness, a multivariate regression model has been chosen in which a dependent variable Y, surface roughness, has been described as a function of three independent variables, which are, feed, speed, and depth of cut. For this purpose Y, X1, X2, X3 is the notation for the above variables. It is our premise that variable Y can be predicted by means of polynomial estimation via the independent variables X1, X2, X3. The multivariate regression model is sequential. Initially, polynomial estimates are utilized to obtain optimization points for each triad (X1, X2, X3). Finally, these optimization points are utilized to establish an optimization plane in which all three independent variables X1, X2, X3 contribute to the estimated Y, that is, surface roughness, which is being optimized. The initial phase of polynomial regression, done separately for each Xi, is based upon the model

$Y = Bo + B1(X) + B2(X)^2 + B3(X)^3 + \text{-----} Bn(X)^n$ ———— (a)

where

Bo, B1, B2, ---- Bn are regression coefficients

To simplify the process we initially choose to limit the polynomial to a quadratic approximation. The polynomial may be expanded later on if the confidence levels of our estimation process are not adequate. The SAE program afore mentioned was used to perform regression analysis on a set of data consisting of 15 observations of 3 input variables, that is, Xi, $(Xi)^2$, and Y for

i = 1, 2, 3

The quadratic model, in general form, can be expressed as

$Y = Bo + B1(X) + B2(X)^2$ ———— (b)

In equation (b) differentiating Y with respect to X and then equating it to zero, we obtain

$Y' = B1 + 2(B2)X = 0$ ———— (c)

$X = -B1/2(B2)$ ———— (d)

Now in equation c differentiating Y with respect to X, we obtain

$Y'' = 2(B2)$ ———— (e)

which shows that for maximum surface roughness B2 must be negative which then guarantees Y'' to be negative.

Hence

when B2 is negative, we observe maximum value of surface roughness; and when B2 is positive, we observe minimum value. Now for each independent variable, equation (b) can be expressed as

$$Y1 = Bo + B1(X1) + B2(X1)^2 \qquad \text{———————} \qquad (f)$$

$$Y2 = Bo + B1(X2) + B2(X2)^2 \qquad \text{———————} \qquad (g)$$

$$Y3 = Bo + B1(X3) + B2(X3)^2 \qquad \text{———————} \qquad (h)$$

where

Yi = Surface roughness, X1 = Speed, X2 = Feed

X3 = Depth of cut

The values of the regression coefficients, [along with their respective confidence level(a confidence level is the probability of avoiding a type I error; a type I error occurs when we conclude that a particular estimation polynomial is valid when it is not)] have been determined by repeated application of SAE to 54 sets of data. The values of the regression coefficients have then been utilized in equations f, g, and h, to generate 54 optimization points which are then divided into two sets of 27 points each for two types of tool materials, that is, experimental data associated with High Speed Steel in set 1; and experimental data associated with Carbide tool in set 2. Each set of 27 points(X1, X2, X3, Y) has been used to create an optimization plane. This plane serves as a linear approximation(that is, first degree Taylor series) to the true optimization function. We then have as our conclusion two equations which predict surface roughness critical points, one for the High Speed Steel and the second for the Carbide tool.

4.8.2 THE MATHEMATICAL MODEL

Given a set of predictor variables X1, X2, -------,X_k, we may use classical regression analysis to estimate the dependent variable Y. A variety of approaches are possible. It is possible to estimate Y by a single predictor variable if all other predictors are held constant. Moreover, this estimation may be linear, quadratic, or a higher degree polynomial function.

Hence

$Y = f(X1, ----X_k)$

may be estimated by $Y = f(X_i)$

if X1, --------, X_{i-1}, X_{i+1}, -----, X_k

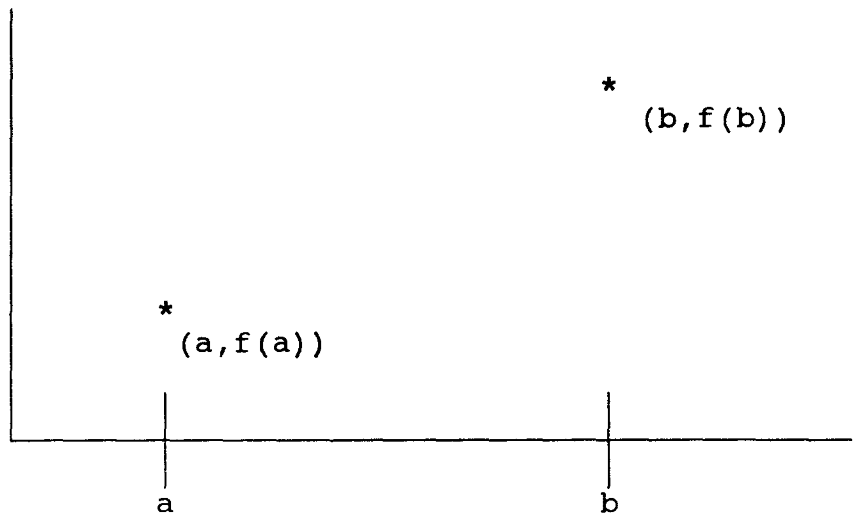
are all held constant.

and in addition

$Y = f(X_i) = Bo + B1(X_i) + B2(X_i)^2 + \text{---------} B_j(X_i)^j$

where our choice for j = 1, 2, 3, --------is based upon prescribed confidence levels in conjunction with the available sample size for the predictor variable X_i.

In this study, we are searching for critical points. A linear regression model would yield maximum and minimum values at the end points of the domain of X_i.



$a \leqslant X_i \leqslant b$; $f(X_i)$ is monotone increasing

$f(a)$ = minimum value of $f(X_i)$

$f(b)$ = minimum value of $f(X_i)$

where

$$f(X_i) = Y = Bo + B1(X_i)$$

Since we seek critical points within the domain, we extend the estimate to a parabolic (quadratic function) model.

Thus

$$f(X_i) = Bo + B1(X_i) + B2(X_i)^2$$

and clearly the critical point is obtained by setting

$$f'(X_i) = 0$$

Furthermore, maximum and minimum values may be distinguished by looking at the value of $f''(X_i)$.

We see that $f'(X_i) = B1 + 2(B2)(X_i)$

$$f''(X_i) = 2(B2)$$

and hence $(X_i)_{critical} = - B1/2(B2)$

and $B2 > 0$ (minimum)

$B2 < 0$ (maximum)

$B2 = 0$ (quadratic regression is not a plausible approach for the available data set).

These quadratic regressions were performed for X1, X2, X3 separately using SAE to identify the values of the regression coefficients (Bo, B1, B2). In most cases, the confidence level associated with these quadratic curve-fits was quite adequate and hence higher order models (i.e., $j > 3$) were not required.

By comparing the actual values of critical points

$$(X_i)_{critical} = -B1/2(B2)$$

and ascertaining that each of these was in the appropriate domain, 2 sets of critical points were generated consisting of 27 points for Carbide tool and 27 points for high speed steel tool as shown in table 55 and 56.

HIGH SPEED STEEL TOOL

$Y = Bo + B1(X3) + B2(X3)^2$
Optimum Value of $X3 = -B1/2(B2)$

1. Bo = 11.45 X1 = 392.5
   B1 = -140.548 X2 = 0.001
   B2 = 2854.440
   C.L = 91%
   $Y = 11.45 +(-140.548)X3 + 2854.44(X3)^2$
   Optimum value = X3 = 0.0246
   Optimum value = Y = 9.72

2. Bo = 10.321 X1 = 392.5
   B1 = 160.831 X2 = 0.0025
   B2 = -2251.405
   C.L = 98.1%
   $Y = 10.321 +(160.831)X3 + (-2251.405)(X3)^2$
   Optimum value = X3 = 0.0357
   Optimum value = Y = 13.193

3. Bo = 10.958 X1 = 392.5
   B1 = 782.098 X2 = 0.004
   B2 = -9598.492
   C.L = 99.99%
   $Y = 10.958 +(782.098)X3 + (-9598.492)(X3)^2$
   Optimum value = X3 = 0.0407
   Optimum value = Y = 26.89

4. Bo = 9.444 X1 = 1570.8
   B1 = -3.989 X2 = 0.001
   B2 = 888.468
   C.L = 88.46%
   $Y = 9.444 +(-3.989)X3 + (888.468)(X3)^2$
   Optimum value = X3 = 0.0022
   Optimum value = Y = 9.448

5. Bo = 10.81 X1 = 1570.8
   B1 = 159.603 X2 = 0.0025
   B2 = -2400.754
   C.L = 99.56%
   $Y = 10.81 +(159.603)X3 + (-2400.754)(X3)^2$
   Optimum value = X3 = 0.033
   Optimum value = Y = 13.461

6. Bo = 10.42 X1 = 1570.8
   B1 = 652.836 X2 = 0.004
   B2 = -6317.593
   C.L = 99.99%
   $Y = 10.42 + (652.836)X3 + (-6317.593)(X3)^2$
   Optimum value = X3 = 0.05
   Optimum value = Y = 27.26

7. Bo = 10.414 X1 = 2748.89
   B1 = 53.743 X2 = 0.001
   B2 = -283.553
   C.L = 90.7%
   $Y = 10.414 + (53.743)X3 + (-6317.593)(X3)^2$
   Optimum value = X3 = 0.0947
   Optimum value = Y = 12.96

8. Bo = 9.937 X1 = 2748.89
   B1 = 238.091 X2 = 0.0025
   B2 = -2196.598
   C.L = 99.97%
   $Y = 9.937 + (238.091)X3 + (-2196.598)(X3)^2$
   Optimum value = X3 = 0.0542
   Optimum value = Y = 16.38

9. Bo = 10.519 X1 = 2748.89
   B1 = 736.957 X2 = 0.004
   B2 = -8260.879
   C.L = 99.99%
   $Y = 10.519 + (736.957)X3 + (-8260.879)(X3)^2$
   Optimum value = X3 = 0.0446
   Optimum value = Y = 26.95

$Y = Bo + B1(X2) + B2(X2)^2$
Optimum Value of $X2 = -B1/2(B2)$

10. Bo = 12.864   X1 = 392.5
B1 = -2182.242   X3 = 0.002
B2 = 4.9E+05
C.L = 58.9%
$Y = 12.864 +(-2182.242)X2 + 4.9E{+}05(X2)^2$
Optimum value = X2 = 0.0044
Optimum value = Y = 12.74

11. Bo = 11.96   X1 = 392.5
B1 = -4202.73   X3 = 0.025
B2 = 1.96E+06
C.L = 99.99%
$Y = 11.96 +(-4202.73)X2 + 1.96E{+}06(X2)^2$
Optimum value = X2 = 0.001
Optimum value = Y = 9.72

12. Bo = 16.862   X1 = 392.5
B1 = -8204.528   X3 = 0.048
B2 = 2.62E+06
C.L = 99.99%
$Y = 16.862 +(-8204.528)X2 + 2.62E{+}06(X2)^2$
Optimum value = X2 = 0.0031
Optimum value = Y = 16.6

13. Bo = 7.709   X1 = 1570.8
B1 = 1975.566   X3 = 0.002
B2 = -2.44E+05
C.L = 94.1%
$Y = 7.709 +(1975.566)X2 - 2.44E{+}05(X2)^2$
Optimum value = X2 = 0.004
Optimum value = Y = 11.7

14 Bo = 11.018   X1 = 1570.8
B1 = -2471.609   X2 = 0.025
B2 = 1.35E+06
C.L = 99.99%
$Y = 11.018 +(-2471.609)X2 + 1.35E{+}06(X2)^2$
Optimum value = X2 = 0.0009
Optimum value = Y = 9.88

15. Bo = 17.218 X1 = 1570.8
B1 = -8722.321 X3 = 0.048
B2 = 2.8E+06
C.L = 99.99%
$Y = 17.218 + (-8722.321)X2 + 2.8E+06(X2)^2$
Optimummum value = X2 = 0.0015
Optimummum value = Y = 10.42

16. Bo = 11.462 X1 = 2748.89
B1 = -1297.791 X2 = 0.002
B2 = 3.56E+05
C.L = 85.1%
$Y = 11.462 + (-1297.791)X2 + 3.56E+05(X2)^2$
Optimum value = X2 = 0.0018
Optimum value = Y = 10.28

