PREDICTION OF CUTTING POWER IN END-MILLING OPERATION OF MODIFIED AISI P20 TOOL STEEL

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I hereby declare that the work in this project is my own except for quotations and summaries which have been duly acknowledged. The project has not been accepted for any degree and is not concurently submitted for award of other degree.

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To my Beloved Family:

PUAN SAODAH BINTI BADELI

ENCIK ABU BIN SARNI

NORHALIZAH BINTI ABU

MOHD ZAHID BIN ABU

ERWINA NURSYAHEERA BINTI SULAIMAN

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ABSTRACT

The present paper discusses the development of the first and second order models for predicting the cutting power produced in end-milling operation of modified AISI P20 tool steel. The first and second order cutting force equations are developed using the response surface methodology (RSM) to study the effect of four input cutting parameters which is cutting speed, feed rate, radial depth and axial depth of cut on cutting power. The cutting power contours with respect to input parameters are presented and the predictive models analyses are performed with the aid of the statistical software package Minitab. The separate affect of individual input factors and the interaction between these factors are also investigated in this study. In first order model, the increase in the cutting speed, feed rate, axial and radial depths of cut will cause the cutting power to become larger. The received second order equation shows, based on the variance analysis, that the cutting power decreased when cutting speed, federate, axial and radial depth of cut is reduced. The predictive models in this study are believed to produce values of the longitudinal component of the cutting power close to those readings recorded experimentally with a 95% confident interval.

ABSTRAK

Kertas projek ini membincangkan perkembangan dalam pertama dan kedua susunan model untuk menjangkakan kekuatan pemotongan yang dihasilkan dalam operasi hujung kisaran terhadap modifikasi AISI P20 alatan besi. Persamaan pertama dan kedua susunan kekuatan pemotongan telah dikembangkan dengan menggunakan kaedah tindakbalas permukaan untuk mempelajari kesan terhadap empat pengeluar kekuatan pemotongan di mana ianya adalah kelajuan pemotongan, kadar pembekal, kedalaman axial dan radial terhadap kekuatan pemotongan. Kecerunan kekuatan pemotongan yang berkait dengan parameter pengeluar telah dibentangkan dan jangkaan model yang dianalisis telah dilakukan dengan bantuan perisian statistik Minitab. Pembahagian kesan terhadap individu faktor pengeluar dan interaksi antara factor-faktor ini juga telah disiasat dalam kertas projek ini. Dalam susunan model pertama, peningkatan kelajuan pemotongan, kadar pembekal, kedalaman axial dan radial terhadap kekuatan pemotongan telah menyebabkan kekuatan pomotongan juga meningkat. Penerimaan persamaan susunan kedua berdasarkan perbezaan analisis di mana kekuatan pemotongan berkurangan apabila kelajuan pemotongan, kadar pembekal, kedalaman axial dan radial terhadap kekuatan pemotongan telah dikurangkan. Jangkaan model dalam kertas projek ini dipercayai dapat menghasilkan nilai komponen membujur terhadap kekuatan pemotongan menghampiri kepada bacaan yg direkodkan secara experimen dengan 95% jeda keyakinan.

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LIST OF SYMBOLS

Vc	Velocity vector
kC	Specific cutting force
FD	Thrust force
p	Cutting power response
cs	Cutting speed
fr	Federate
ad	Axial depth
rd	Radial depth
y	Cutting power experimental value
$\hat{y}$	Cutting power predicted value
β_0, β_1, β_2, β_3 and β_4	Model parameter
ε	Experimental error
Py	Power component
x_0	Dummy variable
x_1, x_2, x_3 and x_4	Cutting speed, feed rate, axial depth of cut and radial depth of cut substitute in cutting power model.

LIST OF ABBREVIATIONS

AISI	American Iron Steel Institute
ANOVA	Analysis of Variance
ASME	American Society Mechanical Engineer
BUE	Built Up Edge
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CVD	Chemical Vapor Deposition
CNC	Computer Numerical Control
DOE	Design of Experiment
HSS	High Speed Steel
ISO	International Standard Organization
NN	Neural Network
PVD	Physical Vapor Deposition
RSM	Response Surface Methodology

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

The advances in technology and the recent industrial revolution have led to an increased use of highly automated machine tools, machining centre and coordinate measuring machines. These modern machine tools with their inherent accuracy and associated precision, capable of being driven by computers have been responsible for the recent 'industrial revolution' leading to flexible manufacturing systems and modem computer based manufacturing. Efforts to further improve and optimize machining times and costs by reliable estimation of performance features such as forces, power, tool-life, temperatures and surface finish is increasingly becoming important in modern manufacturing industry (V. Karri and H. Talhami, 1995). To accommodate modern resource-intensive high-performance applications, large-scale computing and storage platforms have grown at a rapid pace in a variety of domains ranging from research labs and academic groups to industry. The fast-growing power consumption of these platforms is a major concern due to its implications on the cost and efficiency of these platforms as well as the well-being of environment. Trends from such platforms suggest that the power consumption in high-performance computing platforms accounts for 1.2% of the overall electricity consumption in the United State. More alarmingly, if current practices for the design and operation of these platforms continue, their power consumption is projected to keep growing at 18% every year. These observations have spurred great interest among providers of high-end computing platforms to explore ways to dampen the growth rate of servers by doing better consolidation as workload conditions change, it may be desirable to pack hosted applications on to different subsets of racks/servers within the data center and turn off machines that are not needed (P. Bohrer, D. Cohn, E. Elnozahy, T. Keller, M. Kistler, C. Lefurgy, R. Rajamony, F. Rawson and E. V. Hensbergen, 2001). Another major concern for such large-scale computing platforms is the increase in power density of the servers which are reaching the limits of the power delivery and cooling infrastructure of these platforms, thereby affecting the reliability concerns of these platforms. This has been addressed in literature by reducing the peak power consumption both at the server level (W. Felter, K. Rajamani, T. Keller, and C. Rusu, 2005) as well as at the cluster level (P. Ranganathan, P. Leech, D. Irwin, and J. Chase, 2006). Power budget is typically enforced at different hierarchies of a data center and it specifies a cap on the power consumption of applications consolidated under that hierarchy. Such research would be useful to an energy-friendly operation and management of consolidated platforms in a variety of ways. First, it will facilitate the prediction and control of energy consumption in consolidated environments. Second, in combination with existing research on workload characterization and application modeling, it will facilitate meaningful trade-offs between energy costs and application performance. Finally, ongoing efforts to develop power benchmarks would also benefit from such characterization. Consolidation may occur at multiple spatial granularities, ranging from co-location of multiple applications on a single server to diversion of workloads to a subset of the server racks or rooms. Correspondingly, characterization of power consumption is desirable at each of these levels.

