An Analytical and Experimental Investigation of Effects of High-pressure Coolant on Tool Wear, Tool Life and Surface Roughness in Turning Steel

Md. Tanveer Ahmed

DEPARTMENT OF INDUSTRIAL & PRODUCTION ENGINEERING
BANGLADESH UNIVERSITY OF ENGINEERING & TECHNOLOGY
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The thesis titled "**An Analytical and Experimental Investigation of Effects of High-pressure Coolant on Tool Wear, Tool Life and Surface Roughness in Turning Steel**" submitted by Md. Tanveer Ahmed, Student No. 040508005P, Session- April 2005, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Science In Industrial & Production Engineering on April 10, 2007

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Department of Industrial & Production Engineering
BUET, Dhaka-1000

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Professor
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Md. Tanveer Ahmed

This work is dedicated
to my loving

Father

Sekender Ali

&

Mother

Halima Khatun

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Abstract

Manufacturing quality products at a higher rate and low cost is the key to exist and sustain in the modern era of cut-throat competition. To do that, machining is practised at extreme conditions. As part of this approach, high speed machining is adopted. However, high speed machining is inherently associated with generation of intense heat and cutting temperature at the cutting zone resulting increased tool wear and deterioration of machined surface. New methods are being explored to reduce the heat. Application of high-pressure coolant is perceived to be a superior choice in this regard. Technological beneficial effects of proper high-pressure coolant on machining already been established in number of previous investigations

Surface roughness is a determinant of product quality and reduction of tool wear and consequent increase of tool life can reduce the machining cost. However, estimation of these two machining performance parameters can contribute to manufacturing optimization and planning. Mathematical models are instrumental to predict machining performance at different machining combinations.

Response surface method is adopted to develop statistical models of tool life and surface roughness. Cutting speed and feed rate are the independent variables of the models. As part of this method, based on the experimental results of turning medium carbon steel statistically designed speed-feed combination by uncoated carbide insert using high-pressure coolant jet, regression analysis will be performed to determine the coefficients of the model followed by analysis of variance to check the adequacy of the model.The models are expected to quantify machining performance in terms of tool life and surface roughness at various cutting speed and feed.

Chapter-1

Introduction

1.1 Introduction

Machining is a term covering a large collection of manufacturing processes designed to remove material from a workpiece. Black [**Black 1979**] defined machining as the removal of metal chips from a workpiece in order to obtain a finished product with desired attributes of size, shape, and surface roughness. Machining operations comprise a substantial portion of the world's manufacturing infrastructure. At the 1st CIRP International Workshop on Machining Operations, Atlanta GA 19 May 1998, one of the founding fathers of the scientific study of machining operations, Dr. Eugene Merchant [**Merchant 1998**], estimated that 15% of the value of all mechanical components manufactured worldwide is derived from machining operations.

Machined parts are universally used in industrial and consumer products of every description. For high dimensional accuracy in terms of good surface finish, flatness, roundness, circularity, parallelism or close fit, some machining of the workpiece will practically always be involved. Almost invariably, if the part is in motion, is in contact with a part that is in motion or fits precisely with another part, machining operation will be employed in its manufacture. For most interchangeable parts, machining is an essential step in the manufacturing sequence.

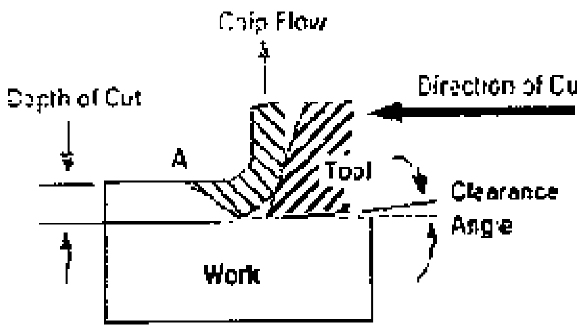


Fig. 1.1 Machining Process [**Boothroyd and Knight 1989]**

In principle, all metal cutting or metal removal operation can be likened a basic process as in Fig.1.1 where the wedge-shaped tool with straight cutting edge is constrained to move relative to the workpiece in such a way that a layer of metal is removed in the form of chip so that the workpiece is shaped to desired dimensions. In the process of forming chip, the tool edge "plows" its way through the work material requiring a considerable amount of energy, which is converted into heat, mostly in frictional heat and heat caused by destruction of molecular or atomic bonds in the shear plane. The friction between the tool and workpiece and high stress acting near the tool cutting edge leads to eventual cutting edge deformation and ultimately removal of material from the tool affecting tool sharpness to machine properly. The high temperature generated during machining combining with tool cutting edge deformation may result in poor machining performance in terms of form accuracy and surface quality.

The factors affecting cutting process, the mechanism of chip forming and the phenomena accompanying the process are known. The evergreen problem is how to raise machining efficiency, i.e. to guarantee the required quality with higher productivity and a lower cost of production. In this regard, the prediction of machining performance in relation to machining process characteristics can contribute to utilizing the full machining capability as well as economic benefits.

Turning is a conventional material removal operation which is shown in Fig.1.2 on a manual lathe and from a side view. It produces surface of rotation on the workpiece. Like other machining operations, turning removes material by the shear process to produce the desired size, shape and surface finish. It is generally accomplished by causing cutting tools, varying in geometry and working separately or simultaneously, to move in a precise path with respect to a workpiece rotating about its centre axis and the centerline of the machine spindle.

Turning is a major machining operation. The most common application of turning is in secondary operations performed on workpieces produced by other processes. If precision surfaces are required when some portion have a round shape, specially in cases where the surface in question contacts a moving part or is used for sealing, turning is an obvious choice.

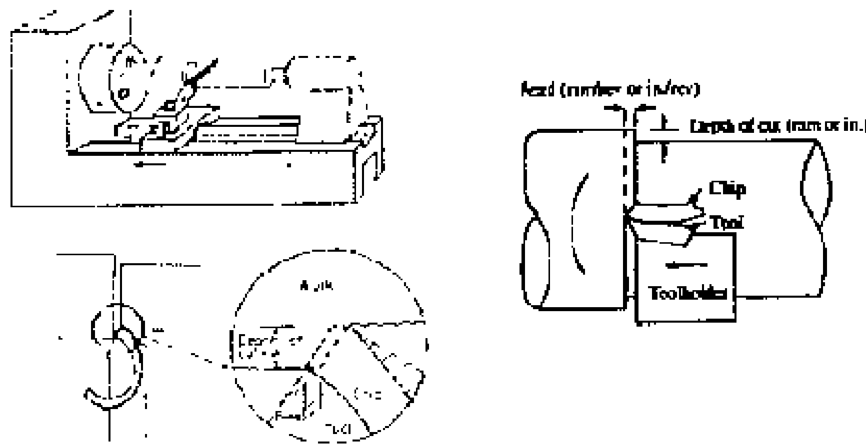


Fig. 1.2 Traditional Turning Process [**Trent 1977**]

Prior to adoption and practice of any machining technology, considering economic benefits is obvious choice for assessing sustainability. A new dimension, environment is getting more important role to play in this respect. Along with financial return, any manufacturing process needs to be environment friendly.

1.2 High Speed Machining

Global trade liberalization results in an intense international as well as domestic competition in manufacturing in terms of cost, quality and reliability. Production at a low cost maintaining desired quality and reach the market with a competitive price is the key to make profit and sustenance. These requirements can be met through higher productivity maintaining product quality that insists high material removal rate, high stability and long life of the cutting tools. Products need to be manufactured at a higher rate with desired quality and at minimum possible cost to reach and sustain in the market. Production volume needs to be large to achieve economy of scale. Again, the price should be fixed with a low margin of profit and thereby sustain to continue doing business. High material removal rate can be achieved by employing higher speed, large feed and depth of cut.

Machining with high speeds is one of the modern technologies, which in comparison with conventional cutting enables to increase efficiency, accuracy and quality of workpieces and at the same time to decrease costs and machining time [**Schulz and Moriwaki 1992**]. Even though high speed machining (HSM) is known for a long time, there are still a lot of questions and less or more complicated definitions of HSM. The first definition of HSM was proposed by Carl Salomon in 1931. He has assumed that at a certain cutting speed which is 5–10 times higher then in conventional machining, the chip tool interface temperature will start to decrease as can be seen in Fig. 1.3. Practically, it can be noted that HSM is not simply high cutting speed. It should be regarded as a process where the operations are performed with specific methods and production equipment. HSM is not only machining with high spindle speed because many applications are performed with conventional spindle speeds. HSM is often used in finishing in hardened steels with both high speeds and feeds. HSM can be called rather the high productive machining when machining components in roughing to finishing and also in finishing to super-finishing in components of all sizes [**Pasko et al. 2000**].

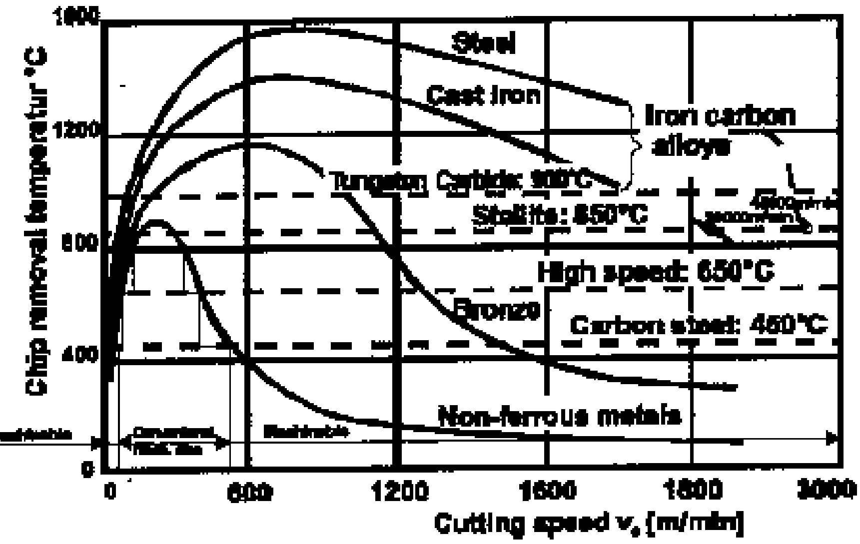


Fig. 1.3 Temperature as a Function of Speed [**Schulz and Moriwaki 1992**].

High speed machining process is introduced in manufacturing enterprises to improve production condition, product quality and organizational efficiency, etc. High-speed machining (HSM) has become one of the most promising advanced manufacturing technologies in the last decade. Indeed, this strategic technological area has a wide application field that ranges from the aerospace industry to the automobile industry, due to the influence of higher cutting speeds and higher surface quality on efficiency. The advantages of high-speed-cutting lie not only in the speed of machining (lower costs and higher productivity) but also in attaining higher surface quality. This allows producing finished parts using only one machine. In such cases, the necessary post-machining operation (i.e. grinding) is no longer required; furthermore, the intermediate transport, and highly demanding operations for the subsequent fixing and positioning of the workpiece can also be avoided. One of the main goals in HSM is to find an appropriate trade-off among tool wear, surface quality and productivity considering the tool's cost, its replacement cost, the cost of writing off the machine's idle time, and so forth. In industries, the machining temperature and its detrimental effects are generally reduced by:

- proper selection of process parameters and cutting tools geometry
- proper selection and application of cutting fluid
- using heat and wear resistant cutting tool materials like carbides, coated carbides and high performance ceramics

1.3 Tool Wear and Tool life

Machining involves the gradual action of a tool on a workpiece, and the tool is subject to friction, high stresses, and high temperatures. During machining, the rake face of the cutting tool comes into contact with the chip, and the flank face with the machined workpiece, both at high velocities. So friction exists between these surfaces of the tool and the chip and workpiece, and, as a result, the tool wears gradually. The tool commonly wears in the face (crater wear), flank (flank wear or wear land), or nose **[Raman 1995]**.

A tool is considered to be worn out when the replacement cost is less than the cost for not replacing the tool" **[Carlsson and Strand 1992]**. Tool failure is said to occur when the tool no longer performs the desired function whereas total failure is defined as the complete removal of the cutting edge, a condition obtained when catastrophic failure occurs **[Armarego and Whitefield 1985]**. So, tool is considered to expire its life by wearing out and is changed long before total failures to avoid incurring high costs associated with such catastrophic failures.