17. Bo = 13.074 X1 = 2748.89
B1 = -2884.517 X3 = 0.025
B2 = 1.39E+06
C.L = 99.99%
$Y = 13.074(-2884.517)X2 + 1.39E+06(X2)^2$
Optimum value = X2 = 0.001
Optimum value = Y = 11.58

18. Bo = 13.362 X1 = 2748.89
B1 = -2497.861 X3 = 0.048
B2 = 1.48E+06
C.L = 99.99%
$Y = 13.362(-2497.861)X2 + 1.48E+06(X2)^2$
Optimum value = X2 = 0.0008
Optimum value = Y = 12.31

$Y = Bo + B1(X1) + B2(X1)^2$
Optimum Value of X1 = -B1/2(B2)

19. Bo = 12.386 X2 = 0.001
    B1 = -0.003 X3 = 0.002
    B2 = 1.02E+(-06)
    C.L = 92.27%
    $Y = 12.386 +(-0.003)X1 + 1.02E-06(X1)^2$
    Optimum value = X1 = 1470.588
    Optimum value = Y = 10.18

20. Bo = 9.993 X2 = 0.001
    B1 = -0.000908 X3 = 0.025
    B2 = 5.40E+(-07)
    C.L = 90.0%
    $Y = 9.993 +(-0.000908)X1 + 5.40E-07(X1)^2$
    Optimum value = X1 = 840.74
    Optimum value = Y = 9.606

21. Bo = 11.5 X2 = 0.001
    B1 = -7.04E+(-04) X3 = 0.048
    B2 = 3.67E+(-07)
    C.L = 68.3%
    $Y = 11.5 +(-7.04E-04)X1 + 3.67E-07(X1)^2$
    Optimum value = X1 = 959.12
    Optimum value = Y = 11.16

22. Bo = 10.036 X2 = 0.0025
    B1 = 0.001 X3 = 0.002
    B2 = -4.6E+(-07)
    C.L = 22.99%
    $Y = 10.036 +(0.001)X1 - 4.6E-07(X1)^2$
    Optimum value = X1 = 1086.9
    Optimum value = Y = 10.58

23. Bo = 14.231 X2 = 0.0025
    B1 = -0.002 X3 = 0.025
    B2 = 6.02E+(-07)
    C.L = 70.0%
    $Y = 14.231 +(-0.002)X1 + 6.02E-07(X1)^2$
    Optimum value = X1 = 1661.11
    Optimum value = Y = 12.57

24. Bo = 13.384   X2 = 0.0025
B1 = -0.002   X3 = 0.048
B2 = 1.15E+(-06)
C.L = 99.9%
$Y = 13.384 +(-0.002)X1 + 1.15E-06(X1)^2$
Optimum value = X1 = 869.56
Optimum value = Y = 12.51

25. Bo = 12.38   X2 = 0.004
B1 = -8.06E-04   X3 = 0.002
B2 = 2.38E+(-07)
C.L = 7.0%
$Y = 12.38 +(-8.06E-04\ )X1 + 2.38E+(-07)\ (X1)^2$
Optimum value = X1 = 1861.34
Optimum value = Y = 11.7

26. Bo = 28.63   X2 = 0.004
B1 = -8.006   X3 = 0.025
B2 = 1.62E+(-06)
C.L = 99.27.0%
$Y = 28.38 +(-8.006)X1 + 1.62E+(-06)\ (X1)^2$
Optimum value = X1 = 1851.85
Optimum value = Y = 22.82

27. Bo = 25.14   X2 = 0.004
B1 = 8.002   X3 = 0.048
B2 = -5.94E+(-07)
C.L = 54.0%
$Y = 25.14 +(0.002)X1 - 5.94E+(-07)\ (X1)^2$
Optimum value = X1 = 1683.5
Optimum value = y = 26.82

CARBIBE TOOL

$Y = Bo + B1(X3) + B2(X3)^2$
Optimum Value of X3 = -B1/2(B2)

1. Bo = 5.562 X1 = 392.5
   B1 = 50.168 X2 = 0.001
   B2 = -96.408
   C.L = 89.7%
   $Y = 5.562 + (50.168)X3 - 96.408(X3)^2$
   Optimum value = X3 = 0.26
   Optimum value = Y = 12.08

2. Bo = 6.998 X1 = 392.5
   B1 = 38.372 X2 = 0.0025
   B2 = -190.925
   C.L = 70.71%
   $Y = 6.998 + (38.372)X3 - 190.925(X3)^2$
   Optimum value = X3 = 0.1
   Optimum value = Y = 8.92

3. Bo = 18.67 X1 = 392.5
   B1 = -169.414 X2 = 0.004
   B2 = 2657.844
   C.L = 99.5%
   $Y = 18.67 + (-169.414)X3 + 2657.844(X3)^2$
   Optimum value = X3 = 0.0318
   Optimum value = Y = 15.97

4. Bo = 7.46 X1 = 1570.8
   B1 = -15.59 X2 = 0.001
   B2 = 190.926
   C.L = 7.0%
   $Y = 7.46 + (-15.59)X3 + 190.926(X3)^2$
   Optimum value = X3 = 0.0408
   Optimum value = Y = 7.14

5. Bo = 7.952 X1 = 1570.8
   B1 = 100.794 X2 = 0.0025
   B2 = -2328.921
   C.L = 91.63%
   $Y = 7.952 + (100.794)X3 - 2328.921(X3)^2$
   Optimum value = X3 = 0.0216
   Optimum value = Y = 9.04

6. Bo = 17.893 X1 = 1570.8
   B1 = -75.752 X2 = 0.004
   B2 = 731.566
   C.L = 92.52%
   $Y = 17.893 +(-75.752)X3 + 731.566(X3)^2$
   Optimum value = X3 = 0.0517
   Optimum value = Y = 15.93

7. Bo = 9.041 X1 = 2748.89
   B1 = -111.904 X2 = 0.001
   B2 = 1291.114
   C.L = 99.89%
   $Y = 9.041 +(-111.904)X3 + 1291.114(X3)^2$
   Optimum value = X3 = 0.0433
   Optimum value = Y = 6.61

8. Bo = 9.996 X1 = 2748.89
   B1 = -98.611 X2 = 0.0025
   B2 = 1185.255
   C.L = 98.35%
   $Y = 9.996 +(-98.611)X3 + 1185.255(X3)^2$
   Optimum value = X3 = 0.0416
   Optimum value = Y = 7.94

9. Bo = 18.52 X1 = 2748.89
   B1 = -172.499 X2 = 0.004
   B2 = 2211.719
   C.L = 99.9%
   $Y = 18.52 +(-172.499)X3 + 2211.719(X3)^2$
   Optimum value = X3 = 0.0389
   Optimum value = Y = 15.15

$Y = Bo + B1(X2) + B2(X2)^2$
Optimum Value of X2 = -B1/2(B2)

10. Bo = 10.196 X1 = 395.2
    B1 = -6724.538 X3 = 0.002
    B2 = 2.19E+06
    C.L = 99.99%
    $Y = 10.196 +(-6724.538)X2 + 2.19E+06(X2)^2$
    Optimum value = X2 = 0.0015
    Optimum value = Y = 5.03

11. Bo = 10.021 X1 = 392.5
    B1 = -4860.053 X3 = 0.025
    B2 = 1.59E+06
    C.L = 99.99%
    $Y = 10.021 +(-4860.053)X2 + 1.59E+06(X2)^2$
    Optimum value = X2 = 0.0015
    Optimum value = Y = 6.31

12. Bo = 11.541 X1 = 392.5
    B1 = -5484.285 X3 = 0.048
    B2 = 1.69E+06
    C. L = 99.99%
    $Y = 11.541 +(-5484.285)X2 + 1.69E+06(X2)^2$
    Optimum value = X2 = 0.0016
    Optimum value = Y = 7.08

13. Bo = 11.891 X1 = 1570.8
    B1 = -6435.414 X3 = 0.002
    B2 = 1.97E+06
    C.L = 99.99%
    $Y = 11.891 +(-6435.414)X2 + 1.97E+06(X2)^2$
    Optimum value = X2 = 0.0016
    Optimum value = Y = 6.63

14. Bo = 9.092 X1 = 1570.8
    B1 = -3149.154 X3 = 0.025
    B2 = 1.25E+06
    C.L = 99.99%
    $Y = 9.092 +(-3149.154)X2 + 1.25E+06(X2)^2$
    Optimum value = X2 = 0.0012
    Optimum value = Y = 7.11

15. Bo = 11.552   X1 = 1570.8
B1 = -6232.287   X2 = 0.048
B2 = 1.83E+06
C.L = 99.99%
$Y = 11.552 + (-6232.287)X2 + 1.83E{+}06(X2)^2$
Optimum value = X2 = 0.0017
Optimum value = Y = 6.24

16. Bo = 12.277   X1 = 2748.89
B1 = -5099.371   X3 = 0.002
B2 = 1.64E+06
C.L = 99.99%
$Y = 12.277 + (-5099.371)X2 + 1.64E{+}06(X2)^2$
Optimum value = X2 = 0.0015
Optimum value = Y = 8.32

17. Bo = 9.622   X1 = 2748.89
B1 = -3926.717   X3 = 0.025
B2 = 1.35E+06
C.L = 99.99%
$Y = 9.622 + (-3926.717)X2 + 1.35E{+}06(X2)^2$
Optimum value = X2 = 0.0014
Optimum value = Y = 6.77

18. Bo = 9.1   X1 = 2748.89
B1 = -3777.83   X3 = 0.048
B2 = 1.33E+06
C.L = 99.99%
$Y = 9.1 + (-3777.83)X2 + 1.33E{+}06(X2)^2$
Optimum value = X2 = 0.0014
Optimum value = Y = 6.41

$Y = Bo + B1(X1) + B2(X1)^2$
Optimum Value of X1 = -B1/2(B2)

19. Bo = 4.99　　X2 = 0.001
    B1 = 0.002　　X3 = 0.002
    B2 = -1.35E+(-07)
    C.L = 99.99%
    $Y = 4.99 + (0.002)X1 - 1.35E{-}07(X1)^2$
    Optimum value = X1 = 7407.4
    Optimum value = Y = 12.39

20. Bo = 6.484　　X2 = 0.001
    B1 = 7.74E+-04　　X3 = 0.025
    B2 = -2.07E+(-07)
    C.L = 17.5%
    $Y = 6.484 + (7.74E{-}04)X1 - 2.87E{-}07(X1)^2$
    Optimum value = X1 = 1869.56
    Optimum value = Y = 6.93

21. Bo = 7.966　　X2 = 0.001
    B1 = -5.68E+-04　　X3 = 0.048
    B2 = 3.17E+(-08)
    C.L = 43.91%
    $Y = 7.966 + (-5.68E{-}04)X1 + 3.17E{-}08(X1)^2$
    Optimum value = X1 = 8958.99
    Optimum value = Y = 5.42

22. Bo = 6.849　　X2 = 0.0025
    B1 = 4.91E+-04　　x3 = 0.002
    B2 = 2.13E+(-07)
    C.L = 99.99%
    $Y = 6.849 + (4.91E{-}04)X1 + 2.13E{-}07(X1)^2$
    Optimum value = X1 = 1152.58
    Optimum value = Y = 6.56

23. Bo = 7.026　　X2 = 0.0025
    B1 = 0.002　　X3 = 0.025
    B2 = -6.91E+(-07)
    C.L = 62.33%
    $Y = 7.026 + (0.002)X1 - 6.91\ E{-}07(X1)^2$
    Optimum value = X1 = 1447.178
    Optimum value = Y = 5.57

24. Bo = 9.068 $\quad$ X2 = 0.0025
B1 = -0.002 $\quad$ X3 = 0.048
B2 = 5.57E+(-07)
C.L = 49.58%
$Y = 9.068 + (-0.002)X1 + 5.57\ E\text{-}07(X1)^2$
Optimum value = X1 = 1795.33
Optimum value = Y = 7.27

25. Bo = 18.772 $\quad$ X2 = 0.004
B1 = -0.001 $\quad$ X3 = 0.002
B2 = 3.74E+(-07)
C.L = 22.68%
$Y = 18.772 + (-0.001)X1 + 3.74E\text{-}07(X1)^2$
Optimum value = X1 = 1336.89
Optimum value = Y = 18.1

26. Bo = 15.704 $\quad$ X2 = 0.004
B1 = 0.001 $\quad$ X3 = 0.025
B2 = -4.42E+(-07)
C.L = 81.8%
$Y = 15.704 + (0.001)X1 - 4.42E\text{-}07(X1)^2$
Optimum value = X1 = 2066.11
Optimum value = Y = 15.52

27. Bo = 16.927 $\quad$ X2 = 0.004
B1 = -6.92E-04 $\quad$ X3 = 0.048
B2 = 4.10E+(-08)
C.L = 91.79%
$Y = 16.927 + (-6.92E\text{-}04)X1 + 4.1E\text{-}08(X1)^2$
Optimum value = X1 = 8439.0
Optimum value = y = 14.0

4.9 A DISCUSSION OF OPTIMIZATION PLANES

Without separating the critical points into a set of maximum values of surface roughness and a set of minimum values as well, we proceed to a linear curve fit for the composite model, as shown

$$Y = f(X1, X2, X3) = Bo + B1(X1) + B2(X2) + B3(X3)$$

A linear model was sufficient since its curve fitting process yielded a reasonably high confidence level value. Thus we obtained 2 optimization planes(one for Carbide tool and the other for High Speed Steel).