1.2 PROBLEM STATEMENT

The long-term average power consumption within a subsystem dictates the energy costs involved in operating it. The possibility of sustained power consumption above thresholds associated with fuses/circuit-breakers critically affects the safe operation of devices protected by these elements (P. Bohrer, D. Cohn, E. Elnozahy, T. Keller, M. Kistler, C. Lefurgy, R. Rajamony, F. Rawson, and E. V. Hensbergen, 2001). Characterizing the properties of power consumption within a given consolidation hierarchy results in problems that are significantly different from those encountered in characterizing performance and resource usage. As a motivate example, considering the comparison of power consumption for two different consolidation scenarios, each packing a pair of applications on the same server. The power consumptions compared of individual applications with that when they were co-located. Prediction of power consumption requires to accurately identifying these dependencies. Furthermore, the success of such prediction also depends on the methodology used to measure and characterize individual consumption. Consolidation further increases the power density of the servers, aggravating the reliability concerns of the facility. Literature has addressed the energy and reliability related concerns in a data center using the notion of power budgets (R. Raghavendra, P. Ranganathan, V. Talwar, Z. Wang, and X. Zhu, 2008).

1.3 OBJECTIVES

The objectives of this study is to develop prediction first and second mathematical model for cutting power using response surface methodology when milling AISI P20 tool steel and to investigate the relationship between cutting parameters which is cutting speed, federate, axial and radial depth of cut with cutting power.

1.4 LIMITATION

The develop models only can be used in the certain range; cutting speed between 100 to 180 m/min, feedrate between 0.1 to 0.2 mm/tooth, axial depth between 1 to 2 mm and radial depth between 2 to 5 mm.

1.5 THESIS OUTLINE

This thesis consists of five chapters. Chapter 1 will state the background study, problem statement, objective and limitation of study while chapter 2 consists of literature review. Then followed by chapter 3 regarding experiment setup and design of experiment. Chapter 4 clearly explains the analysis and result obtained during experiment and finally chapter 5 will conclude the whole thesis and some recommended for future planning.

CHAPTER 2

LITERATURE REVIEW

2.1 OBLIGUE CUTTING

One of the earliest studies of three-dimensional cutting was undertaken in which the mechanics of cutting were analyzed for both orthogonal and oblique cutting. Mechant developed an equation for the chip flow angle, which is defined as the angle between a line that is normal to the cutting edge and the direction of chip flow on the tool face (M.E. Mechant, 1944). The cutting action along the cutting lips can be interpreted as occurring within a series of oblique sections, in which the rake and inclination angles vary radially along each lip (Foldvick, A.K., U. Kristiansen and J. Kvoerness, 1995). Figure 2.1 below shows the model of oblique cutting.

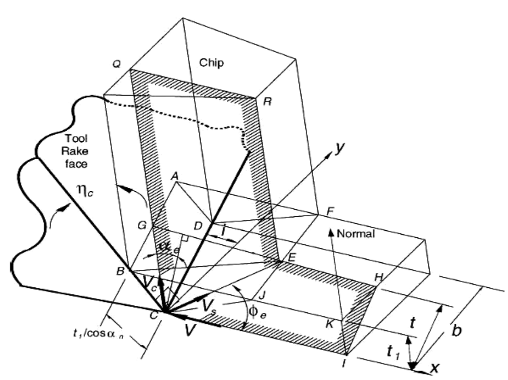


Figure 2.1: Model of oblique cutting

Source: J.S. Strenkowski, C.C. Hsieh and A.J. Shih (2004)

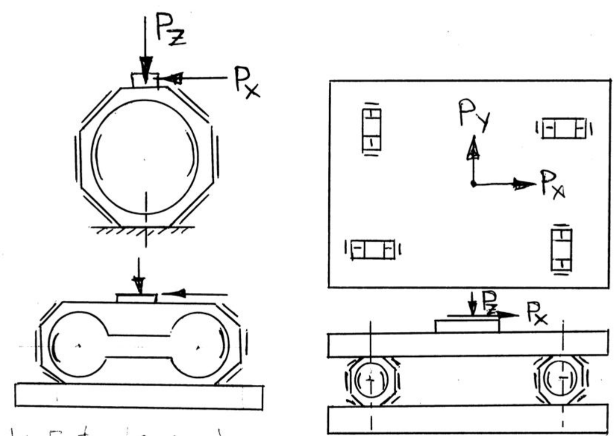
The three-dimensional cutting is interpreted as a series of orthogonal slices, each with the same effective shear plane angle and effective rake angle along the main cutting edge. In case of oblique cutting, which is practically more common, the actual direction of chip flow and the corresponding rake angle, effective rake should be used for more reasonably accurate analysis and assessment of cutting forces, friction and tool wear. An analytical model developed for predicting the chip flow angle and three-dimensional tool forces is first reviewed. The analysis is based on an energy approach in which three-dimensional cutting is approximated as a series of orthogonal slices. Using orthogonal cutting data under equivalent cutting conditions, the chip flow angle and three-dimensional tool forces can be determined for single-point tools with a nose radius (E. Usui and A. Hirota, 1978). An early attempt to predict three-dimensional cutting forces was also reported in which the forces were predicted from the workpiece flow stress measured in a machining test (G.C.I. Lin and P.L.B. Oxley, 1972).

2.2 CUTTING POWER

There have been many studies concerning the effect of cutting parameters and rake angle on the cutting forces. The influence of machining parameters such as cutting speed, feed rate, axial and radial depth of cut for different materials have been investigated (J.W. Youn, M.Y. Yang and H.Y. Park. 1994; A.J. Shih. 1996). The earliest model to describe the metal cutting process is based on the shear plane assumption of Ernst and Merchant (Ernst, H. and Merchant, M. E. 1941). Development a model for orthogonal cutting to predict forces and average temperatures and stresses in the deformation zones by using cutting conditions .Cutting forces are either measured in the real machining process or predicted in the machining process design. Cutting forces are measured by means of special device called tool force dynamometer mounted on the machine tool. More advanced options for cutting force prediction are based on analytical or numerical modeling of metal cutting. Due to the complex nature of the cutting process, the modeling is typically restricted to orthogonal cutting conditions, although solutions for the three-dimensional cutting are also available in the literature. The cutting force value is primarily affected by cutting conditions such as cutting speed, federate and depth of cut, cutting tool geometry such as tool orthogonal rake angle and properties of work material. In machining industries and research and development sections the cutting power are desired and required to be measured by experiments for determining the cutting power accurately, precisely and reliably unlike analytical method. It could also determining the magnitude of the cutting forces directly when equations are not available or adequate and to experimentally verify mathematical models. Otherwise, the purpose of measurement cutting power to explore and evaluate role or effects of variation of any parameters such as cutting speed, federate, axial and radial of depth, involved in machining, on cutting forces and friction which cannot be done analytically. It could also determine and study the shear or fracture strength of the work material under the various machining conditions and predict the cutting tool condition such as wear, chipping, fracturing and plastic deformation from the online measured cutting forces. Nevertheless, it could directly assess the relative performance of any new work material, tool geometry, cutting fluid application and special technique in respect of cutting forces and power consumption. Experimental evidence had shown that the dependence of the specific cutting energy on the chip thickness and cutting velocity can be well described by a power law relationship (Sabberwal, A. J. P. 1961; Oxley, P. L. B. 1963). The specific cutting energy decreased significantly with speed using relatively large negative rake angle tools (Davies, M. A., Chou, Y., and Evans, C. J. 1996).