Tool life is defined as the active life of the tool when it is cutting satisfactorily. The tool life may be brought to an end through gradual mechanisms such as wear or by sudden mechanisms such as fracture and chipping. Wear in cutting tools may occur due to plastic deformation, diffusion, attrition, adhesion, abrasion, or other mechanisms. The exact mechanism causing wear is difficult and depends on the tool-work pairing.

Tool wear has a large influence on the economics of the machining operations. So, it is useful to predict to wear for optimizing process chains, improving product surface quality and automatic tool management to predict wear before cutting **[Luo 2004]**. The need for accurate assessment of tool wear has increased considerably in order to produce the required end products in an automated industry so that a new tool may be introduced at the instant at which the existing tool has worn out, thus preventing any hazards occurring to the machine or deterioration of the product surface finish. The model of tool wear analysis is used to reduce the planning uncertainties and to optimize tool application.

1.3.1 Technical Background

Tool wear in cutting process is produced by the contact and relative sliding between the cutting tool and the workpiece and between the cutting tool and the chip under the extreme conditions of cutting area; temperature at the cutting edge can exceed 1800^0 F and pressure is greater than 2,000psi [**Johnson 2001**]. Any element changing contact conditions in cutting area affects tool wear. These elements come from the whole machining system comprising four major functional groups workpiece, tool, interface and machine tool [**Yung-Chang et al. 2004**] as seen in Fig. 1.4.

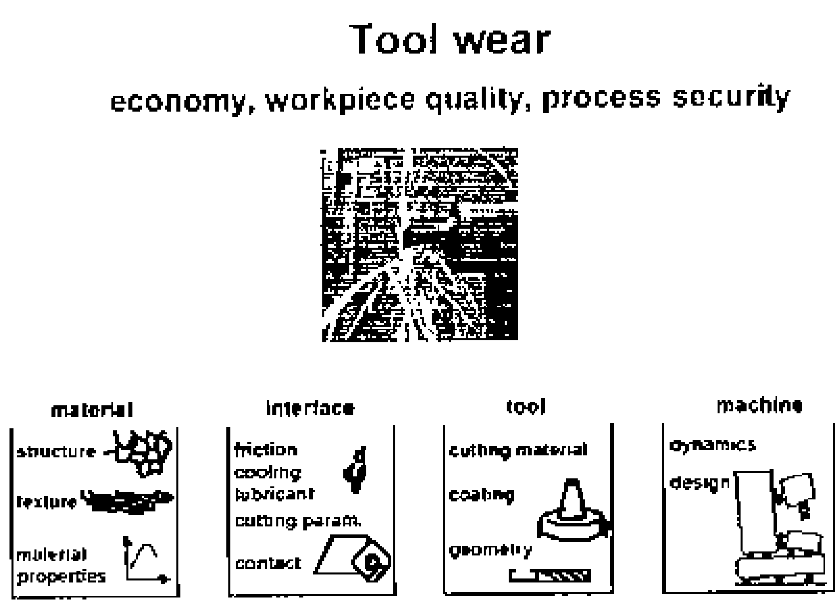


Fig. 1.4 Influencing Elements of Tool Wear [**Yung-Chang et al. 2004**]

The workpiece material and its physical properties (mechanical and thermal properties, microstructure, hardness, etc) determine cutting force and energy for the applied cutting conditions.

The interface conditions affect wear of the tool. In 80% of the industrial cutting applications, coolants are used to decrease cutting temperatures and likely to reduce tool wear. Increasingly new technologies, such as application of HPC is being used for better machining performance.

Tool material, tool coatings and tool geometric design (edge preparation, rake angle, etc) need to be appropriately chosen for different operations (roughing, semi-roughing, or finishing). The optimal performance of a cutting tool requires a right combination of the above tool parameters and cutting conditions (cutting speed, feed rate, depth of cut).

The dynamic characteristic of the machine tool, affected by the machine tool structure and all the components taking part in the cutting process, plays an important role for a successful cutting. Instable cutting processes with large vibrations (chatters) result in a fluctuating overload on the cutting tool and often lead to the premature failure of the cutting edge by tool chipping and excessive tool wear.

1.3.2 Types of Wear

Under high temperature, high pressure, high sliding velocity and mechanical or thermal shock in cutting area, cutting tool has normally complex wear appearance, which consists of some basic wear types such as crater wear, flank wear, thermal crack, brittle crack, fatigue crack, insert breakage, plastic deformation and build-up edge. The dominating basic wear types vary with the change of cutting conditions. Crater wear and flank wear shown in Fig. 1.5 are the most common wear types.

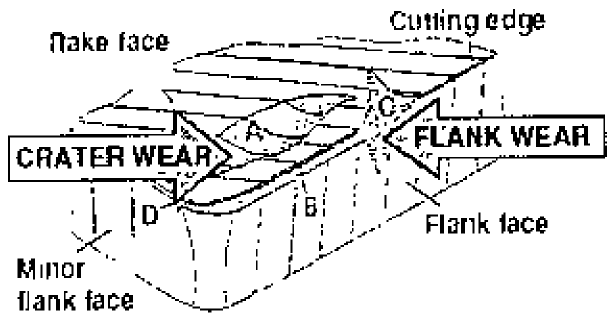


Fig. 1.5 Flank Wear and Crater Wear

Crater wear occurs on the tool rake and tool–chip interface geometry is affected. The most significant factors influencing crater wear are temperature at the tool–chip interface and the chemical affinity between tool **[Kumar and Sornakumar 2006]** and workpiece materials and dissolution and diffusion mechanisms have been postulated for it by Trent **[1963]** and Naerheim and Trent **[1977]**. Crater wear conforms to the shape of the chip underside and reaches the maximum depth at a distance away from the cutting edge where highest temperature occurs. It is thus a tribochemical wear as a result of the chemical affinity between the workpiece materials and the cutting tool materials **[Stachowiak and Stachowiak 1994]**. Crater wear is improved by selecting suitable cutting parameters using coated tool or ultra-hard material tool and changing chip flow direction by incorporating favorable chip breaking provisions.

Flank wear is generally attributed to rubbing of the tool with the hard second phases in the work material workpiece at the interface, causing adhesive wear and/or abrasive wear. **[Byrd and Ferguson 1978, Ramalingam and Wright 1981]**. The main wear mechanism in flank wear is abrasion characterized by development of grooves and ridges in the direction of tool sliding against a newly machined surface of the workpiece or chip sliding against the tool rake. The severity of abrasion can be increased in cases where the workpiece materials contain hard inclusions, or when there is debris from the workpiece or the tool, at the interface [**Kumar et al. 2006**]. Although Adhesive and abrasive wear mechanisms are predominant in flank wear, some diffusion wear also exists [**Altintas 2000**]. The flank wear results in [**Asibu 1985**]:

- changes in the mechanics of the cutting process
- an increased tendency for chatter
- changes in the dimension of the product
- decrease in surface finish
- increase in cutting force and temperature

Flank wear has been traditionally emphasized more than crater wear during the analysis of cutting tool wear. This is because of the more direct influence that flank wear has on the accuracy of the product. Hence the width of the flank wear lend is usually taken as a measure of the amount of wear and a threshold value of the width is defined as tool life/reshape criterion

Apart from these two types, notch wear is also observed. Notch wear occurs by the rubbing of the machined surface with the cutting tool at the boundary where the chip is no longer in contact with the tool. Since a machined surface may develop a thin work hardened layer, this contact could contribute to notch wear. The notch wear in Ti[C, N] mixed alumina ceramic cutting tool when machining martensitic stainless steel is presented in Fig.1.6 **[Kumar at al. 2006]**. Abrasion and adhesion are the main mechanisms involved in notch wear.

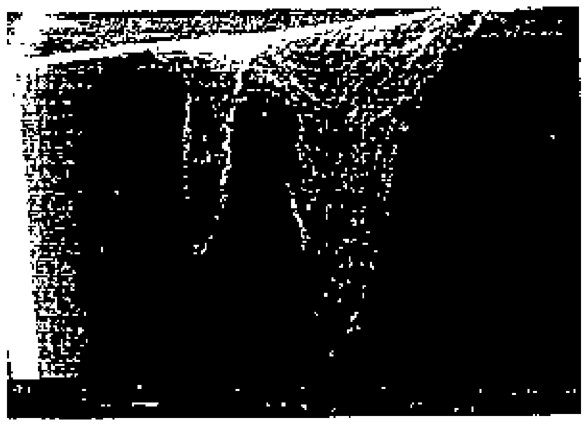


Fig. 1.6 Notch Wear [**Kumar et al. 2006]**

1.3.3 Wear Mechanisms

Metal cutting causes several types of wear mechanisms depending on cutting parameters (primarily cutting speed and feed), work-piece material, and cutting tool material. Like most wear applications, tool wear has proved difficult to understand and predict. It is generally considered that the wear of the cutting tool is a result of mechanical (thermo-dynamic wear, i.e. abrasion, adhesion) and chemical (thermo-chemical wear i.e. diffusion, oxidation) interactions between the tool and workpiece **[Kubaschevski and Hopkins 1992]**. Among them, abrasive wear, adhesive wear, diffusion wear and oxidation wear are very important. However, tool wear is formed a combination of several tool wear mechanisms.

Abrasive wear involves loss of material by the formation of small particles, as in abrasive machining. In this case, one material (tool) of the sliding pair has to be harder then the other one. However, softer work material also removes small particles from the tool material although at a smaller rate. Tool material is removed away by the mechanical action of hard particles in the contact interface passing over the tool face. These hard particles may be hard constituents in the work material, fragments of the hard tool material removed in some way or highly strain-hardened fragments of an unstable built-up edge [**Boothroyd and Knight 1989**].This mechanism can dominate when one or both of the tool and work materials contain carbide or oxide inclusions, metal matrix composites, and ceramics [**Yusuf 2000**]. The hard endogenous inclusions of the work material such as carbides, oxides and silicates possess a strong abrasive ability even at the elevated temperatures typical for cutting. Some of these particles retain hardness at high temperature comparable to or even higher than that of carbides. In machining, such particles can cut into the tool surface, acting as a cutting tool and producing craters or grooves. In some circumstances they will split off grains or entire grain conglomerates which on their part play the role of abrasive particles [**Marinov 1996**].

Adhesive wear is due to the action of small particles at the interface between two parts. If the bond between two mating surfaces is stronger than the local strength of the material a particle may adhere from a surface to the other. The adhered metal is unstable, and it separates from the cutting tool and tears small fragments of the tool material [**Yusuf 2000**]. In short, adhesive wear is caused by the formation and fracture of welded asperity junctions between the cutting tool and the workpiece. Some amount of abrasive and adhesive wear is desired to allow gradual tool wear and prevent premature tool fracture or chipping of the cutting edge [**Mehrotra 1998**].

Diffusion wear takes place when atoms move from the tool material to the workpiece material because of the concentration difference. Diffusion wear that occurs when the temperatures of the tool and work material increase at the contact zones, the atoms in the two material become restive and migrate to the opposite material where the concentration of the same atom is less [**Yusuf 2000**]. Atoms diffusing from the tool into the chip are finally carried away by the flow of the work material along the contact surface. The material transfer then leads to the formation of a crater on the tool rake face and consequently reduces the tool mechanical resistance and its efficiency. Diffusion wear is predominant for cemented carbide, high speed steel, and ceramic cutting tools.

In high speed machining, diffusion is a strongly active process close to the contact zone between tool and chip. This is due to the significant gradients of chemical species and of temperature in this zone. Diffusion wear is often accompanied by the decomposition of a component of one of the sliding surfaces. Diffusion strongly depends on several variables, such as chemical composition, solubility of carbon in the chip, temperature, time, secondary shear flow; unfortunately effective studies are very difficult to be carried out since any proposed test involves other wear mechanisms in addition to diffusion. The rate of diffusion increases exponentially with the increase of temperature. Diffusion phenomena were first reported by Loladze [1981] who showed that at conventional speed, tool wear is mainly due to abrasion and adhesion, but is dominated by diffusion process at higher speeds. Weill [1966] confirmed, by carrying out wear tests on the tungsten–molybdenum couple, that there are three wear modes depending on the cutting speed used. Abrasion wear occurs at low cutting speed (≤35 m/min). Between 35 m/min and 110 m/min, wear mode changes from abrasive to adhesive wear. Finally, it was shown that diffusion wear (third mode) increases rapidly with speed beyond 110 m/min and temperature beyond (critical temperature). The atoms in the cutting tool and work material form new oxide molecules at the contact boundary exposed to oxygen [Yusuf 2000]. A slight oxidation of tool face is helpful to reduce adhesion, diffusion and current by isolating the tool and the workpiece. But at high temperature, soft oxide layers form rapidly to be taken away by the chip and the workpiece resulting in a rapid tool material loss.