A further analysis was performed in which the nature of the critical point was of issue. This led us to produce separate maximization and minimization planes for both Carbide tool and for High Speed Steel tool. A similar linear regression was performed on the sorted data and the results follow in tables 57, 58, 59, and 60.

HIGH SPEED STEEL

TABLE 55

When B2 = Positive = + ; Surface roughness = Minimum

When B2 = Negative = - ; Surface roughness = Maximum

SET	X1	X2	X3	Y	B2
1	392.5	0.001	0.025	9.720	+
2	392.5	0.0025	0.036	13.193	-
3	392.5	0.0040	0.041	26.890	-
4	1570.8	0.0010	0.002	9.448	+
5	1570.8	0.0025	0.033	13.461	-
6	1570.8	0.0040	0.050	27.260	-
7	2748.89	0.0010	0.095	12.960	-
8	2748.89	0.0025	0.054	16.380	-
9	2748.89	0.004	0.045	26.950	-
10	392.5	0.004	0.002	12.740	+
11	392.5	0.001	0.025	9.720	+
12	392.5	0.003	0.048	16.600	+
13	1570.8	0.004	0.002	11.700	-
14	1579.8	0.0009	0.025	9.880	+
15	1570.8	0.002	0.048	10.420	+
16	2748.89	0.002	0.002	10.280	+
17	2748.89	0.001	0.025	11.580	+
18	2748.89	0.0008	0.048	12.310	+
19	1470.588	0.001	0.002	10.180	+
20	840.74	0.001	0.025	9.606	+
21	959.12	0.001	0.048	11.160	+
22	1086.90	0.0025	0.002	10.580	-
23	1661.11	0.0025	0.025	12.570	+
24	869.56	0.0025	0.048	12.510	+
25	1861.34	0.004	0.002	11.700	+
26	1851.85	0.004	0.025	22.820	+
27	1683.50	0.004	0.048	26.820	-

CARBIDE TOOL

TABLE 56

When B2 = Positive = + ; Surface roughness = Minimum

When B2 = Negative = - ; Surface roughness = Maximum

SET	X1	X2	X3	Y	B2
1	392.5	0.001	0.260	12.080	-
2	392.5	0.0025	0.100	8.9200	-
3	392.5	0.0040	0.032	15.970	+
4	1570.8	0.0010	0.041	7.140	+
5	1570.8	0.0025	0.022	9.040	-
6	1570.8	0.0040	0.052	15.930	+
7	2748.89	0.0010	0.043	6.610	+
8	2748.89	0.0025	0.042	7.940	+
9	2748.89	0.004	0.039	15.150	+
10	392.5	0.002	0.002	5.030	+
11	392.5	0.002	0.025	6.310	+
12	392.5	0.002	0.048	7.080	+
13	1570.8	0.002	0.002	6.630	+
14	1579.8	0.001	0.025	7.110	+
15	1570.8	0.002	0.048	6.240	+
16	2748.89	0.002	0.002	8.320	+
17	2748.89	0.001	0.025	6.770	+
18	2748.89	0.001	0.048	6.410	+
19	7407.40	0.001	0.002	12.390	-
20	1869.56	0.001	0.025	6.930	-
21	8958.99	0.001	0.048	5.420	+
22	1152.58	0.0025	0.002	6.56	+
23	1447.17	0.0025	0.025	5.57	-
24	1795.33	0.0025	0.048	7.270	+
25	1336.89	0.004	0.002	18.10	+
26	2066.11	0.004	0.025	15.52	-
27	8439.00	0.004	0.048	14.0	+

4.9.1 RESULTING OPTIMIZATION PLANES

The optimization planes for **Hss tool** and carbide tool are:

4.9.2 High Speed Steel tool

Ycritical = Bo + B1(X1) + B2(X2) + B3(X3)

Ycritical = 1.811 + 0.000676(X1) + 3442.44(X2) + 113.94(X3)

Confidence level = 99.99%

for example, if we choose

X1 = 900

X2 = 0.0018

X3 = 0.03

then we estimate that

Ycritical = 1.811+0.000676(900)+3442.44(0.0018)+113.94(0.03)

4.9.3 Carbide tool

Ycritical = Bo + B1(X1) + B2(X2) + B3(X3)

Ycritical = 1.846 + 0.000253(X1) + 2818.823(X2) + 19.039(X3)

confidence level = 99.99%

Note that Bo is almost the same for both planes. This means that for (X1, X2, X3) all very small, the surface roughness is about the same. A possible explanation for the close values of Bo is that an external effect (which constitutes a confounding variable) such as an initial vibration is present for both Carbide tool and High Speed Steel tool during the initial moment of tool operation.

Also observe that B1 which is the proportionality constant for X1(speed) is 2 and 1/2 times larger for High Speed Steel than for Carbide tool. In other words, speed has more impact on the optimization problem for High Speed Steel tool. We expect to get larger surface roughness values if a High Speed Steel tool is used under the same speed value.

Also observe that, once again, the High Speed Steel tool optimization is more sensitive to X2, that is, feed. This is true because

$$(B2)_{HSS} > (B2)_{\text{Carbide tool}}.$$

Since

$$(B1)_{HSS} > (B1)_{\text{Carbide tool}}$$

$$(B2)_{HSS} > (B2)_{\text{Carbide tool}}$$

$$(B3)_{HSS} > (B3)_{\text{Carbide tool}}$$

We see that Carbide tool produces smaller values of surface roughness for the same input, except for very small values of(X1, X2, X3).

4.10 MAXIMA AND MINIMA OPTIMIZATION PLANES

In section 4.9, We have defined the optimization plane to include any critical points of surface roughness. Let us now distinguish the many possible extrema. We separate the critical maximum values from critical minimum values as shown in tables 57 to 60.

High Speed Steel

Table 57

B2 = positive
Surface roughness = Minimum
Number of points = 17

SET	X1	X2	X3	Y	B2
1	392.5	0.001	0.025	9.720	+
2	1570.8	0.0010	0.002	9.448	+
3	392.5	0.004	0.002	12.740	+
4	392.5	0.001	0.025	9.720	+
5	392.5	0.003	0.048	16.600	+
6	1579.8	0.0009	0.025	9.880	+
7	1570.8	0.002	0.048	10.420	+
8	2748.89	0.002	0.002	10.280	+
9	2748.89	0.001	0.025	11.580	+
10	2748.89	0.0008	0.048	12.310	+
11	1470.588	0.001	0.002	10.180	+
12	840.74	0.001	0.025	9.606	+
13	959.12	0.001	0.048	11.160	+
14	1661.11	0.0025	0.025	12.570	+
15	869.56	0.0025	0.048	12.510	+
16	1861.34	0.004	0.002	11.700	+
17	1851.85	0.004	0.025	22.820	+

HIGH SPEED STEEL

Table 58

B2 = Negative
Surface roughness = Maximum
Number of points = 10

SET	X1	X2	X3	Y	B2
1	392.5	0.0025	0.036	13.193	-
2	392.5	0.0040	0.041	26.890	-
3	1570.8	0.0025	0.033	13.461	-
4	1570.8	0.0040	0.050	27.260	-
5	2748.89	0.0010	0.095	12.960	-
6	2748.89	0.0025	0.054	16.380	-
7	2748.89	0.004	0.045	26.950	-
8	1570.8	0.004	0.002	11.700	-
9	1086.90	0.0025	0.002	10.580	-
10	1683.50	0.004	0.048	26.820	-

CARBIDE TOOL

Table 59

B2 = Positive
Surface roughness = Minimum
Number of points = 20

SET	X1	X2	X3	Y	B2
1	392.5	0.0040	0.032	15.970	+
2	1570.8	0.0010	0.041	7.140	+
3	1570.8	0.0040	0.052	15.930	+
4	2748.89	0.0010	0.043	6.610	+
5	2748.89	0.0025	0.042	7.940	+
6	2748.89	0.004	0.039	15.150	+
7	392.5	0.002	0.002	5.030	+
8	392.5	0.002	0.025	6.310	+
9	392.5	0.002	0.048	7.080	+
10	1570.8	0.002	0.002	6.630	+
11	1579.8	0.001	0.025	7.110	+
12	1570.8	0.002	0.048	6.240	+
13	2748.89	0.002	0.002	8.320	+
14	2748.89	0.001	0.025	6.770	+
15	2748.89	0.001	0.048	6.410	+
16	8958.99	0.001	0.048	5.420	+
17	1152.58	0.0025	0.002	6.56	+
18	1795.33	0.0025	0.048	7.270	+
19	1336.89	0.004	0.002	18.10	+
20	8439.00	0.004	0.048	14.0	+

CARBIDE TOOL

TABLE 60

B2 = Negative
Surface roughness = Maximum
Number of points = 7

SET	X1	X2	X3	Y	B2
1	392.5	0.001	0.260	12.080	-
2	392.5	0.0025	0.100	8.9200	-
3	1570.8	0.0025	0.022	9.040	-
4	7407.40	0.001	0.002	12.390	-
5	1869.56	0.001	0.025	6.930	-
6	1447.17	0.0025	0.025	5.57	-
7	2066.11	0.004	0.025	15.52	-

With the help of data in table 57, 58, 59, and 60, regression coefficients have been determined by utilizing the SAE program to calculate the equations of minimization plane and the maximization plane as defined before.

4.10.1 THE MINIMIZATION PLANE FOR HIGH SPEED STEEL

$$Ymin = 5.335 + 0.000706(X1) + 2059.573(X2) + 66.409(X3)$$

Confidence level = 99.1%

4.10.2 THE MINIMIZATION PLANE FOR CARBIDE TOOL

$$Ymin = 1.256 + 0.000678(X1) + 3187.1(X2) + 10.665(X3)$$

Confidence level = 99.99%

4.10.3 THE MAXIMIZATION PLANE FOR HIGH SPEED STEEL

$$Ymax = -9.898 - 0.000904(X1) + 6945.452(X2) + 208.864(X3)$$

Confidence level = 99.7%

4.10.4 THE MAXIMIZATION PLANE FOR CARBIDE TOOL

$$Ymax = -1.759 + 0.002(X1) + 2824.155(X2) + 39.02(X3)$$

Confidence level = 82% (due to small sample size)

4.11 PLANE REGRESSION COEFFICIENTS AND ASSOCIATED LEVEL OF CONFIDENCE

C.L = Confidence level
S = Sample size

Plane	Bo	B1	B2	B3	C.L	S
HSS MAX	-9.898	-0.000904	6945.452	208.864	99.7%	10
HSS MIN	5.335	0.000706	2059.573	66.409	99.1%	17
C.T MAX	-1.759	0.002	2824.155	39.02	81.9%	7
C.T MIN	1.256	0.000678	3187.100	10.665	99.99%	20