2.3 DYNAMOMETER

Various dynamometer design techniques have been used in force measurement based on strain measurement and ring theory (M.C. Shaw. 1984; K.N. Strafford and J. Audy. 1997; M. Santochi, G. Dini, G. Tantussi and M. Beghini, 1997) mechanical force measurement device with three axis (N. Otmanboluk, I. Ay and Z. Aksoy. 1987), dynamometers with dial gage, piezoelectric dynamometer with three part (L.J. Plebani and J.J. Fu. 1993; A.J. Shih. 1996; W.L. Jin, P.K. Venuviod and X. Wang. 1995), sensor integrated into rotary tool (X. Dai and G.H. Gautschi. 1997; B. Yardimoglu and L. Boyar. 1992) and dynamometer included load cells based on strain measurement (J.W. Youn, M.Y. Yang and H.Y. Park. 1994). The existence of some physical variables like force and temperature and its magnitude or strength cannot be detected or quantified directly but can be so through their effects only. For example, a force which can neither be seen nor be gripped but can be detected and also quantified respectively by its effects and the amount of those effects on some material like elastic deflection, deformation, pressure and strain. These effects, called signals, often need proper conditioning for easy, accurate and reliable detection and measurement. The measurement process is comprised of three stages. On the first stage, the target physical variable is converted proportionally into another suitable variable called signal, by using appropriate sensor or transducer. On the second stage, the feeble and noisy signal is amplified, filtered, rectified and stabilized for convenience and accuracy of measurement and the final stage where the conditioned signal is quantitatively determined and recorded by using some read out unit like galvanometer, oscilloscope, recorder or computer. In milling dynamometer, since the cutting or loading point is not fixed and the dynamometer, the job platform rests on four symmetrically located supports in the form of four O-rings. The forces on each O-ring are monitored and summed up correspondingly for getting the total magnitude of all the three forces in X, Y and Z direction respectively. Figure 2.2 below shows schematically the principle of using O-ring for measuring two forces by mounting strain gauges, 4 for radial force and 4 for transverse force.



(a) Extended O-ring (b) Four O-rings for PX, PY and PZ

Figure 2.2: Scheme of strain gauge type 3 – D milling dynamometer

Source: onlinefreeebooks.net

2.4 COOLANT

Although cutting fluids account for only a small fraction of the cost of metalworking operations, disposal of spent cutting fluid can be expensive and troublesome. In past years, shops simply disposed of their metalworking fluid as soon as it showed signs of degradation and decreased performance. It was easier to get rid of and replenish fluids than to extend their life. Now, with more stringent environmental regulations, stricter rules for sanitary sewer discharges, increasing costs for cutting fluids, and higher costs for disposal, shops have become increasingly aware of the advantages of prolonging cutting fluid life. Besides the direct economic benefits, more effective and longer lasting cutting fluids and the development of efficient coolant-cleaning technologies has made coolant management and maintenance beneficial for the environment. New coolant management and maintenance programs can minimize contamination, prolong cutting fluid life and reduce operating costs (Benes, J. 2007). Cutting fluids have been used extensively in metal cutting operations for the last 200 years. In the beginning, cutting fluids consisted of simple oils applied with brushes to lubricate and cool the machine tool. Occasionally, lard, animal fat or whale oil was added to improve the oil's lubricity. As cutting operations became more severe, cutting fluid formulations became more complex. Today’s cutting fluids are special blends of chemical additives, lubricants and water formulated to meet the performance demands of the metalworking industry. There are now several types of cutting fluids on the market, the most common of which can be broadly categorized as cutting oils or water-miscible fluids. Water-miscible fluids, including soluble oils, synthetics and semisynthetics, are now used in approximately 80 to 90 percent of all applications (Aronson, R.B. 1994). Figure 2.3 below shows a mineral-oil based chlorine-free fluid.

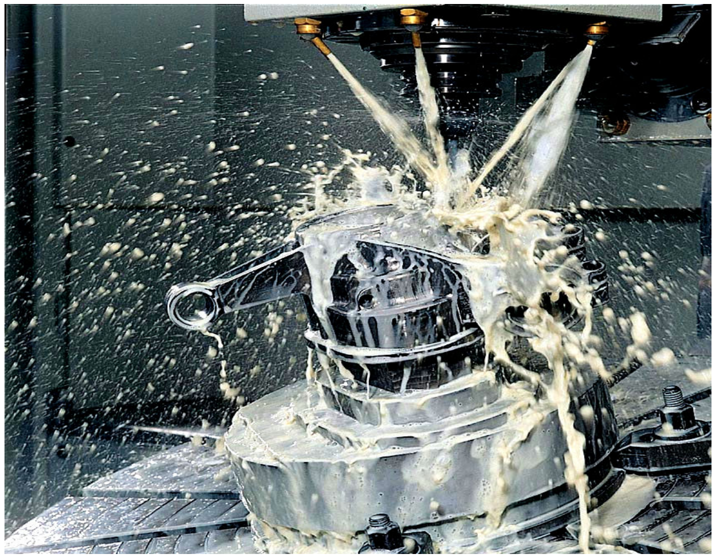


Figure 2.3: A mineral-oil based, chlorine-free fluid is formulated to reduce instability, separations and short fluid life when cutting magnesium

Source: Benes, J. (2007)

Although straight cutting oils are less popular than they were in the past, they are still the fluid of choice for certain metalworking applications. Fortunately, cutting fluid life may be extended significantly by implementing an effective fluid management program. The primary objective of fluid management is to maintain fluid quality and performance through administration, monitoring, maintenance and recycling practices. This allows machine shops to make the most cost-effective use of their fluid. It is also the best pollution prevention technology available. Overall, fluid management provides a means to operate in a more environmentally sound manner, improve productivity and reduce costs, increase competitiveness, maintain environmental compliance and reduce environmental liability, consistently manufacture quality products and provide a healthier and safer work environment for employees. Cutting fluids may also be atomized and blown onto the tool/workpiece interface via mist application. This application method requires adequate ventilation to protect the machine tool operator. The pressure and direction of the mist stream are also crucial to the success of the application. Metalworking fluid used in flood or mist applications is typically stored and distributed utilizing an individual machine tool system or a central reservoir system