Under different cutting conditions dominating wear mechanisms are different. For a certain combination of cutting tool and workpiece, the dominating wear mechanisms vary with cutting temperature, as shown in Fig.1.7. According to the temperature distribution on the tool face, it is assumed that crater wear is mainly caused by abrasive wear, diffusion wear and oxidation wear, but flank wear mainly dominated by abrasive wear due to hard second phase in the workpiece material.

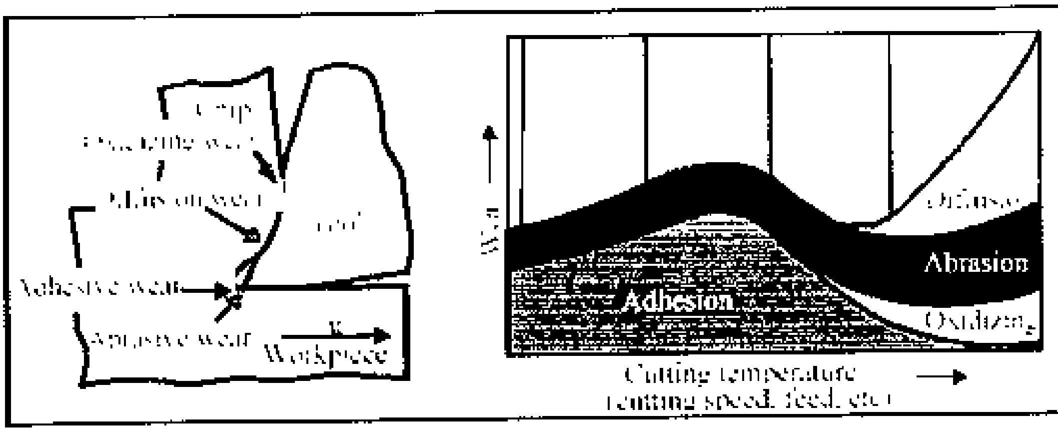


Fig. 1.7 Wear Mechanism **[König 1984]**

Whatever may be the process, the amount of wear reaches a threshold value beyond which there is a drastic decline in performance of the tool. Generally, this threshold value is predetermined which is known a tool life criterion. Tool life depends on an assumed maximum of the wear of the tool and is therefore a matter of agreement and standardization. The criteria recommended in the new ISO standard dealing with tool-life testing varies for different tool materials depending on their properties. Some of the tool life rejection criteria presented in ISO 3685 **[1993]** are listed below:

i. Average flank wear >0.3 mm

ii. Maximum flank wear >0.7 mm.

iii. Maximum crater wear >0.14 mm.

iv. Notch wear >1.0 mm.

v. Surface roughness >6.0 mm.

vi. Excessive chipping (flaking) or catastrophic fracture of the cutting edge.

1.3.4 Mathematical Models of Tool Wear

The ability to predict tool wear or tool life is obviously important for tool management. From the beginning, the effort to predict tool wear or tool life takes into account the dependence on the combination on the properties of tool (material, geometry, surface integrity and internal defects), the work (hardness, strength, chemical composition, etc), the cutting conditions (speed, feed, depth of cut, cutting fluids), the cutting mode (turning, milling, drilling and others) and the machine tool (for example stiffness, state of maintenance). Moreover, the studies concerning tool wear are mainly experimental ones and few numerical investigations may be recognized in technical literatures. However, it must be acknowledged that a universal model considering all aspects is a theoretical and practical impossibility. It is, however, possible to develop tool life equations if the cutting mode and machine tool are limited and the tool wear is simple and dominated by a single mechanism. Many mathematical models are developed to quantity tool wear. They can be categorized into two types: tool life models and tool wear rate models (Table-1.1).

Since the tool wear in cutting operations involves complex wear mechanisms, researchers have attempted to directly correlate the results of tool life to the applied machining parameters (cutting speed, feed rate, etc.). The well-known Taylor's tool life relationship and its various extended equations are of this type [**Jawahir et al.1995, Oxley 1989**]. These equations describe the relationship between tool life and machining parameters and involve a few constants that need to be experimentally determined for the given combination of tool and workpiece materials.

Table-1.1 Tool Wear and Wear Rate Models

Empirical Tool Life Models	**Differential Tool Wear Rate Models**
Taylor's Tool life Equation. $VT^{\alpha} = C_1$ (α, C_1 = constants)	Takeyama & Murata Model, considering Abrasive wear and diffusive wear [**1963**]: $dW/_{dt} = G(V,S) + D.\exp(-E/_{R\theta})$
Taylor's Extended Equation: $T = \dfrac{C_2}{V^{\alpha} S^{\beta} a^{\gamma}}$ (α, β, γ, C_2 = constant)	(G, D = constants)
Taylor's Extended Equation: $T = \dfrac{C_3}{V^{\alpha} S^{\beta} a^{\gamma} (BHN/200)^{r}}$ (α, β, γ, r, C_3 = constants)	Usui's Model, derived from equation of adhesive wear [**Usui et al.,1978**]: $dW/_{dt} = C\sigma_n V_S \exp(-\lambda/_{\theta})$ (C, λ = Wear characteristic constants)
Temperature Based Equation [**Schallborch et al., 1938**]: $T\theta^{n} = C_4$ (n, C_1 = constants)	
$dW/_{dt}$ = Wear Rate (volume loss per unit contact area per unit time) T = Tool Life R = Universal Gas constant E = Process Activation Energy V = Cutting Speed	S = Feed VS = Sliding Velocity BHN = Workpiece Hardness σ_n = Normal Stress θ = Cutting Temperature

Tool life equations are suitable to very limited range of cutting conditions. As the new machining technologies, e.g. high speed cutting using high-pressure coolant, are getting spread in manufacturing industry, the existing tool life equations need to be updated with new constants and a lot of experimental work has to be done. In addition, except that tool life can be predicted by these equations, it is difficult to get further information about the tool wear progress, tool wear profile or tool wear mechanisms that are sometimes important for tool designers. The tool life equation of Taylor relates influence of cutting speed on tool life over limited ranges of cutting speed. In mathematical form the equation can be expressed as:

$$VT^{\alpha} = C$$

where V is the cutting speed, *T* the tool life, α the slope of the log *T*-log *V* and *C* is the Taylor constant; that is the cutting speed for a 1 min tool life. This formula indicates that a linear relationship between log *T* and log *V* (that is α is a constant). However, experience has shown that a linear curve (that is α is constant) resulted from a log *T*-log *V* plot occurs in certain conditions **[Barrow 1971]**. The Taylor equation seems to be valid reasonably valid when machining carbon and low alloy steels with all types of material in semi roughing conditions (Depth of Cut 0.050-0.150 in and feeds of less than 0.020in) when cutting with speeds to give tool lives of 10-50 min, because it is in this region that optimum economic conditions are approached.

To deal with non-linear curve, Kronenberg **[1971]** suggested a method of straightening a curved log *T*-log *V* plots. This is achieved by adding or subtracting a constant straightening factor to or from all values of speed and tool the curvature of the original data determines whether the straightening factor is added or subtracted. Kronenberg **[1966]** opined that non-linearity may due to change of tool material. In some instances curves may result of insufficient number of tests. According to his experience, a straight logarithmic line relation between cutting speed and tool life is obtained if cutting speed variation does not exceed a ratio of approximately 1:15. The range is sufficiently large to cover the cases of interest and should not be considered as a definite limit, but rather as a practical 'rule of thumb' to be observed in the running of tests.

Lorenz [1963] came to conclusion that the Taylor equation is also valid for very short tool life and high cutting speeds. He developed a method of short-run tests replacing the conventional long-run tool life tests and evaluated the results by means of regression analysis. Boston [1939] and his associates when using coolants in their tests also obtained straight lines always. Tool life exponent varied between 0.097 and 0.152, using conventional method of averaging data plotted on a log-log paper. Taylor equation only relates cutting speed to the tool life for a particular tool-workpiece combination and does not consider other cutting variable and tool geometry. To connect tool life with several other variables, Taylor derived an equation winch includes the important variables, feed and depth of cut, as well as nose radius. However, it is too complex and limited to be of any practical use. Again, as tool inserts with definite standard nose radius are widely used now a days, considering nose radius a variant in determining tool life is redundant.

Though Taylor noted the influence of cutting temperature of tool life quite earlier, it was Schallborch et al. [1938] to demonstrate that tool life could be related to temperature. The work of Schallborch was undertaken on high speed steel cutting tools, but several other workers have demonstrated the validity of the equation using carbide tools with flank wear as the tool life criteria. Experience has shown that a unique relationship between temperature and tool life only exists for one tool-workpiece combination over a limited range of cutting conditions. Barrow have found that the tool wear depends on , in addition to temperature, normal stress which act on the flank face of the cutting tool, Barrow [1973] proposed that the total volume of the tool material removed is due to both 'primary' being removed and secondary mechanical wear taking place as the primary particles traverse the wear land. The temperature will exert a strong influence on the primary wear either through its influence on the properties of the tool material, the thermal stressing of the tool material or by facilitating of diffusion processes. As the length of the wear 'land' increase to relatively high values, the temperature gradient down the wear 'land' will decrease and more and more primary particles will be formed at a greater distance from the tool edge, additionally the same phenomenon will facilitate the formation of secondary wear, i.e. an avalanching effect will bring about the terliary region of the tool wear land time relationship.

In contrast to the above tool life models, the tool wear rate models describe the rate of local volume loss on the tool contact face (rake or flank face) per unit area per unit time. The derivations of this type of tool wear rate models require the knowledge of wear mechanisms associated with the tool and workpiece materials and the range of cutting conditions used. These models are derived from one or several wear mechanisms. They provide the information about wear growth rate due to some wear mechanisms. In these modes, the wear growth rate, i.e. the rate of volume loss at the tool face (rake or flank) per unit contact area per unit time (mm/min), are related to several cutting process variables that have to be decided by experiment or using some methods **[Kwon 2000]**. Choudhury **[2004]** developed an empirical tool flank wear rate model as a function of cutting velocity, feed, depth of cut, and variation of the normal load with respect to flank wear, wear coefficient, hardness of the cutting tool and the index of the diffusion coefficient. Based on Archard **[1953]** model of volumetric wear rate depending on the deformation producing particles and considering diffusion of materials from the tool material, the model employs regression analysis to determine the constants defining the model. He found that all the input variables parameters influences tool wear rate, however, at different extent. The cutting velocity is the predominant factor affecting tool wear. The flank wear increases with increase in feed and depth of cut though the influence of feed is much significant than depth of cut.

It is generally accepted that for carbide tools under practical cutting conditions, the wear rate is dominated by a temperature-sensitive diffusion process, in particular at higher cutting speeds [**Mathew 1989, Molinari and Nouari 2002, Usui et al. 1978**]. Takeyama and Murata derived a fundamental wear rate equation by considering abrasive wear, which is proportional to cutting distance, and diffusive wear. Therefore, this model is developed by considering the combination action of abrasive wear and diffusive wear. The equation sums two parts up; one part shows that abrasive wear is influenced by the cutting speed and feed. Another part includes diffusive wear as function of universal gas constant and tool temperature. Mathew [1989] analyzed the tool wear of carbide tools when machining carbon steels and results have shown that the Takeyama and Murata's diffusion equation can be used to effectively relate the tool wear rate to the average contact temperature of the tool. At cutting temperature higher than 800^{0}C, the abrasive term can be neglected.