4.12 CLASSICAL NORMALIZATION OF INDEPENDENT VARIABLES

We wish

$$0 \leqslant X1' \leqslant 1$$

$$0 \leqslant X2' \leqslant 1$$

$$0 \leqslant X3' \leqslant 1$$

Thus

$$X1' = (X1 - 392.5)/2748.89$$

$$X2' = (X2 - 0.001)/0.004$$

$$X3' = (X3 - 0.002)/0.048$$

From above expressions

$$X1 = (2748.89X1' + 392.5)$$

$$X2 = (0.004X2' + 0.001)$$

$$X3 = (0.048X3' + 0.002)$$

Hence

HSS

$$Y^{*}G.Min = 5.335+0.000706(2748.89X1'+392.5)$$
$$+2059.573(0.004X2'+0.001)+ 66.409(0.048X3'+0.002)$$

$$Y^{*}G.Min = 7.804 + 1.941X1' + 8.2383X2' + 3.1876X3'$$

Carbide tool

$$Y^{*}G.Min = 1.256 + 0.000678(2748.89X1'+392.5)$$
$$+ 3187.1(0.004X2'+0.001) + 10.665(0.048X3'+0.002)$$

$$Y^{*}G.Min = 4.7305 + 1.86375X1' + 12.7484X2' + 0.51192X3'$$

Similarly for maximum values of surface roughness

HSS

$$Y^{*}G.Max = -9.8980.000904(2748.89X1'+392.5)$$
$$+ 6945.452(0.004X2'+0.001) + 208.864(0.048X3'+0.002)$$

$$Y^{*}G.Max = -2.8896 - 2.484996X1' + 27.7818X2' + 10.025X3'$$

Carbide tool

$$Y^{*}G.Max = -1.759+0.002(2748.89X'_1+392.5)$$
$$+2824.155(0.004X'_2+0.001)+39.02(0.048X'_3+0.002)$$

$$Y^{*}G.Max = 1.928 + 5.49778X'_1 + 11.2966X'_2 + 1.87296X'_3$$

4.13 COMPARISON

4.13.1 Conclusion 1

For minimum planes

$(Bo)_{HSS} > (Bo)_{C.T}$
$(B1)_{HSS} > (B1)_{C.T}$
$(B2)_{HSS} < (B2)_{C.T}$
$(B3)_{HSS} > (B3)_{C.T}$

HSS process is more sensitive to small inputs, speed, and depth of cut than Carbide tool in terms of minimizing surface roughness.

Carbide tool is more sensitive to feed than HSS in terms of minimizing surface roughness.

4.13.2 Conclusion 2

For maximum planes

$(Bo)_{HSS} < (Bo)_{C.T}$
$(B1)_{HSS} < (B1)_{C.T}$
$(B2)_{HSS} > (B2)_{C.T}$
$(B3)_{HSS} > (B3)_{C.T}$

HSS process is more sensitive to feed and depth of cut in terms of maximizing surface roughness.

Carbide tool is more sensitive to very small inputs and speed in terms of maximizing surface roughness.

4.13.3 Conclusion 3

We recall that the following **reasonable** domains apply for (X1, X2, X3) for both HSS **and Carbide** tool.

$$392.5 \leqslant X1 \leqslant 2748.89$$
$$0.001 \leqslant X2 \leqslant 0.004$$
$$0.002 \leqslant X3 \leqslant 0.048$$

This allows us to calculate **global** values for minimum and maximum surface roughness **for both** HSS and Carbide tool.

Hence

(X1min, X2min, X3min) = (392.5, 0.001, 0.002) for both HSS and Carbide tool.

Hence

The global values of minimum surface roughness are

HSS

$Y_{G.Min}$ = 5.335+0.000706(392.5)+2059.573(0.001)+66.409(0.002)

$Y_{G.Min}$ = 7.8045 micro inches

Also

For Carbide tool

$Y_{G.Min}$ = 1.256+0.000678(392.5)+3187.1(0.001)+10.665(0.002)

$Y_{G.Min}$ = 4.7305 micro inches

Also since (X1max, X2max, X3max) = (2748.89, 0.004, 0.048) for both HSS and Carbide tool, the global values of maximum surface roughness are

HSS

$Y_{G.Max}$=-9.898-0.000904(2748.89)+6945.452(0.004)
+208.864(0.048)

$Y_{G.Max}$ = 25.4243 micro inches

For Carbide tool

$Y_{G.Max}$ = -1.759+0.002(2748.89)+2824.155(0.004)+39.02(0.048)

$Y_{G.Max}$ = 16.9084 micro inches

In tabular form, a global ststement is presented below

TOOL	RANGE FOR SURFACE ROUGHNESS
HSS	7.8045 < Surface Roughness < 25.4243 C.L = 99.1% C.L = 99.7%
C.T	4.7035 < Surface Roughness < 16.9084 C.L = 99.99% C.L = 82%

4.14 NORMALIZATION BASED UPON AVERAGING

We recognize that we can rewrite our optimization plane equations as follows.

Y_{min} = Bo + B1(C1)(X1/C1) + B2(C2)(X2/C2) + B3(C3)(X3/C3)

Y_{min} = Bo + B1(C1)($\widetilde{X1}$) + B2(C2)($\widetilde{X2}$) + B3(C3)($\widetilde{X3}$)

Where

X1/C1 = $\widetilde{X1}$

X2/C2 = $\widetilde{X2}$

X3/C3 = $\widetilde{X3}$, and

C1 = (392.5 + 2748.89)/2 = 1570.695

C2 = (0.001 + 0.004)/2 = 0.0025

C3 = (0.002 + 0.048)/2 = 0.025

Hence

HSS

$Y_{G.Min}$ = 5.335+0.000706(1570.695)($\widetilde{X1}$)+2059.573(0.0025)($\widetilde{X2}$)
+66.409(0.025)($\widetilde{X3}$)

$Y_{G.Min}$ = 5.335 + 1.1089($\widetilde{X1}$) + 5.1489($\widetilde{X2}$) + 1.66($\widetilde{X3}$)

For Carbide tool

$$Y_{G.Min} = 1.256+0.000678(1570.695)(\widetilde{X1})+3187.1(0.0025)(\widetilde{X2}) +10.665(\widetilde{X3})$$

$$Y_{G.Min} = 1.256 + 1.0649(\widetilde{X1}) + 7.967(\widetilde{X2}) + 0.266(\widetilde{X3})$$

HSS

$$Y_{G.Max} = -9.898-0.000904(1570.695)(\widetilde{X1})+6945.452(0.0025)(\widetilde{X2}) +208.864(\widetilde{X3})$$

$$Y_{G.Max} = -9.898 - 1.419(\widetilde{X1}) + 17.36(\widetilde{X2}) + 5.22(\widetilde{X3})$$

For Carbide tool

$$Y_{G.Max} = 1.759+0.002(1570.695)(\widetilde{X1})+2824.155(0.0025)(\widetilde{X2}) +39.02(0.025)(\widetilde{X3})$$

$$Y_{G.Max} = 1.759 + 3.14(\widetilde{X1}) + 7.06(\widetilde{X2}) + 0.9755(\widetilde{X3})$$

4.14.1 RELEVANT DOMAINS

The relevant domains are as follows

$$392.5 \leqslant X1 \leqslant 2748.89$$

$$392.5/C1 \leqslant \widetilde{X1} = X1/C1 \leqslant 2748.89/C1$$

$$392.5/1570.695 \leqslant \widetilde{X1} = X1/C1 \leqslant 2748.89/1570.695$$

$$\mathbf{0.2498 \leqslant \widetilde{X1} \leqslant 1.75}$$

$$0.001 \leqslant X2 \leqslant 0.004$$

$$0.001/C1 \leqslant \widetilde{X2} = X2/C2 \leqslant 0.004/C1$$

$$0.001/0.0025 \leqslant \widetilde{X2} = X2/C2 \leqslant 0.004/0.0025$$

$$\mathbf{0.4 \leqslant \widetilde{X2} \leqslant 1.6}$$

$$0.002 \leqslant X3 \leqslant 0.048$$

$$0.002/C3 \leqslant \widetilde{X3} = X3/C3 \leqslant 0.048/C3$$

$$0.002/0.025 \leqslant \widetilde{X3} = X3/C3 \leqslant 0.048/0.025$$

$$\mathbf{0.08 \leqslant \widetilde{X3} \leqslant 1.92}$$

APPENDIX A

HIGH SPEED STEEL TOOL

Table 1

X1 = speed = constant ;   X2 = feed = constant

X3 = depth of cut = variable; Y = surface roughness

#	(X1)	(X2)	(X3)	$(X3)^2$	Y
1	392.5	0.001	0.002	0.000004	11.8
2	392.5	0.001	0.002	0.000004	12.2
3	392.5	0.001	0.002	0.000004	12.0
4	392.5	0.001	0.002	0.000004	10.7
5	392.5	0.001	0.002	0.000004	9.2
6	392.5	0.001	0.025	0.000625	9.7
7	392.5	0.001	0.025	0.000625	9.2
8	392.5	0.001	0.025	0.000625	10.7
9	392.5	0.001	0.025	0.000625	10.6
10	392.5	0.001	0.025	0.000625	8.4
11	392.5	0.001	0.048	0.002304	11.6
12	392.5	0.001	0.048	0.002304	12.1
13	392.5	0.001	0.048	0.002304	11.8
14	392.5	0.001	0.048	0.002304	11.7
15	392.5	0.001	0.048	0.002304	9.2

Table 2

#	(X1)	(X2)	(X3)	$(X3)^2$	Y
1	392.5	0.0025	0.002	0.000004	8.8
2	392.5	0.0025	0.002	0.000004	12.7
3	392.5	0.0025	0.002	0.000004	12.5
4	392.5	0.0025	0.002	0.000004	9.6
5	392.5	0.0025	0.002	0.000004	9.0
6	392.5	0.0025	0.025	0.000625	13.2
7	392.5	0.0025	0.025	0.000625	13.8
8	392.5	0.0025	0.025	0.000625	13.9
9	392.5	0.0025	0.025	0.000625	14.0
10	392.5	0.0025	0.025	0.000625	13.7
11	392.5	0.0025	0.048	0.002304	13.4
12	392.5	0.0025	0.048	0.002304	11.2
13	392.5	0.0025	0.048	0.002304	11.7
14	392.5	0.0025	0.048	0.002304	15.0
15	392.5	0.0025	0.048	0.002304	12.4

Table 3

#	(X1)	(X2)	(X3)	$(X3)^2$	Y
1	392.5	0.004	0.002	0.000004	12.40
2	392.5	0.004	0.002	0.000004	15.20
3	392.5	0.004	0.002	0.000004	12.60
4	392.5	0.004	0.002	0.000004	10.70
5	392.5	0.004	0.002	0.000004	9.60
6	392.5	0.004	0.025	0.000625	29.20
7	392.5	0.004	0.025	0.000625	25.30
8	392.5	0.004	0.025	0.000625	27.00
9	392.5	0.004	0.025	0.000625	25.76
10	392.5	0.004	0.025	0.000625	25.50
11	392.5	0.004	0.048	0.002304	28.30
12	392.5	0.004	0.048	0.002304	24.70
13	392.5	0.004	0.048	0.002304	24.30
14	392.5	0.004	0.048	0.002304	29.20
15	392.5	0.004	0.048	0.002304	23.50

Table 4

#	(X1)	(X2)	(X3)	$(X3)^2$	Y
1	1570.8	0.001	0.002	0.000004	9.3
2	1570.8	0.001	0.002	0.000004	10.6
3	1570.8	0.001	0.002	0.000004	9.8
4	1570.8	0.001	0.002	0.000004	9.4
5	1570.8	0.001	0.002	0.000004	8.1
6	1570.8	0.001	0.025	0.000625	7.6
7	1570.8	0.001	0.025	0.000625	11.3
8	1570.8	0.001	0.025	0.000625	10.5
9	1570.8	0.001	0.025	0.000625	8.4
10	1570.8	0.001	0.025	0.000625	11.7
11	1570.8	0.001	0.048	0.002304	10.9
12	1570.8	0.001	0.048	0.002304	11.2
13	1570.8	0.001	0.048	0.002304	11.6
14	1570.8	0.001	0.048	0.002304	13.0
15	1570.8	0.001	0.048	0.002304	9.8

Table 5

#	(X1)	(X2)	(X3)	$(X3)^2$	Y
1	1570.8	0.0025	0.002	0.000004	13.4
2	1570.8	0.0025	0.002	0.000004	11.2
3	1570.8	0.0025	0.002	0.000004	10.5
4	1570.8	0.0025	0.002	0.000004	9.8
5	1570.8	0.0025	0.002	0.000004	10.7
6	1570.8	0.0025	0.025	0.000625	12.8
7	1570.8	0.0025	0.025	0.000625	13.9
8	1570.8	0.0025	0.025	0.000625	13.2
9	1570.8	0.0025	0.025	0.000625	13.5
10	1570.8	0.0025	0.025	0.000625	13.1
11	1570.8	0.0025	0.048	0.002304	12.9
12	1570.8	0.0025	0.048	0.002304	13.3
13	1570.8	0.0025	0.048	0.002304	12.2
14	1570.8	0.0025	0.048	0.002304	13.5
15	1570.8	0.0025	0.048	0.002304	12.8