(Tuholski, R.J. 1993). Individual machine tools with internal cutting fluid systems consist of a sump for fluid storage, a pump, delivery piping, a spent fluid collection and return system, and a filter to remove contaminants. Coolant recirculates from the machine sump to the machine tool. A fluid’s cooling and lubrication properties are critical in decreasing tool wear and extending tool life. Cooling and lubrication are also important in achieving the desired size, finish and shape of the workpiece (Sluhan, C.A. 1994). To inhibit corrosion, a fluid must prevent metal, moisture and oxygen from coming together. Chemical metalworking fluids now contain additives which prevent corrosion through formation of invisible, nonporous films. Two types of invisible, nonporous films are produced by metalworking fluids to prevent corrosion from occurring. These include polar and passivating films (Bienkowski, K. 1993). Polar films consist of organic compounds (such as amines and fatty acids) which form a protective coating on a metal's surface, blocking chemical reactions. Passivating films are formed by inorganic compounds containing oxygen (such as borates, phosphates and silicates). These compounds react with the metal surface, producing a coating that inhibits corrosion.

2.4.1 Choosing the Right Coolant

Selecting the proper coolant depends on the type of metal and machining operations that it will be used for. Coolant manufacturers formulate different grades of products for all types of machining operations, but some products can be used for multiple purposes, such as grinding and milling. The life of the coolant can be reduced if it is not made for the job. Minimizing the number of cutting fluids used in a shop is a good shop practice. Many metalworking facilities require only two types of coolants: one for machining, one for grinding. Using more types of coolants requires extra storage space, adds to inventory and maintenance needs, and increases the chances that the fluids would be mixed up and contaminated by each other. Higher priced coolants tend to perform better and last longer than low-priced coolants, but selecting a coolant solely on the basis of its initial cost can lead to problems. A cutting fluid should be selected to match the function for which it is needed. Then, the true cost of the fluid can be determined based on its cost per gallon divided by its life expectancy. Once performance parameters and the true cost of a cutting fluid are determined, the fluid's long-term cost and effectiveness can be determined. Cutting fluids commonly are oil-based or water-based. The oil-based fluids include straight oils and soluble oil, and water-based fluids include synthetics and high-oil, semi-synthetics. Bio-based lubricants, such as soybean oil or methyl soyate formulations, match the price and performance of petroleum or semi-synthetic oils but offer other advantages that include the promotion of better surface finishes on the workpiece and reduced risk of fire, smoke and misting while they are in use. Additionally, these coolants are biodegradable, and do not contain chlorine or sulfur, so they are more easily disposed of (Benes, J. 2007). Figure 2.4 below shows advantages and disadvantages types of cutting fluids.

Type of cutting fluids		
	Advantages	**Disadvantages**
Straight oils	Excellent lubricity; good rush protection and sump life; easy maintenance; rancid resistant.	Poor heat dissipation; increased risk of fire; limited to low-speed cutting.
Soluble oils	Good lubrication; improved cooling capacity; limited to light and medium-duty applications.	More susceptible to rush problems and bacterial growth; tramp-oil and evaporation losses.
Synthetics	Excellent microbial control and rancid resistance; relatively nontoxic; good cooling qualities; easy maintenance; long service life; heavy-duty cutting.	Reduced lubricity; may cause misting, foaming and dermatitis; may emulsify tramp oil; easily contaminated by other machine fluids.
Semi-synthetics	Good microbial control and rancid resistance; relatively nontoxic; superior cutting qualities; easy maintenance; long service life.	Water hardness affects stability; may emulsify tramp oil; easy contaminated by other machine fluids.

Figure 2.4: Advantages and disadvantages types of cutting fluids

Source: Benes, J. (2007)

2.5 CUTTING TOOL

In the mid 1800's a scientist named Faraday evaporated thin films in a vacuum when he exploded wires in his laboratory. It was not until the late 1800's that the first films would be deposited in a vacuum by Nahrwold. This was the beginning of the vacuum deposition method that we now call PVD (Physical Vapor Deposition) coating. The application of this technology remained primarily academic until the post World War II era. The branch of PVD coating technology called ion plating was not developed until 1963 by Donald Mattox. Figure 2.5 below shows a thin PVD-coating on a positive indexable insert for an endmill.

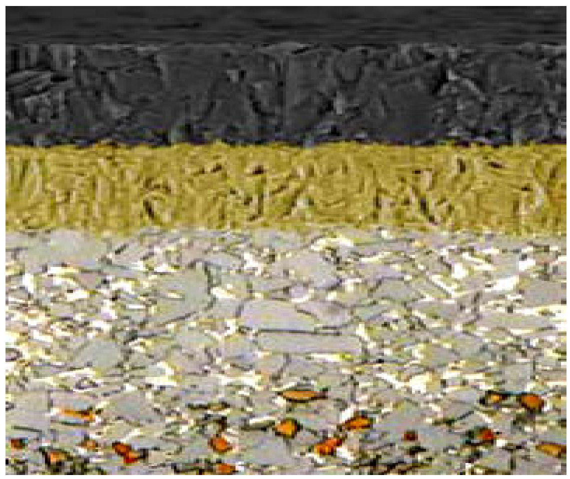


Figure 2.5: PVD-coatings are on the increase. There is a growing need for these thinner coatings, more suitable for positive, sharper tools. Smaller machine tools need tools that cut with lower power consumption and are more forgiving when it comes to instability, intermittent cuts and unfavorable tool entries and exits

Source: Paulsson, M., Richt, C. and Coromant S. (2007)

The PVD technology consists of three primary deposition methods, evaporation, sputtering and cathodic arc. The PVD coating process is an environmentally friendly vacuum coating process that has the ability to apply various films at various process temperatures. This flexibility allows coatings to be applied to a variety of substrates (Dearnly, P. A. and Grearson, A. N. 1986). Application reports and various application areas for PVD coating can be found by choosing the Applications option from the menu. Ion plating is a branch of PVD coating. The ion plating process ionizes the material being evaporated. This ionization greatly enhances the properties and adhesion of the film being applied. For more detailed information about the PVD coating process and ion plating, choose the Coating Process option from the menu. The PVD coating process is often times confused with the CVD (Chemical Vapor Deposition) process. The CVD process is a thermal deposition process rather than a physical deposition process. For more information concerning the differences between the PVD and the CVD process, choose the Coating Process option from the menu. The ideal cutting tool material should have characteristics such as harder than the work it is cutting, high temperature stability, resists wear and thermal shock, impact resistant and chemically inert to the work material and cutting fluid. In industry today, carbide tools have replaced high-speed steels in most applications. These carbide and coated carbide tools cut about 3 to 5 times faster than high-speed steels. The major categories of hard carbide include tungsten carbide, titanium carbide, tantalum carbide, and niobium carbide. Each type of carbide affects the cutting tool's characteristics differently. For example, a higher tungsten content increase wears resistance, but reduces tool strength. A higher percentage of cobalt binder increases strength, but lowers the wear resistance. Carbide is used in solid round tools or in the form of replaceable inserts. Every manufacturer of carbide tools offers a variety for specific applications. The proper choice can double tool life or double the cutting speed of the same tool. Shock-resistant types are used for interrupted cutting. Harder, chemically-stable types are required for high speed finishing of steel. More heat-resistant tools are needed for machining the superalloys, like Inconel and Hastelloy. Face milling operation, when coated carbide tools were used, the best cutting conditions with respect to the highest tool life of 30 min was achieved at cutting speed of 55m/min (Dearnly, P. A. and Grearson, A. N. 1986). The right surface treatment on small round tools can increase overall life, decrease cycle time and promote better surface finishes. There is a vast selection of PVD, CVD and alternate surface treatments that are readily available from manufacturers or coating facilities (Scott A. Daggett. 2009). However, depending on the application, materials and coatings for the best performance vary. The properties of cutting tool materials are given in Table 2.1 below. High-speed cutting application for such tool materials and coatings can be classified as: CBN and SiN for cast iron, TiN and TiCN coated carbide for alloy steel up to 42 HRC and TiAlN and AlTiN coated carbide for alloy steels 42 HRC and over.