Recognizing that the effectiveness of any wear model strongly depends on the temperature distribution prediction in the tool, during the process and diffusion is a temperature dependent model, Fillice [2007] developed a finite element model based on Takeyama and Murata model as it is able to properly describe the diffusion wear effects. Considering diffusion as the dominant phenomenon at high machining, Fillice rewrited Takeyama and Murata model. However, Fillice proposed a parameter which can be described using a polynomial function of temperature. Molinari and Nouari [2002] recently proposed a model of tool wear by diffusion, taking into account cutting parameters, working material properties and frictional aspects, and underlined the influence of contact temperature at the interface between tool and chip. Experimental investigations on tungsten carbide tool wear were performed by Yang [2001], who focused his affention on the evaluation of the wear coefficient by several pin-on-disc experiments.

Usui et al. [1978] in the tool wear study for carbide tools derived a wear rate model based on the equation of adhesive wear, which involves temperature, normal stress, and sliding velocity at the contact surface. Their results in machining different carbon steels (0.15–0.46% C) showed that both flank wear and crater wear obey the same wear mechanism and can be described by the proposed wear model. A change of slope of the wear characteristic line at near 877°C (1150 K) was observed, and according to the authors, attributed to the formation of fragile carbide compounds and disappearance of WC grains (a diffused layer) in the tool material at high temperatures. It should be noted that despite considering different tool wear mechanisms, Mathew [1989] could fit the experimental wear data well due to the fact that the diffusive and adhesive wear models used, respectively, have the same form with the temperature dependence in the exponential term.

1.4 Surface Roughness

Each machined surface is a part of engineering component made by any metal removal process, and each engineering component consists of definite set of surfaces. In assembly, an engineering component becomes a part of final product that carries out a certain role. Thus, machined surface comes into contact either with another surface or with fluid, accomplishing functioning of assembled device. In contact, in functioning or in loading, an arbitrary surface has its own functioning properties, or perhaps its behavior that contribute to quality of assembled device, as for instance power transmission (clutch, brake, transmission, driving device), information processing(measurement device, video head) and so on.

Surface roughness is predominantly considered as the most important feature of practical engineering surfaces due to its crucial influence on the mechanical and physical properties of machined parts. As a significant design specification, surface roughness influences on properties such as wear resistance, cleanability, assembly tolerances, coefficient of friction, wear rate, corrosion resistance, and aesthetics and fatigue strength. The quality of the surface is a factor of importance in the evaluation of machine tool productivity. [**Yang and Jeang 1994**]. Surface roughness has formulated an important design feature in many situations such as parts subject to fatigue loads, precision fits, fastener holes, and aesthetic requirements. In addition to tolerances, surface roughness imposes one of the most critical constraints for the selection of machines and cutting parameters in process planning. As competition grows closer, customers now have increasingly high demands on quality, making surface roughness become one of the most competitive dimensions in today's manufacturing industry [**Feng 2001**].

The estimation of the magnitude of surface roughness under given cutting conditions resulting from metal removal operations is one of the major determinant of machining performance. On the other hand, the process dependent nature of the surface roughness formation mechanism along with the numerous uncontrollable factors that influence pertinent phenomena, make almost impossible a straightforward solution.

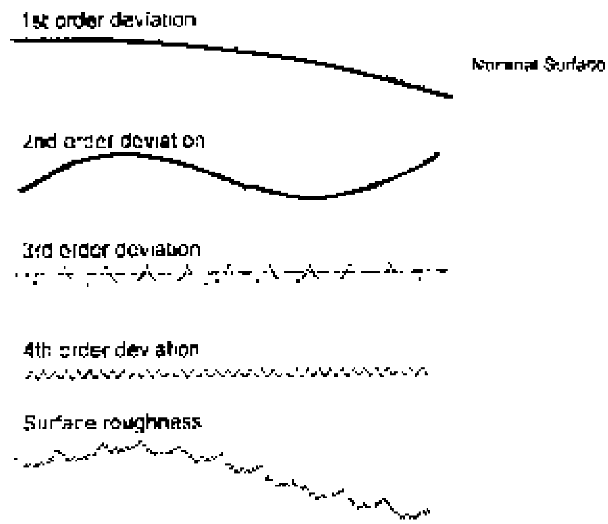
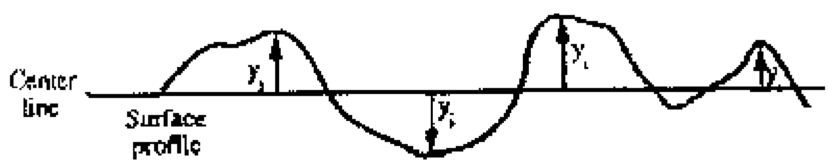


Fig. 1.8 Surface Form Deviation [**DIN4760 1982**]

Surface roughness refers to deviation from the nominal surface of the third up to sixth order. Order of deviation is defined in international standards [**DIN4760 1982**]. First- and second-order deviations refer to form, i.e. flatness, circularity, etc. and to waviness, respectively, and are due to machine tool errors, deformation of the workpiece, erroneous setups and clamping, vibration and workpiece material inhomogenities. Third and fourth-order deviations refer to periodic grooves, and to cracks and dilapidations, which are connected to the shape and condition of the cutting edges, chip formation and process kinematics. Fifth- and sixth-order deviations refer to workpiece material structure, which is connected to physical–chemical mechanisms acting on a grain and lattice scale (slip, diffusion, oxidation, residual stress, etc.). Different order deviations are superimposed and form the surface roughness profile as can be seen in Fig.1.8. There are several measurements that describe the roughness of a machined surface. Average roughness, Ra for the characterization of surface roughness, is used most widely in the industry for specifying surface roughness. The Ra value is obtained by measuring the height and depth of the valleys on a surface with respect to an average centerline. Fig. 1.9 shows a magnified cross section of a typical machined surface.



$$Ra = \frac{\sum_{i=1}^{n} y}{n}$$

Fig.1.9 Arithmetic Average Value of roughness (Ra)

Since turning is the primary operation in most of the production processes in the industry, surface finish of turned components has greater influence on the quality of the product. Surface finish in turning has been found to be influenced in varying amounts by a number of factors such as feed rate, work material characteristics, work hardness, unstable built-up edge, cutting speed, depth of cut, cutting time, tool nose radius and tool cutting edge angles, stability of machine tool and workpiece-setup, chatter, and use of cutting fluids in varying application methods and composition. Almost all the workers have taken into account the variables of speed and feed in surface roughness study. Groover [1996] and Boothroyd and Knight [1989] considers the impact of three factors, namely, the feed, nose radius, and cutting-edge angles, on surface roughness is depicted. Assuming a non-zero cutter nose radius (r), they developed the following equation to estimate the ideal roughness value

$$R_a = \frac{S_0^{2}}{32r}$$

where, Ra = ideal arithmetic average (AA) surface roughness (in. or mm), S_0= feed (in/rev or mm/rev) and r = cutter nose radius (in. or mm). Refer to Fig. 2.6 for illustration. This equation gives a roughness value in inch or mm that can be converted to μinches or mm. This equation assumes that the feed and nose radius are the principal factors that determine the geometry of the surface. The above model assumed a non-zero nose radius.

Fig. 1.10 Effect of Nose Radius on Surface Roughness

If the nose radius would be zero as shown in Fig. 1.10, then the following equation is used to estimate the ideal surface roughness Boothroyd and Knight **[1989]**

$$R_a = \frac{S_0}{4(\cot\alpha + \cot\beta)}$$

where o and β are the working major cutting edge angle (MCEA) and end cutting edge angle (ECEA), respectively.

As equations of roughness values implies that ideal roughness of the surface is a function of only feed rate and tool geometry. It represents the best possible finish which can be obtained for a given tool shape and feed. However, these equations hold true only if built-up-edge, chatter, inaccuracies in the machine tool movement and other factors are eliminated completely. Both theoretical and empirical mathematical models are being developed to predict approximately the magnitude of the surface roughness under given conditions. However, the above mentioned theoretical expressions giving the roughness value obtained in a single point turning operations are closely related to the geometry of feed marks which depends on the feed rate and corner radius but do not include other surface altering factors.

1.5 Machining Environment

In Machining process, the tool removes material from the surface of a less resistant body, through relative movement and application of force. The material removed, called chip, slides on the face of tool submitting it to high normal and shear stresses and, moreover, to a high coefficient of friction during chip formation. Most of the mechanical energy used to form the chip becomes heat, which generates high temperatures in the cutting region. A major portion of the energy is consumed in the formation and removal of chips. The greater the energy consumption, the greater are the temperature and frictional forces at the tool–chip interface and consequently the higher is the tool wear. For this reason, conventional coolant is often used on the cutting tool, to prevent overheating. However, the main problem with conventional coolant is that it does not reach the real cutting area

[**Wertheim and Rotberg 1992**]. The extensive heat generated evaporates the coolant before it can reach the cutting area. Hence, heat generated during machining is not removed and is one of the main causes of the reduction in tool life [**Kumar 2002**].

Cutting fluids is supposed to play a significant role in improving lubrication as well as minimizing temperature at the tool–chip and tool–workpiece interfaces, consequently, minimizing seizure during machining but it can only perform these functions at the point of chip formation if the coolant actually reaches the cutting zone. Cutting fluid can additionally clean the cutting zone and protect the nascent finished surface from contamination by the harmful gases present in the atmosphere. Flood cooling of the cutting zone can effectively reduce the cutting temperature when machining at lower speed. Flood cooling is not effective in terms of lowering cutting temperature when machining exotic materials or machining at high speed. The coolant does not readily access the tool–workpiece and tool–chip interfaces that are under seizure condition as it is vaporized by the high temperature generated close to the tool edge. The majority of the cooling and lubricating aspects of a flood coolant stream are lost as coolants tend to be vaporized prior to entering the cutting zone by the high temperature generated close to the tool edge, forming a high temperature blanket that renders their cooling effect ineffective. The film boiling temperatures of conventional cutting fluids is about 350°C [**Ezugwu 2004**]. When coolant fails to reach the target, it does not perform its two essential functions- cooling and lubricating. Besides that, often in high production machining the cutting fluid may cause premature failure of the cutting tool by fracturing due to close curling of the chips and thermal shocks. For which application of high cooling type water base cutting fluids are generally avoided in machining steels by brittle type cutting tools like carbides and ceramics. But what is of more serious concern is the pollution of the working environment caused by use of cutting fluid, particularly oil-based type.

Use of liquid nitrogen as a coolant and lubricant may be a solution. This technique is not the same as cryogenic machining, where the material to be cut is cooled to a very low temperature prior to the machining operation. Rather, the method currently under development uses liquid nitrogen to perform the cooling and lubricating job of the cutting fluid. Much of the part remains at ambient temperature while the flow of nitrogen is carefully delivered to the point where it is needed. Reportedly, tool life and finish quality are also improved by this technique due to the low temperatures at the tool/part interface. Liquid nitrogen is an inexpensive chemical that is environmentally inert. Nitrogen is the most abundant gas in earth's atmosphere and, when liquid nitrogen warms, it simply mixes with and diffuses harmlessly into the air. Chips generated from this technique have no residual oil on them and can be recycled as scrap metal. However, liquid nitrogen is hazardous to workers due to its extremely low temperature. Exposure can result in mild to extreme frostbite. Nitrogen that is stored in a sealed vessel will increase in pressure dramatically as it warms, potentially resulting in a non-combustion explosion. Large spills can displace all of the oxygen in a room in a short time.

Recognizing that large amount of cutting fluid can be a serious threat to health and environment, leads to adoption of minimum quantity lubrication (MQL), micro lubrication, near dry machining, or "spatter" lubrication method. MQL is a method of delivering metalworking fluids to the point of cut, or just the logical continuation of the age old technique of "brushing on" a lubricant where it is needed. In any case, this technology recognizes that sometimes just a little fluid, when properly selected and applied, can make a substantial difference in how effectively a tool performs. MQL is perceived to provide benefits of both dry machining and flood cooling as MQL results cleaner parts like dry machining and serves the basic cutting functions of metalworking fluids which includes increased tool life, improved surface integrity of the work piece, and protection of in process corrosion (Trim Technical Bulletin: Fluid Solutions for Metalworking). In addition, MQL:

- Reduces mist and spray, therefore offering an attractive alternative on unenclosed machines like a typical tool room mill or lathe.
- Reduces or eliminates problems associated with "thermal shocking" of the cutting tool.
- Produces a cleaner, drier work piece than a flood or high-pressure coolant.