Table 6

#	(X1)	(X2)	(X3)	$(X3)^2$	Y
1	1570.8	0.004	0.002	0.000004	11.2
2	1570.8	0.004	0.002	0.000004	12.7
3	1570.8	0.004	0.002	0.000004	14.2
4	1570.8	0.004	0.002	0.000004	10.6
5	1570.8	0.004	0.002	0.000004	9.8
6	1570.8	0.004	0.025	0.000625	24.4
7	1570.8	0.004	0.025	0.000625	24.1
8	1570.8	0.004	0.025	0.000625	23.1
9	1570.8	0.004	0.025	0.000625	21.0
10	1570.8	0.004	0.025	0.000625	21.36
11	1570.8	0.004	0.048	0.002304	27.7
12	1570.8	0.004	0.048	0.002304	26.6
13	1570.8	0.004	0.048	0.002304	26.2
14	1570.8	0.004	0.048	0.002304	28.4
15	1570.8	0.004	0.048	0.002304	27.1

Table 7

#	(X1)	(X2)	(X3)	$(X3)^2$	Y
1	2748.89	0.001	0.002	0.000004	11.5
2	2748.89	0.001	0.002	0.000004	10.1
3	2748.89	0.001	0.002	0.000004	9.8
4	2748.89	0.001	0.002	0.000004	9.3
5	2748.89	0.001	0.002	0.000004	11.9
6	2748.89	0.001	0.025	0.000625	10.7
7	2748.89	0.001	0.025	0.000625	12.9
8	2748.89	0.001	0.025	0.000625	11.9
9	2748.89	0.001	0.025	0.000625	10.0
10	2748.89	0.001	0.025	0.000625	12.4
11	2748.89	0.001	0.048	0.002304	13.9
12	2748.89	0.001	0.048	0.002304	12.6
13	2748.89	0.001	0.048	0.002304	10.9
14	2748.89	0.001	0.048	0.002304	13.1
15	2748.89	0.001	0.048	0.002304	11.2

Table 8

#	(X1)	(X2)	(X3)	$(X3)^2$	Y
1	2748.89	0.0025	0.002	0.000004	11.4
2	2748.89	0.0025	0.002	0.000004	9.6
3	2748.89	0.0025	0.002	0.000004	10.0
4	2748.89	0.0025	0.002	0.000004	8.8
5	2748.89	0.0025	0.002	0.000004	12.4
6	2748.89	0.0025	0.025	0.000625	15.2
7	2748.89	0.0025	0.025	0.000625	17.0
8	2748.89	0.0025	0.025	0.000625	15.76
9	2748.89	0.0025	0.025	0.000625	12.2
10	2748.89	0.0025	0.025	0.000625	12.6
11	2748.89	0.0025	0.048	0.002304	16.2
12	2748.89	0.0025	0.048	0.002304	16.6
13	2748.89	0.0025	0.048	0.002304	16.3
14	2748.89	0.0025	0.048	0.002304	17.5
15	2748.89	0.0025	0.048	0.002304	15.1

Table 9

#	(X1)	(X2)	(X3)	$(X3)^2$	Y
1	2748.89	0.004	0.002	0.000004	10.7
2	2748.89	0.004	0.002	0.000004	12.0
3	2748.89	0.004	0.002	0.000004	13.8
4	2748.89	0.004	0.002	0.000004	10.9
5	2748.89	0.004	0.002	0.000004	12.4
6	2748.89	0.004	0.025	0.000625	23.6
7	2748.89	0.004	0.025	0.000625	23.7
8	2748.89	0.004	0.025	0.000625	25.8
9	2748.89	0.004	0.025	0.000625	21.9
10	2748.89	0.004	0.025	0.000625	23.9
11	2748.89	0.004	0.048	0.002304	28.3
12	2748.89	0.004	0.048	0.002304	26.4
13	2748.89	0.004	0.048	0.002304	27.6
14	2748.89	0.004	0.048	0.002304	27.0
15	2748.89	0.004	0.048	0.002304	25.6

Table 10

X1 = speed = constant ;   X2 = feed = variable

X3 = depth of cut = constant; Y = surface roughness

#	(X1)	(X2)	(X3)	$(X2)^2$	Y
1	392.5	0.001	0.002	0.000001	11.8
2	392.5	0.001	0.002	0.000001	12.2
3	392.5	0.001	0.002	0.000001	12.0
4	392.5	0.001	0.002	0.000001	10.7
5	392.5	0.001	0.002	0.000001	9.2
6	392.5	0.0025	0.002	0.00000625	8.8
7	392.5	0.0025	0.002	0.00000625	12.7
8	392.5	0.0025	0.002	0.00000625	12.5
9	392.5	0.0025	0.002	0.00000625	9.6
10	392.5	0.0025	0.002	0.00000625	9.0
11	392.5	0.004	0.002	0.000016	12.4
12	392.5	0.004	0.002	0.000016	15.2
13	392.5	0.004	0.002	0.000016	12.6
14	392.5	0.004	0.002	0.000016	10.7
15	392.5	0.004	0.002	0.000016	9.6

Table 11

#	(X1)	(X2)	(X3)	$(X2)^2$	Y
1	392.5	0.001	0.025	0.000001	9.70
2	392.5	0.001	0.025	0.000001	9.20
3	392.5	0.001	0.025	0.000001	10.70
4	392.5	0.001	0.025	0.000001	10.60
5	392.5	0.001	0.025	0.000001	8.40
6	392.5	0.0025	0.025	0.00000625	13.20
7	392.5	0.0025	0.025	0.00000625	13.80
8	392.5	0.0025	0.025	0.00000625	13.90
9	392.5	0.0025	0.025	0.00000625	14.00
10	392.5	0.0025	0.025	0.00000625	13.70
11	392.5	0.004	0.025	0.000016	29.20
12	392.5	0.004	0.025	0.000016	25.30
13	392.5	0.004	0.025	0.000016	27.00
14	392.5	0.004	0.025	0.000016	25.76
15	392.5	0.004	0.025	0.000016	25.50

Table 12

#	(X1)	(X2)	(X3)	$(X2)^2$	Y
1	392.5	0.001	0.048	0.000001	11.60
2	392.5	0.001	0.048	0.000001	12.10
3	392.5	0.001	0.048	0.000001	11.80
4	392.5	0.001	0.048	0.000001	11.70
5	392.5	0.001	0.048	0.000001	9.20
6	392.5	0.0025	0.048	0.0000065	13.40
7	392.5	0.0025	0.048	0.0000062	11.20
8	392.5	0.0025	0.048	0.00000625	11.70
9	392.5	0.0025	0.048	0.00000625	15.00
10	392.5	0.0025	0.048	0.00000625	12.40
11	392.5	0.004	0.048	0.000016	28.30
12	392.5	0.004	0.048	0.000016	24.70
13	392.5	0.004	0.048	0.000016	24.30
14	392.5	0.004	0.048	0.000016	29.20
15	392.5	0.004	0.048	0.000016	23.50

Table 13

#	(X1)	(X2)	(X3)	$(X2)^2$	Y
1	1570.8	0.001	0.002	0.000001	9.30
2	1570.8	0.001	0.002	0.000001	10.60
3	1570.8	0.001	0.002	0.000001	9.80
4	1570.8	0.001	0.002	0.000001	9.40
5	1570.8	0.001	0.002	0.000001	8.10
6	1570.8	0.0025	0.002	0.00000625	13.40
7	1570.8	0.0025	0.002	0.00000625	11.20
8	1570.8	0.0025	0.002	0.00000625	10.50
9	1570.8	0.0025	0.002	0.00000625	9.80
10	1570.8	0.0025	0.002	0.00000625	10.70
11	1570.8	0.004	0.002	0.000016	11.20
12	1570.8	0.004	0.002	0.000016	12.70
13	1570.8	0.004	0.002	0.000016	14.20
14	1570.8	0.004	0.002	0.000016	10.60
15	1570.8	0.004	0.002	0.000016	9.80

Table 14

#	(X1)	(X2)	(X3)	$(X2)^2$	Y
1	1570.8	0.001	0.025	0.000001	7.60
2	1570.8	0.001	0.025	0.000001	11.30
3	1570.8	0.001	0.025	0.000001	10.50
4	1570.8	0.001	0.025	0.000001	8.40
5	1570.8	0.001	0.025	0.000001	11.70
6	1570.8	0.0025	0.025	0.00000625	12.80
7	1570.8	0.0025	0.025	0.00000625	13.90
8	1570.8	0.0025	0.025	0.00000625	13.20
9	1570.8	0.0025	0.025	0.00000625	13.50
10	1570.8	0.0025	0.025	0.00000625	13.10
11	1570.8	0.004	0.025	0.000016	24.40
12	1570.8	0.004	0.025	0.000016	24.10
13	1570.8	0.004	0.025	0.000016	23.10
14	1570.8	0.004	0.025	0.000016	21.00
15	1570.8	0.004	0.025	0.000016	21.36

Table 15

#	(X1)	(X2)	(X3)	$(X2)^2$	Y
1	1570.8	0.001	0.048	0.000001	10.90
2	1570.8	0.001	0.048	0.000001	11.20
3	1570.8	0.001	0.048	0.000001	11.60
4	1570.8	0.001	0.048	0.000001	13.00
5	1570.8	0.001	0.048	0.000001	9.80
6	1570.8	0.0025	0.048	0.00000625	12.90
7	1570.8	0.0025	0.048	0.00000625	13.30
8	1570.8	0.0025	0.048	0.00000625	12.20
9	1570.8	0.0025	0.048	0.00000625	13.50
10	1570.8	0.0025	0.048	0.00000625	12.80
11	1570.8	0.004	0.048	0.000016	27.70
12	1570.8	0.004	0.048	0.000016	26.60
13	1570.8	0.004	0.048	0.000016	26.20
14	1570.8	0.004	0.048	0.000016	28.40
15	1570.8	0.004	0.048	0.000016	27.10

Table 16

#	(X1)	(X2)	(X3)	$(X2)^2$	Y
1	2748.89	0.001	0.002	0.000001	11.50
2	2748.89	0.001	0.002	0.000001	10.10
3	2748.89	0.001	0.002	0.000001	9.80
4	2748.89	0.001	0.002	0.000001	9.30
5	2748.89	0.001	0.002	0.000001	11.90
6	2748.89	0.0025	0.002	0.00000625	11.40
7	2748.89	0.0025	0.002	0.00000625	9.60
8	2748.89	0.0025	0.002	0.00000625	10.00
9	2748.89	0.0025	0.002	0.00000625	8.80
10	2748.89	0.0025	0.002	0.00000625	12.40
11	2748.89	0.004	0.002	0.000016	10.70
12	2748.89	0.004	0.002	0.000016	12.00
13	2748.89	0.004	0.002	0.000016	13.80
14	2748.89	0.004	0.002	0.000016	10.90
15	2748.89	0.004	0.002	0.000016	12.40

Table 17

#	(X1)	(X2)	(X3)	$(X2)^2$	Y
1	2748.89	0.001	0.025	0.000001	10.7
2	2748.89	0.001	0.025	0.000001	12.90
3	2748.89	0.001	0.025	0.000001	11.90
4	2748.89	0.001	0.025	0.000001	10.00
5	2748.89	0.001	0.025	0.000001	12.40
6	2748.89	0.0025	0.025	0.00000625	15.20
7	2748.89	0.0025	0.025	0.00000625	17.00
8	2748.89	0.0025	0.025	0.00000625	15.76
9	2748.89	0.0025	0.025	0.00000625	12.20
10	2748.89	0.0025	0.025	0.00000625	12.60
11	2748.89	0.004	0.025	0.000016	23.60
12	2748.89	0.004	0.025	0.000016	23.70
13	2748.89	0.004	0.025	0.000016	25.80
14	2748.89	0.004	0.025	0.000016	21.90
15	2748.89	0.004	0.025	0.000016	23.90