Table 2.1: Properties of advanced cutting tool materials and coatings

	Tool material			Coatings				
	PCD	**CBN**	**WC**	**SiN**	**AlO**	**TiN**	**TiCN**	**TiAlN**
Micro hardness	6000	3500	1500-1800	1700	1600	2900	3000	3300
Coefficient of friction against steel in dry coolant	-	0.24	0.6	-	-	0.4	0.4	0.3-0.5
Maximum working temperature (°C)	600	-	-	-	-	600	400	815
Thermal conductivity (W/m K)	500	100	40-80	15-35	14-17	-	-	-
Transverse rupture strength (Mpa)	690-965	690	1700-2000	480-750	275-345	-	-	-

Source: Scott A. Daggett (2009)

2.5.1 Coating Characteristic

Hard coatings have come a long way since the mid-1980s, when TiN was first applied by the PVD process on cemented-carbide cutting tools. These first-generation TiN-coated carbide tools were initially used in interrupted-cutting applications such as the milling of steels. The superior milling performance of these PVD-coated tools prompted their use in other machining applications, such as threading, grooving, parting, boring, and turning. The continued success of PVD-coated tools led to the commercial development of second- and third-generation PVD coatings. Tools coated with titanium carbonitride (TiCN) and titanium aluminum nitride (TiAlN) offer higher hardness, toughness, and wear resistance for better machining productivity. While the superior performance of these later-generation coatings has been seen in the field, research is needed to determine exactly how these coatings enhance performance and to identify those applications and cutting conditions that benefit most from the coatings' properties (P.C. Jindal, A.T. Santhanam, A.F. Shuster and B.K. Marsh. 1999). In term of hardness, a high surface hardness from coating is one of the best ways to increase tool life. Generally, the harder the material or surface, the longer the tool will last. Wear resistance is the ability of the coating to protect against abrasion. Although a material may not be hard, elements and processes added during production may aid in the breakdown of cutting edges or forming lobes. In surface lubricity, a high coefficient of friction causes increased heat, leading to a shorter coating life or coating failure. However, a lower coefficient of friction can greatly increase tool life. The amount of heat can be reduced by a surface that lacks coarseness or irregularities. This slick surface lets the chips slide off the face of the tool, generating less heat. A higher surface lubricity also can allow for increased speeds when compared to non-coated versions (Scott A. Daggett. 2009). Built up edge is very common in non-ferrous materials like aluminum or brass. BUE can lead to chipping of the tool or oversizing of the part. Once the material starts adhering to the tool, it continues to attract. In the case of machining aluminum with a forming tap, aluminum deposits grow larger after every hole. Eventually, the pitch diameter becomes so enlarged that the part becomes oversized and needs to be scrapped. A coating with increased anti-seizure properties may even be able to aid where poor coolant quality or concentration is a problem (Scott A. Daggett. 2009). Figure 2.6 below is shown the comparison suitability of common coating used now days.

Type of coating	Suitability
Titanium Nitride (TiN)	General purpose PVD coating that increases hardness and has a high oxidation temperature. This coating works great while cutting or forming with HSS tooling.
Titanium Carbo-Nitride (TiCN)	The addition of carbon adds more hardness and better surface lubricity. This coating is ideal for HSS cutting tools.
Titanium Aluminum Nitride (TiAlN or AlTiN)	A formed layer of aluminum oxide gives this tool better life in high heat applications. This coating is primarily selected for carbide tooling where little to no coolant is being used. AlTiN offers a higher surface hardness than that of TiAlN.
Chromium Nitride (CrN)	The anti-seizure property of this coating makes it preferred in situations where built up edge is common. High speed steel or carbide cutting and forming tools will be seen with this almost invisible coating.

Figure 2.6: Comparison of common types of coating

Source: Scott A. Daggett (2009)

2.5.2 Coating Process

Two principal coating processes are used for indexable inserts to provide cutting edges with fundamentally different properties for machining which is chemical vapor deposition which uses a higher temperature and gives thicker coatings and physical vapor deposition (Paulsson, M., Richt, C. and Coromant, S. 2007). Figure 2.7 below shows a typical cathodic arc coating system with large area cathodes.