However, MQL performs very well in increasing too life particularly when the tool failure mechanism is thermal shocking or with excessive heat or abrasion from flank drag. But, it does not do very well when multiple tools are in play, either at the same time (as with a screw machine) or sequentially (as in a vertical machining center), as tool nozzle alignment is difficult to impossible. MQL is not particularly effective in processes that generate large amounts of heat. MQL totally fails to flush chips and swarf from the cutting zone. MQL in a production environment needs an alternative method of chip removal. MQL does not take heat out of the tool, the work piece or the whole machining system; it will reduce only the amount of heat produced by the chip moving up the face of the tool and parasitic "flank drag." MQL does not prevent corrosion on either chips or parts. Positioning of the nozzle is critical for MQL Method. The nozzle must be located not more than 1 to 2 inches from the tool as it enters the cutting zone, so more often than not, the applicator nozzle must be adjusted for each different tool. Again, the nozzle is susceptible to both damage and being moved (pointed improperly) when either heavy chips or stringers are produced. Though MQL reduces the problems of cutting fluid management and disposal, it fails to address associated health risks.

According to OSHA, two exposure limits may apply to cutting fluids. Workers should be exposed to no more than 5mg/m^3 of mineral oil mist for an 8 hour time weighted average (TWA), and no more than 15 mg/m^3 for any particulate, as an 8 hour TWA. In unenclosed machines, neither flood cooling nor MQL generates mists or particulate below that standard. So, modern

CNC machine tools are enclosed where the mist and particulate are confined within the machine enclosure.

High-pressure assisted cooling is one of the preferred technologies especially for machining exotic materials. The primary objective of machining using high-pressure coolant is to significantly reduce the temperature generated at the tool-workpiece and tool-chip interfaces when cutting at higher speed conditions. High-pressure coolant (HPC) jet is directed to the chip-tool interface at a velocity several hundred mph. The penetration of the high-energy jet through the vapor barrier at the tool–chip interface reduces the temperature gradient and minimizes the seizure effect, offering an adequate lubrication at the tool–chip interface with a significant reduction in friction. Ability to deliver coolant at high pressure very close to the critical point on the secondary shear zone can a third function-breaking chips that do not break neatly with ordinary machining processes **[Mason 2001]**. The chip control achieved with HPC is phenomenal. This is attributed to a coolant wedge which forms between the chip and the tool forcing the chip to bend upwards giving it a desirable up curl required for segmentation. This reduces or eliminates the random tool failures from chip damage, resulting in much improved consistency of the machining process.

Again, in dry, flood, MQL and cryogenic machining, fast cycle times in high speed machining are meaningless if as the machining process needs to be interrupted to remove chips that have "bird nested" on the part, the turret or the tool slide. In the case of machining centers, chips get nested on the fixture, get packed into small holes in the machined part, or wrap around the tool. The high-pressure coolant jet creates a hydraulic wedge between the tool and the workpiece, penetrating the interface with a speed exceeding that required even for high speed machining and also alters the chip flow conditions (Fig. 1.11). The penetration of the high energy jet into the tool-chip interface reduces the temperature gradient and eliminates the seizure effect, offering an adequate lubrication at the tool-chip interface with a significant reduction in friction.

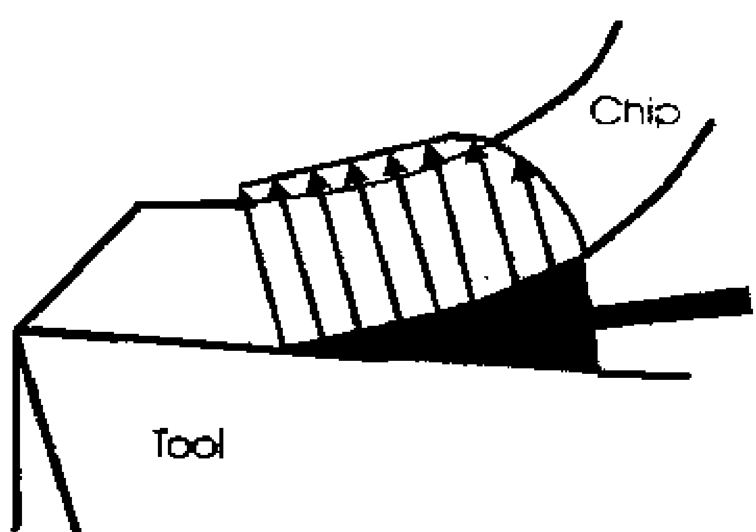


Fig. 1.11 Hydraulic Wedge Created by High-pressure Coolant Jet

1.6 Application of High-pressure Coolant in Machining

Lo´pez et. al. **[2000]** studied drilling and turning with different combinations internal and external cooling of two alloys commonly used in the aircraft industry, specifically, alpha–beta type titanium alloy Ti6A14V and nickel-based super alloy of type with high-pressure lubrication. Examining the results of various machining tests carried out under severe cutting conditions, drills coated with TiNi is found to perform well in the drilling of

Inconel 718. Internal coaxial cooling proved viable in the drilling of titanium. Ceramics behave well in the turning of Inconel. It is effective in the cutting of titanium to use a high-pressure water-jet system; cutting speeds are double the conventional speed with a good drill life.

In machining of hardened steel and other difficult-to-cut materials, Kumar et al. **[2002]** compared milling performance of high-pressure coolant application at 17 bar with Dry cut and conventional coolant application using both uncoated A30N tungsten carbide insert and coated TiAlCN insert. The effectiveness of high-pressure coolant is evaluated in terms of improvement of surface finish, reduction in tool wear and cutting forces, and control of chip shape. Because, the cutting temperature and forces are reduced, the application of high-pressure coolant produces a great reduction in flank wear and hence tool life and produces a significant improvement in surface finish for both uncoated and coated inserts, in a certain range of hardness. However, an effective zone in terms of hardness is found to result better performance both in coated and uncoated inserts.

Ezugwu and Bonney **[2004]** machined Inconel 718 with a triple PVD coated (TiCN/Al2O3/TiN) carbide tool at various using conventional and various high coolant pressures, up to 203 bar with a view to study machining performance in terms of tool life, surface roughness (Ra), tool wear and component forces. The test show that with high coolant pressures resulted acceptable surface finish and improved tool life can be achieved when machining Inconel 718.Compared to conventional coolant supplies, tool life improved as much as 740%, when machining at 203 bar coolant pressure at a speed of 50mm/in. Tool life is found to generally increase with increasing coolant supply pressure which was attributed to the ability of the high-pressure coolant to lift the chip and gain access closer to the cutting interface. This action leads to a reduction of the seizure region, thus, lowering the friction coefficient which in turn results in reduction in cutting temperature and component forces. Chip breakability during machining was found to be dependent on the depth of cut, feed rate and cutting speed employed as well as on the coolant pressure employed. Tool wear increased gradually with prolong machining with high coolant pressures. Nose wear was proved the dominating tool failure mode due probably to a reduction in the tool–chip and tool–workpiece contact length/area.

1.7 Development of Mathematical Model

Qualitative analyses as well as comprehensive predictive models on the surface roughness and tool life are widely available. However, the classification of the research approach was not easy due to two main reasons. First, there are many research that do not strictly follow a certain methodology in its entirety, rather, selecting and combine some of its basic principles, 'new' approach is developed. Secondly, there are many cases where researchers blend different strategies into a single approach and therefore no single classification would be entirely accurate. Taking into account the above three major categories were created to classify the selected papers. These are:

(i) approaches that are based on machining theory to develop analytical models and/or computer algorithms to validate the model.

(ii) approaches that examine the effects of various factors through the execution of experiments and the analysis of the results

(iii) approaches that use designed experiments

1.7.1 Machining Theory Based Approach

This category includes approaches that place emphasis on certain aspects from the theory of machining such as process kinematics, cutting tool properties, chip formation mechanism etc. Computer-aided design (CAD) methods and tools are utilized so as to achieve the goal of building a model that will be able to simulate the creation of the machined surface profile, thus visualizing surface topography and assessing surface roughness. In general, geometric model development forms the basis of the approach through rigorous mathematical equations. This model is then implemented by a computer algorithm in order to handle the complex calculations.

Grzesik [1996] used the minimum undeformed chip thickness to predict surface roughness in turning. The molecular–mechanical theory of friction and the Hencky–Ilyushin theory of plasticity were used to mathematically model the tribological effects at the chip–cutting tool interface. The approach was based on the assumption that the difference between the theoretical and measured surface roughness values is due to adhesion at the chip–cutting tool interface and that the minimum undeformed chip thickness corresponds to the transition from ploughing to microcutting. Consequently, an existing model for predicting the roughness of a turned surface was improved and the difference between the measurements and predicted results was markedly reduced.

1.7.2 Experimental Investigation Approach

The experimental approach may be thought of as the most 'obvious' method: experiments with the factors that are considered to be the most important are conducted and the obtained results are used to investigate the effect of each factor as well as the influencing mechanism on the observed quality characteristic. Regression analysis is often employed in order to build models based on the experimental data. The researcher's intuition and insight play a great role in this approach but a high understanding of the examined phenomenon is also necessary for the experiment to yield any meaningful results. The experimental approach is mainly adopted in cases where there can be no analytical formulation of the cause and effect relationships between the various factors.

Abouelatta and Madl [2001] examined the relationship between tool life, surface roughness and vibration The variables that were considered included the cutting speed, feed rate, depth of cut, tool nose radius, tool overhang, approach angle, workpiece length and workpiece diameter and the accelerations in both radial and feed directions. The acceleration signals were fed to an FFT analyzer that produced ASCII files. The experimental data were analyzed to produce regression analysis models.

The potential for use of cryogenic cooling in turning and particularly its effects on tool wear, dimensional accuracy and surface finish was examined by Dhar and co workers **[2001]**. For that purpose, a comparison between liquid nitrogen jet on the cutting tool and dry machining was performed. The results showed that cryogenic cooling improved the surface finish by reducing the deterioration of the auxiliary cutting edge caused by abrasion, chipping and built-up edge formation.

1.7.3. Designed Experiments Approach

Designed experiments constitute a systematic method concerning the planning of experiments, collection and analysis of data with near-optimum use of available resources. The response surface methodology (RSM) and Taguchi techniques for design of experiments (DOE) seem to be the most wide-spread methodologies for the surface roughness prediction problem.

Lambert & Taraman **[1973]** developed an adequate mathematical model for the cutting force acting on a carbide tool while machining SAE 1018 cold-rolled steel in a turning operation and then utilized the model in the selection of the levels of the machining variables of cutting speed, feed rate, and depth of cut, such that the rate of metal-removal could be at the highest possible value without violating some given force restriction. By using response surface methodology the three independent variables (cutting speed, feed rate and depth of cut) could be investigated simultaneously to study their effects on the cutting force, resulting in considerable saving in time and money over traditional methods of analysis.

El Baradie **[1993]** presented a study of the development of a surface roughness model for turning grey cast iron using tipped carbide inserts under dry conditions and for a constant depth of cut. The mathematical model utilizing the response surface methodology was developed in terms of cutting speed, feed rate and nose radius of the cutting tool. These variables were investigated using design of experiments and utilization of the response surface methodology. Surface roughness measurements were made using a Taylor–Hobson Surtronic surface roughness measuring instrument. A first-order model covering the cutting speed range of 110–350 m/min and a second-order model covering the cutting speed range of 80–495 m/min are presented in this study. Contours of the surface roughness outputs were obtained in planes containing two of the independent variables. These contours were further developed to select the proper combination of the cutting speed and feed rate to increase the metal removal rate without sacrificing the quality of the surface roughness produced.

1.8 Summary of the Review

Review of the literature highlights the immense potential of the control of machining temperature and its detrimental effects. It is realized that the machining temperature has a critical influence on tool wear and tool life. All these responses are very important in deciding the overall performance of the tool. At the elevated temperature the cutting tools may undergo plastic deformation and attain rapid tool wear because by adhesive, abrasive, chemical and diffusion wear at the flanks and the crater. The dimensional accuracy and surface integrity of the workpiece also deteriorate due to high temperature.