Table 18

#	(X1)	(X2)	(X3)	$(X2)^2$	Y
1	2748.89	0.001	0.048	0.000001	13.90
2	2748.89	0.001	0.048	0.000001	12.60
3	2748.89	0.001	0.048	0.000001	10.90
4	2748.89	0.001	0.048	0.000001	13.10
5	2748.89	0.001	0.048	0.000001	11.20
6	2748.89	0.0025	0.048	0.00000625	16.20
7	2748.89	0.0025	0.048	0.00000625	16.60
8	2748.89	0.0025	0.048	0.00000625	16.30
9	2748.89	0.0025	0.048	0.00000625	17.50
10	2748.89	0.0025	0.048	0.00000625	15.10
11	2748.89	0.004	0.048	0.000016	28.30
12	2748.89	0.004	0.048	0.000016	26.40
13	2748.89	0.004	0.048	0.000016	27.60
14	2748.89	0.004	0.048	0.000016	27.00
15	2748.89	0.004	0.048	0.000016	25.60

Table 19

X1 = speed = variable ;   X2 = feed = constant

X3 = depth of cut = constant; Y = surface roughness

#	(X1)	(X2)	(X3)	$(X1)^2$	Y
1	392.5	0.001	0.002	154056.25	11.80
2	392.5	0.001	0.002	154056.25	12.20
3	392.5	0.001	0.002	154056.25	12.00
4	392.5	0.001	0.002	154056.25	10.70
5	392.5	0.001	0.002	154056.25	9.20
6	1570.8	0.001	0.002	2467412.64	9.30
7	1570.8	0.001	0.002	2467412.64	10.60
8	1570.8	0.001	0.002	2467412.64	9.80
9	1570.8	0.001	0.002	2467412.64	9.40
10	1570.8	0.001	0.002	2467412.64	8.10
11	2748.89	0.001	0.002	7556396.232	11.50
12	2748.89	0.001	0.002	7556396.232	10.1
13	2748.89	0.001	0.002	7556396.232	9.80
14	2748.89	0.001	0.002	7556396.232	9.30
15	2748.89	0.001	0.002	7556396.232	11.90

Table 20

#	(X1)	(X2)	(X3)	$(X1)^2$	Y
1	392.5	0.001	0.025	154056.25	9.70
2	392.5	0.001	0.025	154056.25	9.20
3	392.5	0.001	0.025	154056.25	10.70
4	392.5	0.001	0.025	154056.25	10.60
5	392.5	0.001	0.025	154056.25	8.40
6	1570.8	0.001	0.025	2467412.64	7.60
7	1570.8	0.001	0.025	2467412.64	11.30
8	1570.8	0.001	0.025	2467412.64	10.50
9	1570.8	0.001	0.025	2467412.64	8.40
10	1570.8	0.001	0.025	2467412.64	11.70
11	2748.89	0.001	0.025	7556396.232	10.70
12	2748.89	0.001	0.025	7556396.232	12.90
13	2748.89	0.001	0.025	7556396.232	11.90
14	2748.89	0.001	0.025	7556396.232	10.00
15	2748.89	0.001	0.025	7556396.232	12.40

Table 21

#	(X1)	(X2)	(X3)	$(X1)^2$	Y
1	392.5	0.001	0.048	154056.25	11.60
2	392.5	0.001	0.048	154056.25	12.10
3	392.5	0.001	0.048	154056.25	11.80
4	392.5	0.001	0.048	154056.25	11.70
5	392.5	0.001	0.048	154056.25	9.20
6	1570.8	0.001	0.048	2467412.64	10.90
7	1570.8	0.001	0.048	2467412.64	11.20
8	1570.8	0.001	0.048	2467412.64	11.60
9	1570.8	0.001	0.048	2467412.64	13.00
10	1570.8	0.001	0.048	2467412.64	9.80
11	2748.89	0.001	0.048	7556396.232	13.90
12	2748.89	0.001	0.048	7556396.232	12.60
13	2748.89	0.001	0.048	7556396.232	10.90
14	2748.89	0.001	0.048	7556396.232	13.10
15	2748.89	0.001	0.048	7556396.232	11.20

Table 22

#	(X1)	(X2)	(X3)	$(X1)^2$	Y
1	392.5	0.0025	0.002	154056.25	8.80
2	392.5	0.0025	0.002	154056.25	12.70
3	392.5	0.0025	0.002	154056.25	12.50
4	392.5	0.0025	0.002	154056.25	9.60
5	392.5	0.0025	0.002	154056.25	9.00
6	1570.8	0.0025	0.002	2467412.64	13.40
7	1570.8	0.0025	0.002	2467412.64	11.20
8	1570.8	0.0025	0.002	2467412.64	10.50
9	1570.8	0.0025	0.002	2467412.64	9.80
10	1570.8	0.0025	0.002	2467412.64	10.70
11	2748.89	0.0025	0.002	7556396.232	11.40
12	2748.89	0.0025	0.002	7556396.232	9.60
13	2748.89	0.0025	0.002	7556396.232	10.00
14	2748.89	0.0025	0.002	7556396.232	8.80
15	2748.89	0.0025	0.002	7556396.232	12.40

Table 23

#	(X1)	(X2)	(X3)	$(X1)^2$	Y
1	392.5	0.0025	0.025	154056.25	13.20
2	392.5	0.0025	0.025	154056.25	13.80
3	392.5	0.0025	0.025	154056.25	13.90
4	392.5	0.0025	0.025	154056.25	14.00
5	392.5	0.0025	0.025	154056.25	13.70
6	1570.8	0.0025	0.025	2467412.64	12.80
7	1570.8	0.0025	0.025	2467412.64	13.90
8	1570.8	0.0025	0.025	2467412.64	13.20
9	1570.8	0.0025	0.025	2467412.64	13.50
10	1570.8	0.0025	0.025	2467412.64	13.10
11	2748.89	0.0025	0.025	7556396.232	15.20
12	2748.89	0.0025	0.025	7556396.232	17.00
13	2748.89	0.0025	0.025	7556396.232	15.76
14	2748.89	0.0025	0.025	7556396.232	12.20
15	2748.89	0.0025	0.025	7556396.232	12.60

Table 24

#	(X1)	(X2)	(X3)	$(X1)^2$	Y
1	392.5	0.0025	0.048	154056.25	13.40
2	392.5	0.0025	0.048	154056.25	11.20
3	392.5	0.0025	0.048	154056.25	11.70
4	392.5	0.0025	0.048	154056.25	15.00
5	392.5	0.0025	0.048	154056.25	12.40
6	1570.8	0.0025	0.048	2467412.64	12.90
7	1570.8	0.0025	0.048	2467412.64	13.30
8	1570.8	0.0025	0.048	2467412.64	12.20
9	1570.8	0.0025	0.048	2467412.64	13.50
10	1570.8	0.0025	0.048	2467412.64	12.80
11	2748.89	0.0025	0.048	7556396.232	16.20
12	2748.89	0.0025	0.048	7556396.232	16.60
13	2748.89	0.0025	0.048	7556396.232	16.30
14	2748.89	0.0025	0.048	7556396.232	17.50
15	2748.89	0.0025	0.048	7556396.232	15.10

Table 25

#	(X1)	(X2)	(X3)	$(X1)^2$	Y
1	392.5	0.004	0.002	154056.25	12.40
2	392.5	0.004	0.002	154056.25	15.20
3	392.5	0.004	0.002	154056.25	12.60
4	392.5	0.004	0.002	154056.25	10.70
5	392.5	0.004	0.002	154056.25	9.60
6	1570.8	0.004	0.002	2467412.64	11.20
7	1570.8	0.004	0.002	2467412.64	12.70
8	1570.8	0.004	0.002	2467412.64	14.20
9	1570.8	0.004	0.002	2467412.64	10.60
10	1570.8	0.004	0.002	2467412.64	9.80
11	2748.89	0.004	0.002	7556396.232	10.70
12	2748.89	0.004	0.002	7556396.232	12.00
13	2748.89	0.004	0.002	7556396.232	13.80
14	2748.89	0.004	0.002	7556396.232	10.90
15	2748.89	0.004	0.002	7556396.232	12.40

Table 26

#	(X1)	(X2)	(X3)	$(X1)^2$	Y
1	392.5	0.004	0.025	154056.25	29.20
2	392.5	0.004	0.025	154056.25	25.30
3	392.5	0.004	0.025	154056.25	27.00
4	392.5	0.004	0.025	154056.25	25.76
5	392.5	0.004	0.025	154056.25	25.50
6	1570.8	0.004	0.025	2467412.64	24.40
7	1570.8	0.004	0.025	2467412.64	24.10
8	1570.8	0.004	0.025	2467412.64	23.10
9	1570.8	0.004	0.025	2467412.64	21.00
10	1570.8	0.004	0.025	2467412.64	21.36
11	2748.89	0.004	0.025	7556396.232	23.60
12	2748.89	0.004	0.025	7556396.232	23.70
13	2748.89	0.004	0.025	7556396.232	25.80
14	2748.89	0.004	0.025	7556396.232	21.90
15	2748.89	0.004	0.025	7556396.232	23.90

Table 27

#	(X1)	(X2)	(X3)	$(X1)^2$	Y
1	392.5	0.004	0.048	154056.25	28.30
2	392.5	0.004	0.048	154056.25	24.70
3	392.5	0.004	0.048	154056.25	24.30
4	392.5	0.004	0.048	154056.25	29.20
5	392.5	0.004	0.048	154056.25	23.50
6	1570.8	0.004	0.048	2467412.64	27.70
7	1570.8	0.004	0.048	2467412.64	26.60
8	1570.8	0.004	0.048	2467412.64	26.20
9	1570.8	0.004	0.048	2467412.64	28.40
10	1570.8	0.004	0.048	2467412.64	27.10
11	2748.89	0.004	0.048	7556396.232	28.30
12	2748.89	0.004	0.048	7556396.232	26.40
13	2748.89	0.004	0.048	7556396.232	27.60
14	2748.89	0.004	0.048	7556396.232	27.00
15	2748.89	0.004	0.048	7556396.232	25.60

APPENDIX B

CARBIDE TOOL

Table 28

X1 = speed = constant ;   X2 = feed = constant

X3 = depth of cut = variable; Y = surface roughness

#	(X1)	(X2)	(X3)	$(X3)^2$	Y
1	392.5	0.001	0.002	0.000004	5.33
2	392.5	0.001	0.002	0.000004	5.60
3	392.5	0.001	0.002	0.000004	6.16
4	392.5	0.001	0.002	0.000004	5.46
5	392.5	0.001	0.002	0.000004	5.76
6	392.5	0.001	0.025	0.000625	9.06
7	392.5	0.001	0.025	0.000625	7.40
8	392.5	0.001	0.025	0.000625	6.86
9	392.5	0.001	0.025	0.000625	5.40
10	392.5	0.001	0.025	0.000625	5.06
11	392.5	0.001	0.048	0.002304	10.46
12	392.5	0.001	0.048	0.002304	7.46
13	392.5	0.001	0.048	0.002304	8.36
14	392.5	0.001	0.048	0.002304	6.76
15	392.5	0.001	0.048	0.002304	5.70

Table 29

#	(X1)	(X2)	(X3)	$(X3)^2$	Y
1	392.5	0.0025	0.002	0.000004	7.12
2	392.5	0.0025	0.002	0.000004	6.76
3	392.5	0.0025	0.002	0.000004	7.83
4	392.5	0.0025	0.002	0.000004	6.83
5	392.5	0.0025	0.002	0.000004	6.83
6	392.5	0.0025	0.025	0.000625	9.66
7	392.5	0.0025	0.025	0.000625	5.20
8	392.5	0.0025	0.025	0.000625	8.60
9	392.5	0.0025	0.025	0.000625	6.50
10	392.5	0.0025	0.025	0.000625	9.23
11	392.5	0.0025	0.048	0.002304	7.90
12	392.5	0.0025	0.048	0.002304	8.00
13	392.5	0.0025	0.048	0.002304	7.30
14	392.5	0.0025	0.048	0.002304	8.90
15	392.5	0.0025	0.048	0.002304	9.90