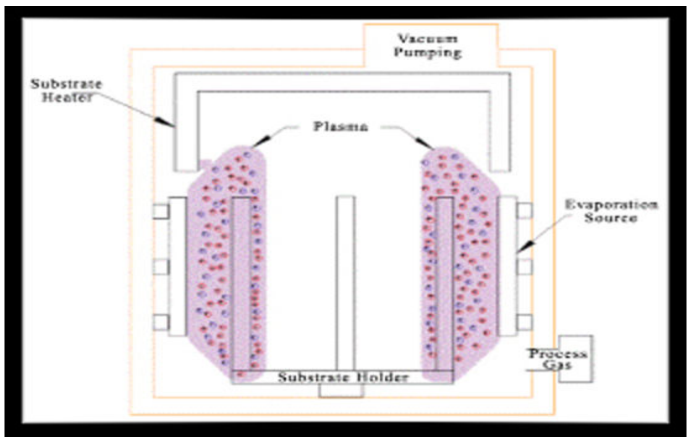


Figure 2.7: A typical cathodic arc coating system with large area cathodes

Source: Northeastcoating.com

Chemical vapor deposition develops tensile stress in the substrate, while physical vapor deposition tends to develop compressive stress. These stresses provide different desirable characteristics for the insert. The CVD-coated insert typically has a thicker coating and has a high degree of wear resistance and coating adherence. The PVD-coated insert has a thinner coating, high toughness and is more suitable for sharper cutting edges. Practically, the CVD insert is more suitable for higher cutting speeds, while the PVD insert is more suitable for lower cutting speeds. The CVD insert can cope better with heat, longer insert engagement times and larger chip thicknesses. The PVD insert copes well with instability and more demanding chip evacuation from the machining zone as well multiple as tool exits from the workpiece such as those encountered in milling. A CVD insert typically is chosen for turning of steel and cast-iron while the PVD is typically a solution for endmilling in a machining centre with limited power. The PVD insert is well suited to the growing number of positive, sharper cutting edges required for intermittent cuts and also is used widely for solid carbide tools – endmills and drills especially. But these characteristics are broad for the insert-coating types, and overlap in both turning and milling. The PVD process is the subject of intense development today because it offers great potential and can make use of more coating materials. The CVD and PVD processes generally should not be seen as competitors, rather as complimentary to each other. Both offer potentials for optimizing machining. CVD is the dominant coating process, partly because it is the only process capable of satisfactorily depositing layers of Al_2O_3. This process has been developed over the years to reduce the negative side-effects of high temperatures on the substrate. Recent developments include CVD processes for depositing TiCN and Al_2O_3 in ways that lower stress levels and develop fewer tendencies for crack formation in the coated surface of the insert. After the heat of the CVD-coating processes a network of cooling cracks tend to form, resembling a dry river-bed. The resulting tensile stresses, due to the different coating materials involved in the several layers, can negatively reduce the toughness properties of the insert (Paulsson, M., Richt, C. and Coromant, S. 2007). Coatings with low inherent stresses have proven to have better properties for tackling the demands of machining. Stress-relief therefore has been developed, and now is achieved by new after-coating processes that transform the coating to provide a smooth, low-stress insert surface. To a certain extent, the cooling cracks from the CVD-process also are closed. The PVD-coating process does not involve as much heat, so it does not need similar precautions. Stress in PVD coatings is reduced through a process that involves high-impact treatment that counters any tensile stresses with suitable levels of compressive stresses. This results in the edge-line of these sharper cutting edges having greater levels of toughness. The use of low-stress CVD coatings on new generations of inserts is providing clear benefits (Paulsson, M., Richt, C. and Coromant, S. 2007). By minimizing material stresses in the coating it has been found that layers can be made thicker without sacrificing insert toughness. Thus, practically in machining, modern low stress coatings have better resistance to insert-fracture, edge chipping, flaking of coatings as well as cutting edge integrity. The result is that inserts with such coatings can be used at higher cutting speeds while lasting longer and having better predictability. The primary advantage of this development for machine shops is that it provides trouble-free machining at higher metal removal rates. Modern insert coatings are characterized by this low-stress technology as well as by having several sub-layers of coating materials, creating a laminating effect. The coatings are optimized to act as heat and chemical barriers, to resist mechanical wear and to promote better adherence between coatings and substrate. The coating combinations and substrates for each insert grade-type today are individually designed to match machine shop requirements (Paulsson, M., Richt, C. and Coromant, S. 2007). Table 2.2 below shows PVD coating selection guidelines.

Table 2.2: PVD coating selection guidelines

Coating	Hardness HV	Friction Coefficient	Corrosion Resistance	Wear Resistance	Maximum Service Temperature	Colour
Titanium Nitride, TiN	2200	0.5	Good	Excellent	525 C	Gold
Titanium CarboNitride, TiCN	3000	0.4	Good	Excellent	400 C	Violet
Titanium Aluminum Nitride, TiAlN	3600	0.6	Good	Excellent	750 C	Black

Source: P.C. Jindal, A.T. Santhanam, A.F. Shuster and B.K. Marsh (1999)

The tool-life improvement in TiAlN-coated tools results from retardation of dissolution wear as well as abrasive wear. In TiCN-coated tools, the abrasive-wear resistance predominates. The superior tool life of TiCN- and TiAlN-coated tools over TiN-coated tools can be partly attributed to the solid-solution strengthening effect of either carbon or aluminum in the TiN lattice. In the case of TiAlN coating, not only is the hot hardness increased due to solid-solution strengthening, but the substituting aluminum atom imparts higher chemical stability through the formation of a stable Al_2O_3 layer. These characteristics can, in turn, endow the coated tool with higher resistance to abrasive wear and dissolution wear, thereby providing longer tool life and higher speed capability on a broad range of workpiece materials (P.C. Jindal, A.T. Santhanam, A.F. Shuster and B.K. Marsh. 1999).

2.6 CNC MILLING

Many industries today, especially in the high-tech world of aerospace and automotive design for example, are turning to 5-axis machining as a means to speed manufacturing ability and increase repeatable accuracy. The ability to machine complex shapes, undercuts and difficult angles in a single setup reduces tooling cost and labor time, resulting in a better cost per part in addition to maintaining parts conformity throughout the run of the part. CNC four-axis milling offers the option of tilting the milling cutter to improve the cutting conditions (V. Gehring, M. Becker and J.H. Camacho. 1990). High-speed machining requires high levels of rigidity, rigid spindles with very low vibration characteristics and balanced tool holders with shrink fits. The servos and controls must be advanced enough to support look-ahead and quick response times, and a high data transfer capability to handle larger sized programs and avoid “data starvation". The CAM system and look-ahead systems must allow the machine tool to accelerate and decelerate most efficiently for tool compensation (F. Mason. 1995). Milling machines move a workpiece into a fixed cutter in vertical or horizontal directions along X, Y and Z axes. Vertical milling machines have a vertical spindle, similar to the drill press, but with an X-Y table that permits positioning the work. Horizontal milling machines also have an X-Y table for workpiece positioning; however, the cutters are mounted on a horizontal arbor across the table. Universal milling machines (UMC) can be used for either vertical or horizontal milling. The spindle head articulates to allow for either of type of milling operation. Gantry milling machines are used with large workpieces. They allow for articulation of the spindle as needed for 5-axis and 6-axis milling machines. Machining centers are machine tools that are used to repeat operations automatically. Most machining centers are computer numerically controlled. Milling machines carry specifications for spindle performance, movement and table size. Spindle speed is the rotational speed range of the spindle head. Drive power is the rated power of the turbine, electric motor or reciprocating engine which drives the spindle. Movement specifications for milling machines include number of axes, maximum X-axis travel, maximum Y-axis travel, and maximum Z-axis travel. In terms of table size, the length of the table is measured parallel to the main axis of movement. The width of the table is measured perpendicular to the main axis of movement. Milling machines may include software packages for computer-aided design (CAD) or computer-aided manufacturing (CAM). Programmable machines can be setup for automated or semi-automated operations. Rotary tables allow rotation of the workpiece and provide travel along multiple axes. Milling machines with a cooling system are designed to prevent overheating and damage to the machinery during prolonged use. Suppliers who provide on-site calibration help can to ensure the precise operation of equipment. Some milling machines have a user interface with a digital readout. Others have an enclosure that houses the workspace. Vertical milling is more common than horizontal milling, largely because the workpiece is simple mounted. Horizontal milling is used if a large amount of material has to be removed, or there is less of a need for accuracy. A five-axis CNC milling machine has an extra axis in the form of a horizontal pivot for the milling head. This allows extra flexibility for machining with the end mill at an angle with respect to the table. A six-axis CNC milling machine would have another horizontal pivot for the milling head, this time perpendicular to the fifth axis. CNC milling machines are traditionally programmed using a set of commands known as G-codes represents specific CNC functions in alphanumeric format. Figure 2.8 below shows the illustration of CNC milling machine.