The prediction of tool wear and surface roughness is important planning considerations. However, different approaches are adopted to develop predictive models to relate machining performance with machining parameters. Of them, design of experiment is a widely practised statistical tool to develop mathematical formulation.

The application of cutting fluids helps in improving the life and function of cutting tools and in achieving the desired size, finish and shape of the workpiece. But the conventional types and methods of application of cutting fluid have been found to become less effective with the increase in cutting velocity and feed when the cutting fluid cannot properly enter the chip-tool interface to cool and lubricate due to bulk plastic contact of the chip with the tool rake surface. At the same time, MQL fails to perform its intended functions properly.

Enormous efforts are, therefore, being made from the viewpoint of technological, performance and application issues relating to the use of cutting fluid or lubricant in metal cutting. In this context, high-pressure coolant which uses a high pressured spray of coolant appears to be a promising technique for effective cooling without the problems associated with conventional cutting fluid applications.

1.9 Objectives of the Present Work

As high-pressure coolant is perceived to be a promising machining practice, the performance of HPC needs to be explored. However, subjective observation and consequent perception would not establish the relative benefits of HPC. Quantitative results can stand as proofs of superiority of this machining practice. Predicting machining performance of high-pressure coolant at different combination of variables can aid in providing quantitative results and decision making for optimization of machining process. Development of mathematical modeling is the obvious choice for prediction of HPC performance. Therefore, this research aims in development of mathematical models to predict machining performance in terms of surface roughness and tool life for different combinations of machining variables, specifically cutting speed and feed rate.

The main objective of the present work is to make a statistically designed experimental investigation with the application high-pressure coolant with a view to predict machining performance in terms of

i. tool life

ii. surface roughness

in turning medium carbon steel by the industrially used uncoated carbide tool (SNMG 120408 TTS) at different cutting velocities and feeds combinations. The results are being expected to be used to develop statistical models to predict the two machining dependent parameters, namely, tool life and surface roughness at different combinations of cutting variables- cutting speed and feed.

The scopes of the present work are

(a) Analysis of data by

  i. measuring tool wear (flank wear) under microscope

  ii. measuring surface roughness

(b) Development of mathematical models of

  i. tool life

  ii. surface roughness

using response surface method to relate machining parameters.

1.9 Organization of the Thesis

The thesis is subdivided into five chapters including this one. The chapters are organized in the following way:

Outline of the experimental setup including the measurement procedure undertaken during the study is explained in chapter 2.

Chapter 3 develops the first order mathematical models of tool life and surface roughness. The coefficients of models are determines from experiments performed. The adequacy of the models was checked by analysis of variance and a second set of tests.

A brief discussion on the experimental method and the model and its development procedure is presented in chapter 4.

Chapter 5 narrates concluding remarks of this study.

Chapter-2

Experimental Investigations

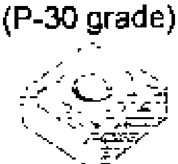
2.1 Experimental Procedure and Conditions

The concept of high-pressure coolant presents itself as a possible solution for high speed machining in achieving slow tool wear and improved surface finish while maintaining cutting forces/power at reasonable levels, if the high pressure cooling parameters can be strategically tuned. High-pressure coolant injection technique not only provided reduction in tool wear and improvement in surface roughness but also reduced the consumption of cutting fluid. The aim of the present work is primarily to develop a mathematical model of tool wear and surface roughness in turning using high-pressure coolant which would contribute in manufacturing planning and economy.

The machining tests have been carried out by straight turning of medium carbon steel on a lathe (10 hp: China) by standard uncoated carbide insert at different cutting velocities (Vc) and feeds (So) and constant depth of cut (t) under dry and high pressure coolant conditions. The experimental conditions have been given in Table-2.1.

Effectiveness of cooling and the related benefits depend on how closely the high pressure coolant jet can reach the chip-tool and the work-tool interfaces where, apart from the primary shear zone, heat is generated. The tool geometry is reasonably expected to play significant role on such cooling effectiveness. Keeping this view tool configuration namely SNMG-120408 has been undertaken for the present investigation. The insert was clamped in a PSBNR-2525 M12 type tool holder.

Table- 2.1 Experimental Conditions

Machine Tool	: Lathe Machine (France), 15 hp	
Work Material	: Medium Carbon Steel (φ173 X 710 mm)	
Cutting Tool (Insert)		
Cutting Insert	: Uncoated Carbide, (P-30 grade), Sandvick  SNMG 120408	
Tool Holder	: PSBNR 2525M12(ISO specification)	
Working Tool Geometry	: Inclination Angle	: -6°
	Orfhogonal Rake Angle	: -6°
	Orthogonal Clearance Angle	: 6°
	Auxiliary Cutting Edge Angle	: 15°
	Principal Cutting Edge Angle	: 75°
	Nose Radius	: 0. 8 mm
Process Parameters		
Cutting Velocity, V	: 133, 186 and 266 m/min	
Feed Rate, S_o	: 0.14, 0.18 and 0.22 mm/rev	
Depth Of Cut, T	: 1.0 mm	
HPC Supply	: Pressure: 70 bar, Lubricant: VG 68 Cutting Oil	

The positioning of the nozzle tip with respect to the cutting insert has been settled after a number of trials. The final arrangement made and used has been shown in Fig.2.1. The high-pressure coolant jet is directed along the auxiliary cutting edge at an angle 30o to reach at the principal flank and partially under the flowing chips through the in-built groove parallel to the cutting edges. The photographic view of the experimental set-up is shown in Fig.2.2.

Fig. 2.1 [illegible] Delivery [illegible]

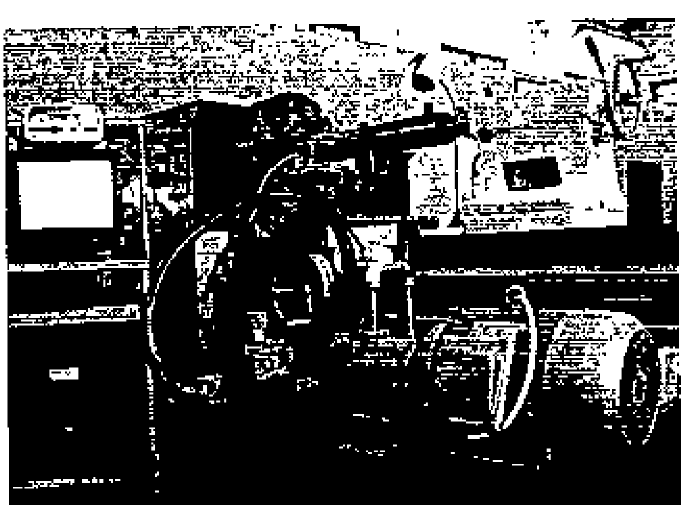


Fig. 2.2 Photographic View of the Experimental Set-up

A cylindrical bar of medium carbon steel of 173 mm diameter was selected for straight turning. During machining, the cutting insert was withdrawn at regular intervals and then VB is measured under metallurgical microscope (Carl Zesis, 351396, Germany) fitted with micrometer of least count 1μm. The readings were taken until tool life criterion was reached.

Surface roughness was measured respectively by a Talysurf (Surtronic 3+ Roughness Checker, Taylor Hobson, UK) using a sampling length of 0.8 mm. The photographic view of the surface roughness technique for measuring surface roughness is shown in Fig. 2.3.

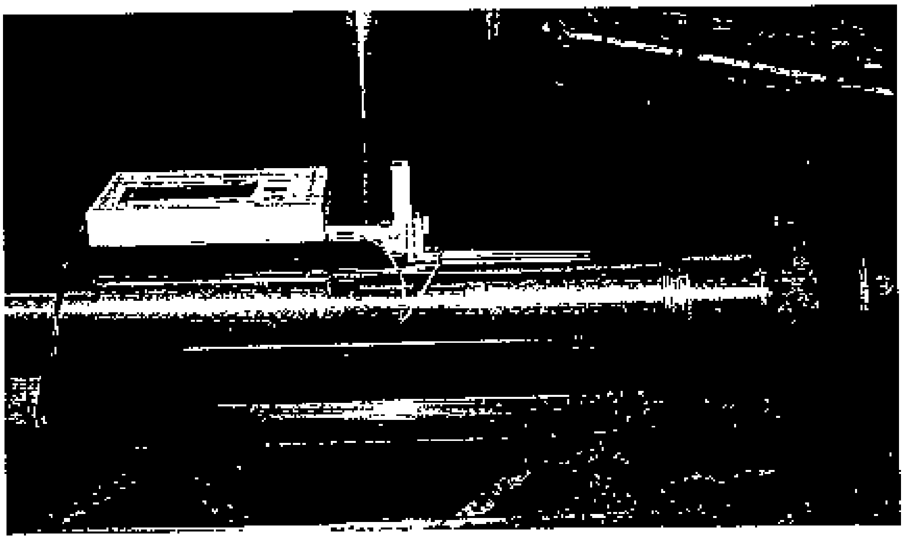


Fig. 2.3 Photographic View of the Surface Roughness Measuring Technique

For statistical analysis, Minitab 11 is used. This software performed analysis of variance (ANOVA) which includes interaction and pure quadratic term checks and regression analysis using least square method to estimate model parameters. The graphical representation of the response surface of the surface roughness and tool wear was generated by Minitab. Microcal Origin 5.1 was used graphical representation between the obtained and predicted values of tool life and surface roughness.

2.2 Experimental Results

2.2.1 Tool Wear and Tool Life

The need for accurate assessment of tool wear has increased considerably in order to produce the required end products in an automated industry so that a new tool may be introduced at the instant at which the existing tool has worn out, thus preventing any hazards occurring to the machine or deterioration of the product surface finish. The importance of maximizing a tool's working time and doing the utmost to keep tools from breaking is directly related with cutting-process optimization. Tool life improvement is essential to reduce the cost of production as much as possible. Cutting tools have a limited life due to inevitable wear and consequent failure, and avenues must be found to increase tool life, the critical parameter of the cutting process. Tool wear sensing should be one of the primary objectives in order to produce the required end products in an automated industry so that a new tool may be introduced at the instant at which the existing tool has worn out, thus preventing any hazards occurring to the machine or deterioration of the surface finish.

In the present work, tool wear is measured at different intervals until the tool life criterion for determining tool life is measured effectively under high-pressure coolant conditions very reliably throughout the experimental domain by metallurgical microscope. The growth of average flank wear under both dry and high-pressure coolant condition is shown in Fig.2.4.

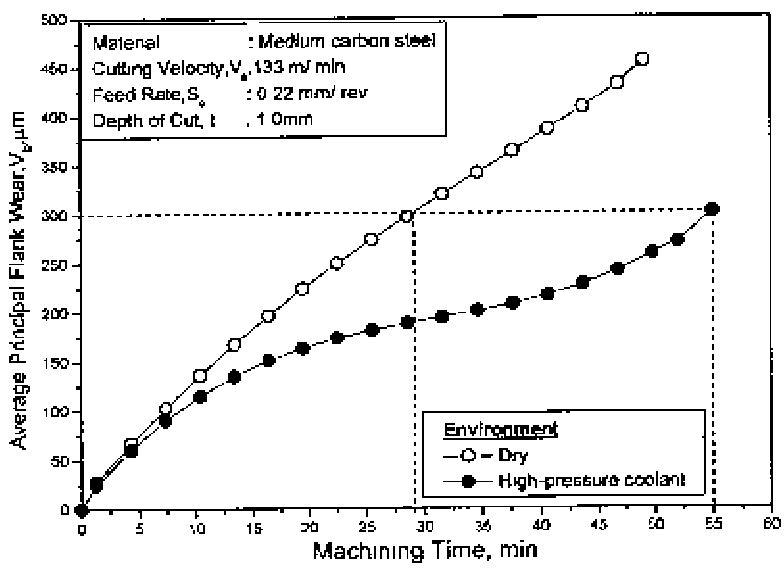


Fig. 2.4 Growth of Average Flank Wear under Dry and High-pressure Coolant Condition

2.2.2 Surface Roughness

Surface roughness is a widely used index of product quality and in most cases a technical requirement for mechanical products. Achieving the desired surface quality is of great importance for the functional behavior of a part. Therefore, the estimation of the magnitude of sauce roughness under given cutting conditions resulting from metal removal operations is one of the major goals in this area.