Table 30

#	(X1)	(X2)	(X3)	$(X3)^2$	Y
1	392.5	0.004	0.002	0.000004	19.23
2	392.5	0.004	0.002	0.000004	17.03
3	392.5	0.004	0.002	0.000004	18.13
4	392.5	0.004	0.002	0.000004	18.66
5	392.5	0.004	0.002	0.000004	18.66
6	392.5	0.004	0.025	0.000625	16.83
7	392.5	0.004	0.025	0.000625	16.20
8	392.5	0.004	0.025	0.000625	16.46
9	392.5	0.004	0.025	0.000625	15.56
10	392.5	0.004	0.025	0.000625	15.43
11	392.5	0.004	0.048	0.002304	18.66
12	392.5	0.004	0.048	0.002304	16.13
13	392.5	0.004	0.048	0.002304	16.46
14	392.5	0.004	0.048	0.002304	15.83
15	392.5	0.004	0.048	0.002304	16.23

Table 31

#	(X1)	(X2)	(X3)	$(X3)^2$	Y
1	1570.8	0.001	0.002	0.000004	7.13
2	1570.8	0.001	0.002	0.000004	6.63
3	1570.8	0.001	0.002	0.000004	8.60
4	1570.8	0.001	0.002	0.000004	6.66
5	1570.8	0.001	0.002	0.000004	8.13
6	1570.8	0.001	0.025	0.000625	6.26
7	1570.8	0.001	0.025	0.000625	6.63
8	1570.8	0.001	0.025	0.000625	8.16
9	1570.8	0.001	0.025	0.000625	7.30
10	1570.8	0.001	0.025	0.000625	7.60
11	1570.8	0.001	0.048	0.002304	9.20
12	1570.8	0.001	0.048	0.002304	4.70
13	1570.8	0.001	0.048	0.002304	8.03
14	1570.8	0.001	0.048	0.002304	5.70
15	1570.8	0.001	0.048	0.002304	8.13

Table 32

#	(X1)	(X2)	(X3)	$(X3)^2$	Y
1	1570.8	0.0025	0.002	0.000004	8.40
2	1570.8	0.0025	0.002	0.000004	8.50
3	1570.8	0.0025	0.002	0.000004	7.93
4	1570.8	0.0025	0.002	0.000004	7.93
5	1570.8	0.0025	0.002	0.000004	7.96
6	1570.8	0.0025	0.025	0.000625	8.93
7	1570.8	0.0025	0.025	0.000625	7.86
8	1570.8	0.0025	0.025	0.000625	9.06
9	1570.8	0.0025	0.025	0.000625	9.90
10	1570.8	0.0025	0.025	0.000625	9.33
11	1570.8	0.0025	0.048	0.002304	9.40
12	1570.8	0.0025	0.048	0.002304	6.13
13	1570.8	0.0025	0.048	0.002304	8.80
14	1570.8	0.0025	0.048	0.002304	6.16
15	1570.8	0.0025	0.048	0.002304	6.63

Table 33

#	(X1)	(X2)	(X3)	$(X3)^2$	Y
1	1570.8	0.004	0.002	0.000004	19.33
2	1570.8	0.004	0.002	0.000004	17.90
3	1570.8	0.004	0.002	0.000004	15.60
4	1570.8	0.004	0.002	0.000004	16.93
5	1570.8	0.004	0.002	0.000004	18.96
6	1570.8	0.004	0.025	0.000625	15.63
7	1570.8	0.004	0.025	0.000625	17.00
8	1570.8	0.004	0.025	0.000625	17.36
9	1570.8	0.004	0.025	0.000625	17.03
10	1570.8	0.004	0.025	0.000625	15.26
11	1570.8	0.004	0.048	0.002304	17.06
12	1570.8	0.004	0.048	0.002304	16.36
13	1570.8	0.004	0.048	0.002304	15.66
14	1570.8	0.004	0.048	0.002304	15.80
15	1570.8	0.004	0.048	0.002304	14.83

Table 34

#	(X1)	(X2)	(X3)	$(X3)^2$	Y
1	2748.89	0.001	0.002	0.000004	8.56
2	2748.89	0.001	0.002	0.000004	8.33
3	2748.89	0.001	0.002	0.000004	9.46
4	2748.89	0.001	0.002	0.000004	8.50
5	2748.89	0.001	0.002	0.000004	9.26
6	2748.89	0.001	0.025	0.000625	7.00
7	2748.89	0.001	0.025	0.000625	7.76
8	2748.89	0.001	0.025	0.000625	7.46
9	2748.89	0.001	0.025	0.000625	5.80
10	2748.89	0.001	0.025	0.000625	7.23
11	2748.89	0.001	0.048	0.002304	7.63
12	2748.89	0.001	0.048	0.002304	6.50
13	2748.89	0.001	0.048	0.002304	6.00
14	2748.89	0.001	0.048	0.002304	7.36
15	2748.89	0.001	0.048	0.002304	5.73

Table 35

#	(X1)	(X2)	(X3)	$(X3)^2$	Y
1	2748.89	0.0025	0.002	0.000004	10.23
2	2748.89	0.0025	0.002	0.000004	9.86
3	2748.89	0.0025	0.002	0.000004	9.70
4	2748.89	0.0025	0.002	0.000004	10.23
5	2748.89	0.0025	0.002	0.000004	9.00
6	2748.89	0.0025	0.025	0.000625	7.50
7	2748.89	0.0025	0.025	0.000625	8.70
8	2748.89	0.0025	0.025	0.000625	9.53
9	2748.89	0.0025	0.025	0.000625	7.93
10	2748.89	0.0025	0.025	0.000625	7.70
11	2748.89	0.0025	0.048	0.002304	9.96
12	2748.89	0.0025	0.048	0.002304	6.86
13	2748.89	0.0025	0.048	0.002304	8.26
14	2748.89	0.0025	0.048	0.002304	7.56
15	2748.89	0.0025	0.048	0.002304	7.33

Table 36

#	(X1)	(X2)	(X3)	$(X3)^2$	Y
1	2748.89	0.004	0.002	0.000004	20.00
2	2748.89	0.004	0.002	0.000004	18.96
3	2748.89	0.004	0.002	0.000004	16.40
4	2748.89	0.004	0.002	0.000004	18.83
5	2748.89	0.004	0.002	0.000004	16.73
6	2748.89	0.004	0.025	0.000625	16.23
7	2748.89	0.004	0.025	0.000625	15.80
8	2748.89	0.004	0.025	0.000625	15.56
9	2748.89	0.004	0.025	0.000625	15.06
10	2748.89	0.004	0.025	0.000625	15.30
11	2748.89	0.004	0.048	0.002304	16.03
12	2748.89	0.004	0.048	0.002304	15.06
13	2748.89	0.004	0.048	0.002304	15.26
14	2748.89	0.004	0.048	0.002304	15.20
15	2748.89	0.004	0.048	0.002304	15.13

Table 37

X1 = speed = constant ;   X2 = feed = variable

X3 = depth of cut = constant; Y = surface roughness

#	(X1)	(X2)	(X3)	$(X2)^2$	Y
1	392.5	0.001	0.002	0.000001	5.33
2	392.5	0.001	0.002	0.000001	5.60
3	392.5	0.001	0.002	0.000001	6.16
4	392.5	0.001	0.002	0.000001	5.46
5	392.5	0.001	0.002	0.000001	5.76
6	392.5	0.0025	0.002	0.00000625	7.12
7	392.5	0.0025	0.002	0.00000625	6.76
8	392.5	0.0025	0.002	0.00000625	7.83
9	392.5	0.0025	0.002	0.00000625	6.83
10	392.5	0.0025	0.002	0.00000625	6.83
11	392.5	0.004	0.002	0.000016	19.23
12	392.5	0.004	0.002	0.000016	17.03
13	392.5	0.004	0.002	0.000016	18.13
14	392.5	0.004	0.002	0.000016	18.66
15	392.5	0.004	0.002	0.000016	18.66

Table 38

#	(X1)	(X2)	(X3)	$(X2)^2$	Y
1	392.5	0.001	0.025	0.000001	9.06
2	392.5	0.001	0.025	0.000001	7.40
3	392.5	0.001	0.025	0.000001	6.86
4	392.5	0.001	0.025	0.000001	5.40
5	392.5	0.001	0.025	0.000001	5.06
6	392.5	0.0025	0.025	0.00000625	9.66
7	392.5	0.0025	0.025	0.00000625	5.20
8	392.5	0.0025	0.025	0.00000625	8.60
9	392.5	0.0025	0.025	0.00000625	6.50
10	392.5	0.0025	0.025	0.00000625	9.23
11	392.5	0.004	0.025	0.000016	16.83
12	392.5	0.004	0.025	0.000016	16.20
13	392.5	0.004	0.025	0.000016	16.46
14	392.5	0.004	0.025	0.000016	15.56
15	392.5	0.004	0.025	0.000016	15.43

Table 39

#	(X1)	(X2)	(X3)	$(X2)^2$	Y
1	392.5	0.001	0.048	0.000001	10.46
2	392.5	0.001	0.048	0.000001	7.46
3	392.5	0.001	0.048	0.000001	8.36
4	392.5	0.001	0.048	0.000001	6.76
5	392.5	0.001	0.048	0.000001	5.70
6	392.5	0.0025	0.048	0.0000065	7.90
7	392.5	0.0025	0.048	0.0000062	8.00
8	392.5	0.0025	0.048	0.00000625	7.30
9	392.5	0.0025	0.048	0.00000625	8.90
10	392.5	0.0025	0.048	0.00000625	9.90
11	392.5	0.004	0.048	0.000016	18.66
12	392.5	0.004	0.048	0.000016	16.13
13	392.5	0.004	0.048	0.000016	16.46
14	392.5	0.004	0.048	0.000016	15.83
15	392.5	0.004	0.048	0.000016	16.23

Table 40

#	(X1)	(X2)	(X3)	$(X2)^2$	Y
1	1570.8	0.001	0.002	0.000001	7.13
2	1570.8	0.001	0.002	0.000001	6.63
3	1570.8	0.001	0.002	0.000001	8.60
4	1570.8	0.001	0.002	0.000001	6.66
5	1570.8	0.001	0.002	0.000001	8.13
6	1570.8	0.0025	0.002	0.00000625	8.40
7	1570.8	0.0025	0.002	0.00000625	8.50
8	1570.8	0.0025	0.002	0.00000625	7.93
9	1570.8	0.0025	0.002	0.00000625	7.93
10	1570.8	0.0025	0.002	0.00000625	7.96
11	1570.8	0.004	0.002	0.000016	19.33
12	1570.8	0.004	0.002	0.000016	17.90
13	1570.8	0.004	0.002	0.000016	15.60
14	1570.8	0.004	0.002	0.000016	16.93
15	1570.8	0.004	0.002	0.000016	18.96

Table 41

#	(X1)	(X2)	(X3)	$(X2)^2$	Y
1	1570.8	0.001	0.025	0.000001	6.26
2	1570.8	0.001	0.025	0.000001	6.63
3	1570.8	0.001	0.025	0.000001	8.16
4	1570.8	0.001	0.025	0.000001	7.30
5	1570.8	0.001	0.025	0.000001	7.60
6	1570.8	0.0025	0.025	0.00000625	8.93
7	1570.8	0.0025	0.025	0.00000625	7.86
8	1570.8	0.0025	0.025	0.00000625	9.06
9	1570.8	0.0025	0.025	0.00000625	9.90
10	1570.8	0.0025	0.025	0.00000625	9.33
11	1570.8	0.004	0.025	0.000016	15.63
12	1570.8	0.004	0.025	0.000016	17.00
13	1570.8	0.004	0.025	0.000016	17.36
14	1570.8	0.004	0.025	0.000016	17.03
15	1570.8	0.004	0.025	0.000016	15.26

Table 42

#	(X1)	(X2)	(X3)	$(X2)^2$	Y
1	1570.8	0.001	0.048	0.000001	9.20
2	1570.8	0.001	0.048	0.000001	4.70
3	1570.8	0.001	0.048	0.000001	8.03
4	1570.8	0.001	0.048	0.000001	5.70
5	1570.8	0.001	0.048	0.000001	8.13
6	1570.8	0.0025	0.048	0.00000625	9.40
7	1570.8	0.0025	0.048	0.00000625	6.13
8	1570.8	0.0025	0.048	0.00000625	8.80
9	1570.8	0.0025	0.048	0.00000625	6.16
10	1570.8	0.0025	0.048	0.00000625	6.63
11	1570.8	0.004	0.048	0.000016	17.06
12	1570.8	0.004	0.048	0.000016	16.36
13	1570.8	0.004	0.048	0.000016	15.66
14	1570.8	0.004	0.048	0.000016	15.80
15	1570.8	0.004	0.048	0.000016	14.83