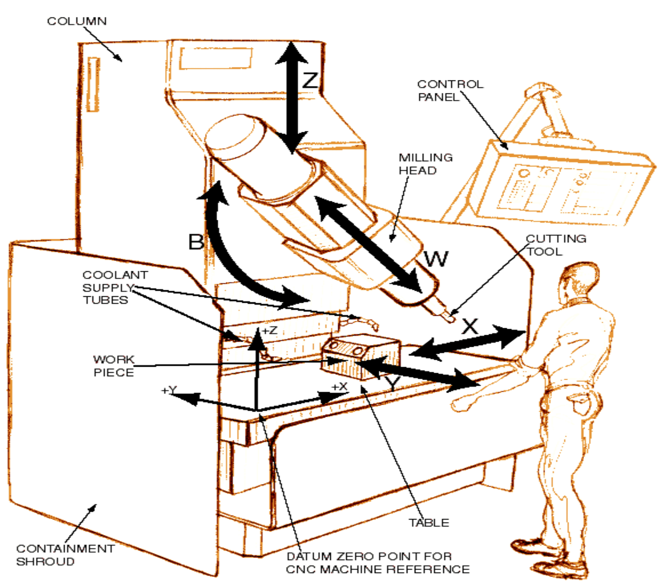


Figure 2.8: Illustration of CNC Milling

Source: Efunda.com

2.7 AISI P20 TOOL STEEL

Generally, AISI P20 is a chromium-molybdenum alloyed steel which is considered as a high speed steel used to build moulds for plastic injection and zinc die-casting, extrusion dies, blow moulds, forming tools and other structural components. The modified form of AISI P20 is distinguished from normal P20 steel by the balanced sulphur content (0.015%) which gives the steel better machinability and more uniform hardness in all dimensions. Modified AISI P20 possesses a tensile strength of 1044 MPa at room temperature and a hardness ranging from 280 to 320 HB (K. Kadirgama, K. A. Abou-El-Hossein, B. Mohammad, M. M. Noor and S. M. Sapuan. 2008). Since metallurgy is only the means, it is of utmost importance to be interested in its effects. In machinability, the first argument for the use of a steel grade light on carbon and prehardened to 300 HB is improved machinability and the related cost reduction. A trial with a car fender mold resulted in a reduction in roughing time of 33 percent. The operation was performed in 60 hours with conventional steel and was reduced to 40 hours with the use of a steel grade light on carbon and prehardened to 300 HB (Doucet, E. 2009). Figures 2.9 below shows the final result was a substantial reduction in machining cost.

	P20	Steel Grade Light on Carbon and Prehardened to 300 HB
Cutting speed (Vc (in/min)	4920	5905
Feed - fz (in/tooth)	0.024	0.029
Axial depth - ap(in)	0.12	0.12
Radial depth ae (in)	2.95	2.95
Machining parameters.		

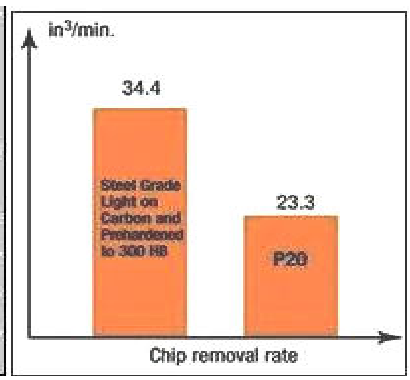


Figure 2.9: The final result was a substantial reduction in machining cost

Source: Doucet, E (2009)

For guidelines in forging, heat slowly and uniformly to 1050°C, Do not forge below 930°C and after forging cool slowly. In annealing, P20 should always be annealed after forging and before rehardening. Heat uniformly to 770/790°C, Soak well and cool slowly in the furnace. In case of hardening**,** Heat uniformly to 820/840°C until heated through and quench in oil. However, tempering need to Heat uniformly and thoroughly at the selected tempering temperatures and hold for at least one hour per inch of total thickness. For nitriding, moulds machined from pre hardened P20 may be nitrided to give a hard surface which is very resistant to wear and erosion. A nitrided surface also increases the corrosion resistance. The surface hardness after nitriding at a temperature of 525° C in ammonia gas will be approximately 650HV. Tufftriding at 570° C will give a surface hardness of approximately 700HV. After hours treatment the hard layer will be approximately 0.01mm. In flame and induction Hardening, P20 can be flame or induction hardened to a hardness of 50 to 55 HRC and cooling in air is preferable. Smaller pieces may however require forced cooling and hardening should be immediately followed by tempering. Nevertheless, in welding process heat to approximately 400 to 500° C. Weld at approximately 400 to 500° C and stress relieve. Use Chromium-Nickel-Molybdenum-alloyed basic electrodes for welding of structural steels. Welding may also be carried out using an austenitic stainless steel electrode. In this case the stipulated increased working temperature may be modified, but the weld metal has a lower strength than the parent material. Table 2.3 below shows Physical properties of AISI P20 tool steel.

Table 2.3: Physical properties of AISI P20 tool steel

	Temperature		
	20° C	**200° C**	**400° C**
Density (kg/m3)	7800	7750	7700
Coefficient of thermal expansion (per ° C from 20°)	-	12.7 x 10^{-6}	13.6 x 10^{-6}
Thermal conductivity (J/m.s. ° C)	29	29.5	31
Modulus of elasticity			
Kp/mm^2	20900	20400	18900
N/mm^2	205000	200000	185000

Source: Westyorkssteel.com

Table 2.4 listed guidelines machining for turning and milling.