The surface roughness of machined parts is a significant design specification that is known to have considerable influence on properties such as wear resistance, cleanability, assembly tolerances, coefficient of friction, wear rate, corrosion resistance, and aesthetics and fatigue strength. The quality of the surface is a factor of importance in the evaluation of machine tool productivity. As roughness of the machined surface is an important quality measure in metal cutting, it is important to monitor and control surface roughness over time during the machining operation.

In the present work, surface roughness of the machined surface is measured using roughness checker as described earlier. The arithmetic average value is measured several times and it is then averaged to obtain the surface roughness value for the definite combination of speed and feed under high-pressure coolant conditions. The surface roughness developed with progress of machining under both dry and high-pressure coolant condition is shown in Fig.2.5

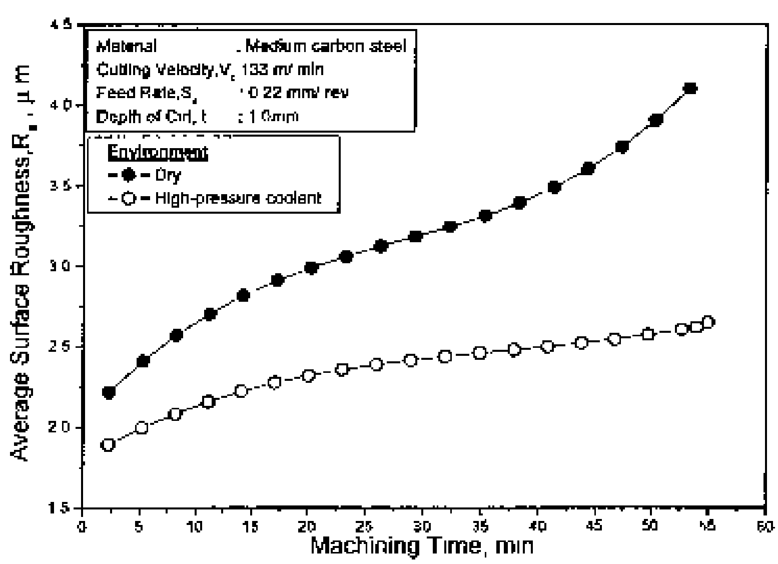


Fig. 2.5 Surface Roughness Developed with Progress of Machining under Dry and High-pressure Coolant Condition

Chapter-3

Mathematical Model

3.1 Model Formulation

The importance of studying the tool wear and machined surface roughness in any machining process is for a proper planning and control of machining parameters and optimization of the cutting conditions to minimize production cost and time and provide products of desired quality.

Before developing models to predict tool life, tool wear or surface roughness, the factors that affects the process performance needs to be considered first:

i) The machining variables or set up variables, which include cutting speed, feed rate, depth of cut. These parameters can be set up in advance. It means that these parameters are controllable.

ii) The tool geometry like nose radius, rake angle, side cutting edge angle, cutting edge. These factors depend on the tool to be chosen for exact machining process. If the tool is qualitative – predictable, then parameters are considered to be controllable. Anyway, it is necessary to keep in mind that such a factor like built-up edge can occur. In such a case tool geometry can not be considered as predictable parameter.

iii) Workpiece and their mechanical properties. If used materials are produced under quality control, the parameter (workpiece properties) can be considered as controllable.

iv) Auxiliary tooling, and used lubrication. Auxiliary tooling, for example clamping system, can be considered as controllable, if clamping process is done correctly. Clamping problems can be figure out by controlling machined parts waviness or cutting machine, for example lathe, vibration parameters. In some processes like finish hard turning lubrication or cooling liquids are not used. In such a case the factor is omitted.

v) Vibrations between workpiece, machine tool and cutting tool. These factors also influence the process performance.

This research aims at developing a model based on machining variables i. e, cutting speed and feed. Research shows that among the machining variables, the influence of depth of cut the minimum [**Choudhury and El-Baradie 1997**].So, the depth of cut was not varied. An uncoated carbide SNMG 120408 insert is used in a PSBNR 2525M12 (ISO specification) tool holder. Both the insert and holder are commercially available and industrially standard. As a result, the tool geometry and resultant machining geometry remain invariant. Commercially available medium carbon steel would be machined using high-pressure coolant jet to determine model parameters experimentally. The machining would be performed in a manner that the vibration between workpiece, machine tool and cutting tool can be neglected. Therefore, all the factors except the machining variable can be omitted from considerations.

3.2 Statistical Approach to Development of Mathematical Model

The basic mechanisms of wear of the cutting tool and the resultant machined surface profile due to feed geometry are well perceived. However, it is difficult to predict the type and extent of different mechanisms and factors at any instant. It is well understood that during tool wear due to single or combination of diffusion, abrasion, adhesion, oxidation, chemical reaction. At low speed abrasion and adhesion dominates whereas diffusion dominates at high speed, but it is difficult to quantify analytically the amount of dominance at any speed. Similarly, the theoretical surface should resemble the feed geometry of the cutting tool. But, due to presence of a good number of unconsidered factors, the actual surface differ form the theoretical predicted surface. Statistical approach can be instrumental to make inferencos to relate machining parameters and performances.

Experimentation and making inferences are the twin features of general scientific methodology. Statistics as a scientific discipline is mainly designed to achieve these objectives. Planning of experiments is particularly very useful in deriving clear and accurate conclusions from the experimental observations, on the basis of which inferences can be made in the best possible manner.

The methodology for making inferences has three main aspects. First, it establishes methods for drawing inferences from observations when these are not exact but subject to variation, because inferences are not exact but probabilistic in nature. Second, it specifies methods for collection of data appropriately, so that assumptions for the application of appropriate statistical methods to them are satisfied. Lastly, techniques for proper interpretation of results are devised.

Much of the research in engineering, science and industry is empirical and makes extensive uses of experimentation. Use of statistical approach in experimental design can greatly increase the efficiency of these experiments and often strengthens the conclusions so obtained. The advantages of design of experiments as reported by Adler et al [**1975**] are as follows:

i. Numbers of trials are reduced.

ii. Optimum values of parameters can be determined.

iii. Assessment of experimental error can be made.

iv. Qualitative estimation of parameters can be made.

v. Inference regarding the effect of parameters on the characteristics of the process can be made.

An important design of experimental approach, Response surface methodology (RSM) is considered instrumental to develop statistical models [**Montgomery 1991**]. RSM is a collection of mathematical and statistical techniques combining design of experiments, regression analysis and statistical inference that are useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response. The methodology may be applied for developing the mathematical models in the form of multiple regression equations correlating the dependent parameters such as cutting force, power consumption, surface roughness, tool life etc. with three independent parameters, viz. cutting speed, feed rate and depth of cut, in a turning process. In applying the response surface methodology, the dependent parameter is viewed as a surface to which a mathematical model is fitted.

In many experimental situations, it is possible to represent independent factors in quantitative form. Then these factors can be thought of as having a functional relationship or response:

$$y = f(x_1, x_2, \ldots\ldots\ldots, x_k) + \in \qquad (3.1)$$

between the response y and x_1, x_2 ,........,x_k of k quantitative factors. The function f is called response surface or response function. The residual $\in$ measures the experimental error. In most cases, the form of the relationship between the response and the independent variables is unknown. To find a suitable approximation for the true functional relationship between response and the independent variables, a low-order polynomial is employed as a first step, the higher the degree of the polynomial the better is the correlation, though at the same time the costs of experimentation become higher. If the response is well modeled by a linear function of the independent variables, the first order model is a good approximation.

$$y = b_0 + \sum_{i=1}^{k} b_i x_i + \in \qquad (3.2)$$

For curvature in the system, the second or higher order response surface may be assumed. The assumed surface response Y contains linear, squared and cross-product terms of variables X_i 's. In order to estimate the regression coefficients a number of experimental design techniques are available

3.3 Mathematical Model

Based on response surface methodology and 2^2 factorial (2 factor, 2 level) designs, first order model is considered in this paper. The proposed relationship between the machining response (the surface roughness and the tool life) and the machining independent variables speed and feed can be represented by the following equation:

$$Z = CV^m S_0^n \in \qquad (3.3)$$

Where Z is the response variable i.e. surface roughness in μm (R_a) and Tool life in minutes (T). V and S_0 are the cutting speed (m/min) and feed (mm/rev). C, m, n are constants and $\in$ is random error with mean zero.

In order to facilitate the determination of constants and parameters, the mathematical models were linearized by performing logarithmic transformation as follows:

$$\ln Z = \ln C + n \ln V + m \ln S_0 + \ln \in \qquad (3.4)$$

This linear model in terms of the estimated response can be written as:

$$\hat{y} = y - \in = b_0 x_0 + b_1 x_1 + b_2 x_2 \qquad (3.5)$$

Where $\hat{y}$ is the estimated response on a logarithmic scale, y is the measured response on a logarithmic scale, x_0 = 1 (dummy variable), $x_1 = \ln V, x_2 = \ln S_0$, $\in$ is the experimentally random error and the *b* values are the estimates of the model parameters to be estimated.

According to equation (3.5) process, the surface roughness and tool wear model can be represented by the following equations respectively:

$$\ln R_a = \ln C + n \ln V + m \ln S_0 + \ln \in \qquad (3.6)$$

$$\ln T = \ln C + n \ln V + m \ln S_0 + \ln \in \qquad (3.7)$$

3.4 Experimental Design and Conditions

Montgomery [1991] explains the details for formulating a first order model for employing first order model. To minimize the variance of the regression coefficients, orthogonal first order designs better fits first-order model. The class of orthogonal first-order design includes 2^2 or 4 factorial series for 2 factor design in which main effects are not aliased with each other. In using these designs, the factors are coded to the standardized levels ±1. However, the 2^2 design does not afford an estimate of the experimental error unless some runs are repeated. A common method of including replication in the 2^2 design with several observations at the centre (the point x_i=0,i= 1,2,3,....k). The addition of centre points to the 2^2 design does not influence the medel parameters. The addition of centre points does not alter the orthogonality property of the design. The proposed design uses will be augmented with three centre points to fit a first order model. In addition to calculating error, 2^2 design with centre points allows to (reveal by Analysis of Variance, ANOVA):

I. Check for interactions(cross-product terms) in the model

II. Check for quadratic effects (curvature).

Depending on the capability of centre lathe and considering the method proposed by Montgomery **[1991]**, the levels and centre of the design was selected and coded. Table-3.1 shows the levels of the dependent variables and coding identifications.

Table-3.1 Levels of Independent Variables

Levels	**Low**	**Centre**	**High**
Coding	-1	0	+1
Speed (m/min)	133	186	266
Feed (mm rev)	0.14	0.18	0.22

The experimental cutting conditions together with the measured surface roughness and tool values are presented in Table-3.2.

Table-3. 2 Experimental Conditions and Results

Trial	Speed (m/min)	Feed (mm/rev)	Coding X_1	Coding X_2	Surface Roughness R_a (μm)	Tool Life T (mins)
1	133	0.14	-1	-1	0.85	90
2	133	0 22	-1	1	1.34	60
3	266	0.14	1	-1	1.23	30
4	266	0.22	1	1	1.27	14
5	186	0.18	0	0	1.33	56
6	186	0.18	0	0	1.25	54
7	186	0.18	0	0	0.81	55

The transforming equations for each of the independent variables are as follows:

$$x_1 = \frac{\ln V - \ln 133}{\ln 266 - \ln 133}$$

$$\Rightarrow x_1 = 1.443 \ln V - 7.055 \qquad (3.8)$$

$$x_2 = \frac{\ln S_o - \ln 0.14}{\ln 0.22 - \ln 0.14}$$

$$\Rightarrow x_2 = 2.212 \ln S_o + 4.35$$

3.5 Results

The postulated model for surface roughness based on 7 set of experiments is

$$\hat{y} = -0.04 + 0.325x_1 + 1.22x_2 \qquad (3.9)$$

Using equation (3.9), the roughness model can be transformed using eq. (3.8) into the following form:

$$R_a=5.46\ V^{-0.37}S_0^{-0.27} \qquad (3.10)$$

This equation indicates that the surface finish improves with increase of cutting speed and feed. The cutting speed has the most significant effect on the surface roughness. Equation (3.10) is plotted in Fig. 3.1 as the response surface of for different combinations of cutting speed and feed.