Table 43

#	(X1)	(X2)	(X3)	$(X2)^2$	Y
1	2748.89	0.001	0.002	0.000001	8.56
2	2748.89	0.001	0.002	0.000001	8.33
3	2748.89	0.001	0.002	0.000001	9.46
4	2748.89	0.001	0.002	0.000001	8.50
5	2748.89	0.001	0.002	0.000001	9.26
6	2748.89	0.0025	0.002	0.00000625	10.23
7	2748.89	0.0025	0.002	0.00000625	9.86
8	2748.89	0.0025	0.002	0.00000625	9.70
9	2748.89	0.0025	0.002	0.00000625	10.23
10	2748.89	0.0025	0.002	0.00000625	9.00
11	2748.89	0.004	0.002	0.000016	20.00
12	2748.89	0.004	0.002	0.000016	18.96
13	2748.89	0.004	0.002	0.000016	16.40
14	2748.89	0.004	0.002	0.000016	18.83
15	2748.89	0.004	0.002	0.000016	16.73

Table 44

#	(X1)	(X2)	(X3)	$(X2)^2$	Y
1	2748.89	0.001	0.025	0.000001	7.00
2	2748.89	0.001	0.025	0.000001	7.76
3	2748.89	0.001	0.025	0.000001	7.46
4	2748.89	0.001	0.025	0.000001	5.80
5	2748.89	0.001	0.025	0.000001	7.23
6	2748.89	0.0025	0.025	0.00000625	7.50
7	2748.89	0.0025	0.025	0.00000625	8.70
8	2748.89	0.0025	0.025	0.00000625	9.53
9	2748.89	0.0025	0.025	0.00000625	7.93
10	2748.89	0.0025	0.025	0.00000625	7.70
11	2748.89	0.004	0.025	0.000016	16.23
12	2748.89	0.004	0.025	0.000016	15.80
13	2748.89	0.004	0.025	0.000016	15.56
14	2748.89	0.004	0.025	0.000016	15.06
15	2748.89	0.004	0.025	0.000016	15.30

Table 45

#	(X1)	(X2)	(X3)	$(X2)^2$	Y
1	2748.89	0.001	0.048	0.000001	7.63
2	2748.89	0.001	0.048	0.000001	6.56
3	2748.89	0.001	0.048	0.000001	6.00
4	2748.89	0.001	0.048	0.000001	7.36
5	2748.89	0.001	0.048	0.000001	5.73
6	2748.89	0.0025	0.048	0.00000625	9.96
7	2748.89	0.0025	0.048	0.00000625	6.86
8	2748.89	0.0025	0.048	0.00000625	8.26
9	2748.89	0.0025	0.048	0.00000625	7.56
10	2748.89	0.0025	0.048	0.00000625	7.33
11	2748.89	0.004	0.048	0.000016	16.03
12	2748.89	0.004	0.048	0.000016	15.06
13	2748.89	0.004	0.048	0.000016	15.26
14	2748.89	0.004	0.048	0.000016	15.20
15	2748.89	0.004	0.048	0.000016	15.13

Table 46

X1 = speed = variable ;   X2 = feed = constant

X3 = depth of cut = constant; Y = surface roughness

#	(X1)	(X2)	(X3)	$(X1)^2$	Y
1	392.5	0.001	0.002	154056.25	5.33
2	392.5	0.001	0.002	154056.25	5.60
3	392.5	0.001	0.002	154056.25	6.16
4	392.5	0.001	0.002	154056.25	5.46
5	392.5	0.001	0.002	154056.25	5.76
6	1570.8	0.001	0.002	2467412.64	7.13
7	1570.8	0.001	0.002	2467412.64	6.63
8	1570.8	0.001	0.002	2467412.64	8.60
9	1570.8	0.001	0.002	2467412.64	6.66
10	1570.8	0.001	0.002	2467412.64	8.13
11	2748.89	0.001	0.002	7556396.232	8.56
12	2748.89	0.001	0.002	7556396.232	8.33
13	2748.89	0.001	0.002	7556396.232	9.46
14	2748.89	0.001	0.002	7556396.232	8.50
15	2748.89	0.001	0.002	7556396.232	9.26

Table 47

#	(X1)	(X2)	(X3)	$(X1)^2$	Y
1	392.5	0.001	0.025	154056.25	9.06
2	392.5	0.001	0.025	154056.25	7.40
3	392.5	0.001	0.025	154056.25	6.86
4	392.5	0.001	0.025	154056.25	5.40
5	392.5	0.001	0.025	154056.25	5.06
6	1570.8	0.001	0.025	2467412.64	6.26
7	1570.8	0.001	0.025	2467412.64	6.63
8	1570.8	0.001	0.025	2467412.64	8.16
9	1570.8	0.001	0.025	2467412.64	7.30
10	1570.8	0.001	0.025	2467412.64	7.60
11	2748.89	0.001	0.025	7556396.232	7.00
12	2748.89	0.001	0.025	7556396.232	7.76
13	2748.89	0.001	0.025	7556396.232	7.46
14	2748.89	0.001	0.025	7556396.232	5.80
15	2748.89	0.001	0.025	7556396.232	7.23

Table 48

#	(X1)	(X2)	(X3)	$(X1)^2$	Y
1	392.5	0.001	0.048	154056.25	10.46
2	392.5	0.001	0.048	154056.25	7.46
3	392.5	0.001	0.048	154056.25	8.36
4	392.5	0.001	0.048	154056.25	6.76
5	392.5	0.001	0.048	154056.25	5.70
6	1570.8	0.001	0.048	2467412.64	9.20
7	1570.8	0.001	0.048	2467412.64	4.70
8	1570.8	0.001	0.048	2467412.64	8.03
9	1570.8	0.001	0.048	2467412.64	5.70
10	1570.8	0.001	0.048	2467412.64	8.13
11	2748.89	0.001	0.048	7556396.232	7.63
12	2748.89	0.001	0.048	7556396.232	6.50
13	2748.89	0.001	0.048	7556396.232	6.00
14	2748.89	0.001	0.048	7556396.232	7.36
15	2748.89	0.001	0.048	7556396.232	5.73

Table 49

#	(X1)	(X2)	(X3)	$(X1)^2$	Y
1	392.5	0.0025	0.002	154056.25	7.12
2	392.5	0.0025	0.002	154056.25	6.76
3	392.5	0.0025	0.002	154056.25	7.83
4	392.5	0.0025	0.002	154056.25	6.83
5	392.5	0.0025	0.002	154056.25	6.83
6	1570.8	0.0025	0.002	2467412.64	8.40
7	1570.8	0.0025	0.002	2467412.64	8.50
8	1570.8	0.0025	0.002	2467412.64	7.93
9	1570.8	0.0025	0.002	2467412.64	7.93
10	1570.8	0.0025	0.002	2467412.64	7.96
11	2748.89	0.0025	0.002	7556396.232	10.23
12	2748.89	0.0025	0.002	7556396.232	9.86
13	2748.89	0.0025	0.002	7556396.232	9.70
14	2748.89	0.0025	0.002	7556396.232	10.23
15	2748.89	0.0025	0.002	7556396.232	9.00

Table 50

#	(X1)	(X2)	(X3)	$(X1)^2$	Y
1	392.5	0.0025	0.025	154056.25	9.66
2	392.5	0.0025	0.025	154056.25	5.20
3	392.5	0.0025	0.025	154056.25	8.60
4	392.5	0.0025	0.025	154056.25	6.50
5	392.5	0.0025	0.025	154056.25	9.23
6	1570.8	0.0025	0.025	2467412.64	8.93
7	1570.8	0.0025	0.025	2467412.64	7.86
8	1570.8	0.0025	0.025	2467412.64	9.06
9	1570.8	0.0025	0.025	2467412.64	9.90
10	1570.8	0.0025	0.025	2467412.64	9.33
11	2748.89	0.0025	0.025	7556396.232	7.50
12	2748.89	0.0025	0.025	7556396.232	8.70
13	2748.89	0.0025	0.025	7556396.232	9.53
14	2748.89	0.0025	0.025	7556396.232	7.93
15	2748.89	0.0025	0.025	7556396.232	7.70

Table 51

#	(X1)	(X2)	(X3)	$(X1)^2$	Y
1	392.5	0.0025	0.048	154056.25	7.90
2	392.5	0.0025	0.048	154056.25	8.00
3	392.5	0.0025	0.048	154056.25	7.30
4	392.5	0.0025	0.048	154056.25	8.90
5	392.5	0.0025	0.048	154056.25	9.90
6	1570.8	0.0025	0.048	2467412.64	9.40
7	1570.8	0.0025	0.048	2467412.64	6.13
8	1570.8	0.0025	0.048	2467412.64	8.80
9	1570.8	0.0025	0.048	2467412.64	6.16
10	1570.8	0.0025	0.048	2467412.64	6.63
11	2748.89	0.0025	0.048	7556396.232	9.96
12	2748.89	0.0025	0.048	7556396.232	6.86
13	2748.89	0.0025	0.048	7556396.232	8.26
14	2748.89	0.0025	0.048	7556396.232	7.56
15	2748.89	0.0025	0.048	7556396.232	7.33

Table 52

#	(X1)	(X2)	(X3)	$(X1)^2$	Y
1	392.5	0.004	0.002	154056.25	19.23
2	392.5	0.004	0.002	154056.25	17.03
3	392.5	0.004	0.002	154056.25	18.13
4	392.5	0.004	0.002	154056.25	18.66
5	392.5	0.004	0.002	154056.25	18.66
6	1570.8	0.004	0.002	2467412.64	19.33
7	1570.8	0.004	0.002	2467412.64	17.90
8	1570.8	0.004	0.002	2467412.64	15.60
9	1570.8	0.004	0.002	2467412.64	16.93
10	1570.8	0.004	0.002	2467412.64	18.96
11	2748.89	0.004	0.002	7556396.232	20.00
12	2748.89	0.004	0.002	7556396.232	18.96
13	2748.89	0.004	0.002	7556396.232	16.40
14	2748.89	0.004	0.002	7556396.232	18.83
15	2748.89	0.004	0.002	7556396.232	16.73

Table 53

#	(X1)	(X2)	(X3)	$(X1)^2$	Y
1	392.5	0.004	0.025	154056.25	16.83
2	392.5	0.004	0.025	154056.25	16.20
3	392.5	0.004	0.025	154056.25	16.46
4	392.5	0.004	0.025	154056.25	15.56
5	392.5	0.004	0.025	154056.25	15.43
6	1570.8	0.004	0.025	2467412.64	15.63
7	1570.8	0.004	0.025	2467412.64	17.00
8	1570.8	0.004	0.025	2467412.64	17.36
9	1570.8	0.004	0.025	2467412.64	17.03
10	1570.8	0.004	0.025	2467412.64	15.26
11	2748.89	0.004	0.025	7556396.232	16.23
12	2748.89	0.004	0.025	7556396.232	15.80
13	2748.89	0.004	0.025	7556396.232	15.56
14	2748.89	0.004	0.025	7556396.232	15.06
15	2748.89	0.004	0.025	7556396.232	15.30

Table 54

#	(X1)	(X2)	(X3)	$(X1)^2$	Y
1	392.5	0.004	0.048	154056.25	18.66
2	392.5	0.004	0.048	154056.25	16.13
3	392.5	0.004	0.048	154056.25	16.46
4	392.5	0.004	0.048	154056.25	15.83
5	392.5	0.004	0.048	154056.25	16.23
6	1570.8	0.004	0.048	2467412.64	17.06
7	1570.8	0.004	0.048	2467412.64	16.36
8	1570.8	0.004	0.048	2467412.64	15.66
9	1570.8	0.004	0.048	2467412.64	15.80
10	1570.8	0.004	0.048	2467412.64	14.83
11	2748.89	0.004	0.048	7556396.232	16.03
12	2748.89	0.004	0.048	7556396.232	15.06
13	2748.89	0.004	0.048	7556396.232	15.26
14	2748.89	0.004	0.048	7556396.232	15.20
15	2748.89	0.004	0.048	7556396.232	15.13

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