Table 2.4: Guideline for machining

Turning **Carbide Tools**	**Rough Turning**	**Medium Turning**	**Finish Turning**
Depth of cut (mm)	min. 10	2-10	max. 2
Feed (mm/rev)	mm 1.0	0.3-1.0	max. 0.3
ISO Machining Group	P30-P40	P20-P30	P10
Cutting speed (m/min)	40-60	60-100	90-160
Milling **Carbide Tools and High Speed Steel Tools**		**Rough Milling**	**Finish Milling**
Depth of cut (mm)		min. 2	max. 2
Feed (mm/tooth)		min. 0.2	max. 0.2
ISO Machining Group		P30-P40	P10-P20
cutting speed (m/min) (Carbide tools)		55-85	75-95
Cutting speed (m/min) (High Speed Steel tools)		10-20	15-30

Source: Westyorkssteel.com

2.8 RESPONSE SURFACE METHODOLOGY (RSM)

Surface roughness measurements were taken after each combination of feed rate, axial depth of cut and cutting speed. Mathematical models for surface roughness have been developed in terms of cutting speed, feed rate and axial depth of cut by response surface methodology. RSM is a collection of experimental strategies, mathematical methods, and statistical inference that enable an experimenter to make efficient empirical exploration of the system of interest. RSM can be defined as a statistical method that uses quantitative data from appropriate experiments to determine and simultaneously solve multi-variable equations. The work which initially generated interest in the package of techniques was a paper by Box and Wilson in year 1951. To solve such problems with conventional optimization, the RSM has been adopted. With RSM, optimization conditions are first set, and then a response surface is created between design variables and objective functions or constraint conditions. Since the expected experimental and theoretical relations in machining are expected to be non-linear, in this work response surface models are used for optimization (Amago. 19).This method is now broadly used in many fields, such as chemistry, biology, and manufacturing. RSM can be used to determine the factor levels that will simultaneously satisfy a set of desired specifications and determine the optimum combination of factors that yields a desired response and describes the response near the optimum. Furthermore, it determines how a specific response is affected by changes in the level of the factors over the specified levels of interest it can achieve a quantitative understanding of the system behavior over the region tested. It could also predict product properties throughout the region even at factor combinations not actually run. In general, a second order regression model is developed because of first order models often give lack off fit (Montgomery, D.C. 1997). In design optimization using RSM, the first task is to determine the optimization model, such as the identification of the interested system measure and the selection of the factors that influence the system measures significantly. To do this, understanding the physical meaning of the problem and some experience are both useful. After this, the important issues are the design of experiments and how to improve the fitting accuracy of the response surface models.RSM designs have the following properties such as predictions always have some degree of uncertainty but there is reasonable prediction throughout the experimental range, uniform prediction error is obtained by using a design the fills out the region of interest, the choice of experimental design is affected by the shape of the experimental region and in most cases, the region is determined by the ranges of the independent variable. Response surface methodology (RSM) is an optimization technique in the field of numerical analysis. For optimization, it uses a function called a response surface. A response surface is a function that approximates a problem with design variables and state quantities, using several analysis or experimental results. In general, design of experiments is used for analysis or experiment point parameter setting, and the least square method is used for function approximation. Response surface methodology is a combination of mathematical and statistical techniques useful for modeling and analyzing the problems in which several independent variables influence a dependent variable or response. The RSM technique attains convergence by repeating numerical and sensitivity analysis until the optimal solution as obtained. For problems with high non-linearity, and for multimodal problems, there may be cases in which no solution can be found because of problems such as inability to obtain sensitivities or a lapse into a local solution. The study uses the Box-Behnken design in the optimization of experiments using RSM to understand the effect of important parameters. Box-Behnken Design is normally used when performing non-sequential experiments. That is, performing the experiment only once. These designs allow efficient estimation of the first and second order coefficients. Because Box-Behnken design has fewer design points, they are less expensive to run than central composite designs with the same number of factors. Box-Behnken Design do not have axial points, thus we can be sure that all design points fall within the safe operating. Box-Behnken Design also ensures that all factors are never set at their high levels simultaneously (Draper, N.R. and H. Smith, 1981; Box, G.E.P. and N.R. Draper. 1987; Box, G.E.P. & Behnken, D.W. 1960). Response Surface Method (RSM) saves cost and time on conducting metal cutting experiments by reducing the overall number of required tests. In addition, RSM helps describe and identify, with a great accuracy, the effect of the interactions of different independent variables on the response when they are varied simultaneously (Hicks, C.R. 1993; Hill, W.J. and Hunter, W.G. 1966; Mead, R. and Pike, D.J. 1975). RSM has been extensively used in the prediction of responses such tool life, surface roughness and cutting forces. The Box-Behnken design is based on the combination of the factorial with incomplete block designs. It does not require a large number of tests as it considers only three levels (-1, 0, 1) of each independent parameter (Hill, W.J. and Hunter, W.G. 1966). The application of experimental design and response surface methodology in fermentations process can result in improved product yields, reduced process variability and development time and overall costs (RAO, K. Jagannadha, KIM, Chul-Ho and RHEE, Sang-Ki. 2000). The Experimental design and response surface methodology were applied for the optimization of the nutrient concentration in the culture medium for the enzyme production in shaken flasks at 200 rpm and 30ºC. The statistical analysis of the results showed that, in the range studied, all the factors had a significant effect ($p < 0.05$) on glucosyltransferase production and the highest enzyme activity was observed in culture medium containing sugar cane molasses (160 g/L), bacteriological peptone (20 g/L) and yeast extract Prodex Lac SD® (15 g/L) (H. Y. Kawaguti, E. Manrich and H. H. Sato. 2006). Response surface methodology (RSM) to describe relationships between a combination of factors and an organism's growth curve parameters (Devlieghere, F., Debevere, J. and Van Impe, J. 1998). In general application of the response surface methodology, the representative peak or average value is usually selected as a response to establish the relationship with the planned factors. For instance, a second-order polynomial equation was proposed to correlate the peak residual stress caused by the milling operation with the cutting conditions and the tensile strength of the material (M. M. EI-Khabeery and M. Fattouh. 1989) and used the same equation to correlate the measured peak residual stress and surface roughness of the milled workpiece with the cutting conditions, flank width and nose radius of the cutter (K. H. Fuh and C. F. Wu. 1995). Response Surface Methodology used to predict the effects of cutting parameters on the variations of cutting forces during end milling operation of Al SiC metal matrix composite material by designing four factors, five level central composite rotatable design matrixes with full replication; for planning, conduction, execution and development of mathematical models (B. Ganesh babu, V. Selladurai and R. Shanmugam. 2008). The average cutting forces are determined at different feed rates in tangential, radial, and axial directions per tooth period by keeping immersion and axial depth of cut as constant. A comparison between modeling and experiment is presented. This model and analysis are useful not only for predicting the tool wear but also for selecting optimum process parameters for achieving the stability of the end milling process. Nevertheless, response surface methodology developed mathematical models for surface roughness in order to optimize the surface finish of the machined surface (Mansour, A. and Abdalla, H. 2002; El baradie, M. A. 1993; K. A. Rosentrater, A. Otieno and P. Melampati. 2008). RSM is a combination of mathematical and statistical techniques used in an empirical study of relationships and optimization, where several independent variables influence the process. The first and second order mathematical models, in terms of machining parameters, were developed for surface roughness prediction using RSM on the basis of experimental results.