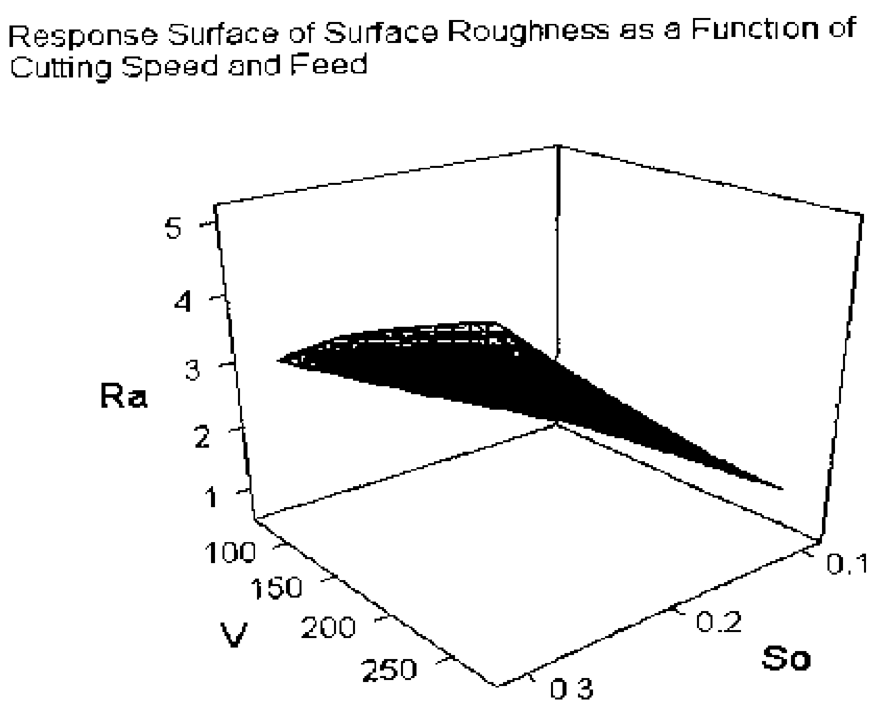


Fig. 3.1 Surface Roughness as a Function of Cutting Speed and Feed

The analysis of variance as shown in Table-3.3 proves the adequacy of the model as the regression effect is dominant in relation to curvature and interaction effects. However, the presence of quadratic and interaction effect justifies development of higher order model specially to accommodate interaction effect.

Table-3.3 Analysis of Variance for Surface Roughness

Sources of Variation	Sum of Squares	Degrees of Freedom	Mean squares	F_{cal}	F_{tab}
Regression	0.33014	2	0.16507	4.84988[a]	7.71
Residual	0.136144	4	0.034036		
(Interaction)	0.059695	1	0.059695	1.635477	18.51
(Pure quadratic)	0.003448	1	0.003448	0.094453	18.51
(Pure error)	0.073001	2	0.0365		
Total		6			

[a] significant at 5%

The postulated model for surface roughness based on 7 set of experiments is

$$\hat{y}= 1.09-1.04\, x_1-1.01x_2 \quad (3.11)$$

Using equation (3.11), the tool life model can be transformed using eq. (3.8) into the following form:

$$T= 9.13X10^3\, V^{-1.92} S_0^{-2.7} \quad (3.12)$$

This equation indicates that under high-pressure coolant condition, the tool life decreases with increase of cutting speed and feed. The feed has the most significant effect on the tool wear. Equation (3.12) is plotted in Fig. 3.2 as the response surface of for different combinations of cutting speed and feed.

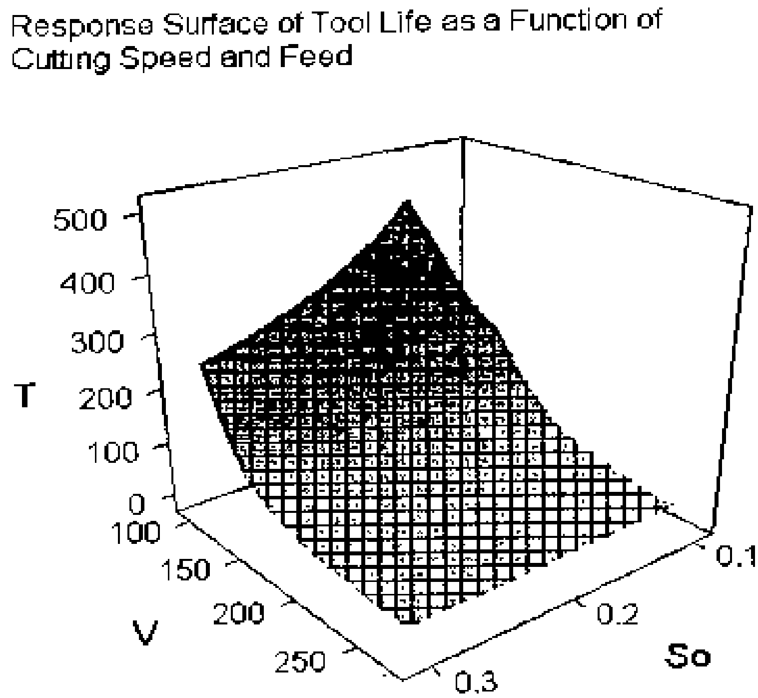


Fig. 3.2 Tool Life as a Function of Cutting Speed and Feed

Table-3.4 Analysis of Variance for Tool Life

Sources of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F_{cal}	F_{tab}
Regression	0.33014	2	0.16507	1.523619[a]	7.71
Residual	0.433363	4	0.108341		
Interaction	0.042406	1	0.042406	0.994271	18.51
Pure quadratic	0.305657	1	0.305657	7.166644	18.51
Pure error	0.0853	2	0.04265		
Total		6			

[a] significant at 5%

The analysis of variance as shown in Table-3.4 proves the adequacy of the model as the regression effect is dominant in relation to curvature and interaction effects. However, the presence of quadratic and interaction effect justifies development of higher order model. The pure quadratic effect is higher than interaction effect. So, effect of quadratic may be considered to obtain better fitted model.

Though analysis of variance is adequate to check the validity of the model, a number of experiments were carried out to substantiate the validity of the model. Table-3.5 presents the predicted results obtained from the models and actual results obtained from the experiments. It also shows the percentage deviation of the predicted value from the model values.

Table-3.5 Comparison between Predicted and Measured Values of Tool Wear and Surface Roughness

Expt. No	Speed m/min	Feed mm/rev	Surface Roughness R_a, µm			Tool Life T, mins		
			Predicted	Measured	Error	Predicted	Measured	Error
1	133	0.18	1.42	1.34	6%	78.2	68	15%
2	186	0.14	1.34	1.27	6%	81	70	16%
3	186	0.22	1.19	1.25	-5%	36.9	40	-8%
4	266	0.18	1.1	0.98	12	20.7	18	15%

Table-3.5 shows that the surface roughness model predicts the actual roughness values more correctly. The maximum error in surface roughness model is 12%. On the other hand, the tool life model predicts the model quite fairly as the maximum error is 16% which is reasonably acceptable. So, both the model can be used to estimate the performances reasonably correctly.

The correlation between the values obtained from measurement and proposed model for tool life and surface roughness have been depicted in Fig. 3.3 and Fig. 3.4.

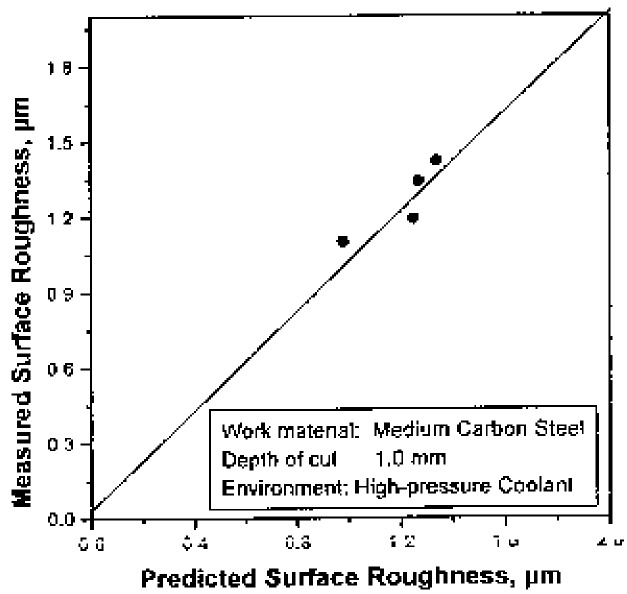


Fig. 3.3 Comparison of Measured and Predicted Surface Roughness

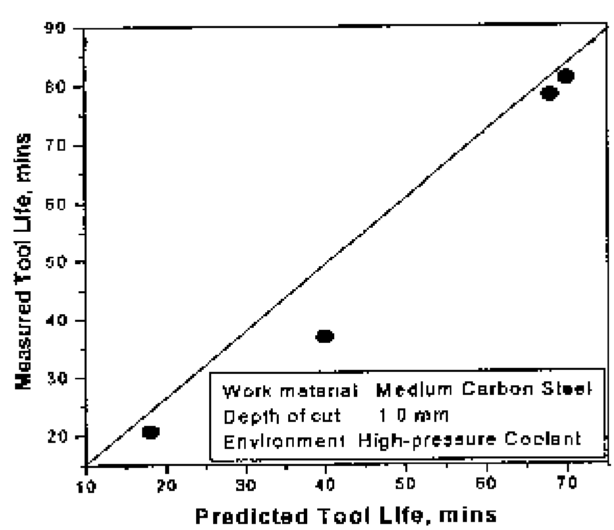


Fig. 3.4 Comparison of Measured and Predicted Tool Life

Chapter-4

Discussion on Results

4.1 Tool Wear and Tool Life

The cutting tools in conventional machining, particularly in continuous chip formation processes like turning, generally fail gradual wear by abrasion, adhesion and diffusion depending upon the tool-work materials and machining condition. Tool wear initially starts with a relatively faster rate due to what is called break-in wear caused by attrition and micro-chipping at the sharp cutting edges.

Cutting tools may also often fail prematurely, randomly and catastrophically by mechanical breakage and plastic deformation under adverse machining conditions caused by intensive pressure and temperature and/or dynamic loading at the tool tips particularly if the tool material lacks strength, hot-hardness and fracture toughness. However, in the present investigations with the tool and work material and the machining conditions undertaken, the tool failure mode has been mostly gradual wear. The geometrical pattern of tool wear that is generally observed in turning by carbide insert is schematically shown in Fig. 2.4.

Among the aforesaid wears, the average principal flank wear is the most important because it raises the cutting forces and the related problems. The life of carbide tool, which mostly fail by wearing, is assessed by the actual machining time after which the average value of its principal flank wear reaches a limiting value, like 0.3 mm.

Fig. 2.5 shows the growths of average principal flank wear on the main cutting edge under high-pressure coolant at a pressure of 70 bar, using VG 68 cutting oil. The gradual growth of average principal flank wear the predominant parameter to ascertain expiry of tool life, observed under high-pressure coolant environments indicates steady machining without any premature tool failure by chipping, fracturing etc. establishing proper choice of domain of process parameters.

The choice for the combination of cutting speed and feed was based on a designed experimental approach, namely, response surface method. According to this method, the experimental results are used to determine the first order model for tool life (response) used by regression analysis. The validity of the model was evaluated applying analysis of variance, ANOVA. As shown in Table-3.4, ANOVA checkad the adequacy of the first order model by determining interaction and quadratic effects. As ANOVA suggested, the first order model proved adequate to ensure the accuracy of the model. However, a subsequent set of tests were carried out to determine the amount of difference between the model-predicted and test results (Table-3.5). This was graphically presented in Fig. 3.4. The amount of error is reasonably within the acceptable limit which proved the model to be appropriate.

4.2 Surface Roughness

The quality of any machined product of given material is generally assessed by dimensional accuracy and surface integrity, which govern the performance and service life of that product. For the present study, only surface finish has been considered for assessment of quality of product machined using high-pressure coolant at a pressure of 70 bar.

Surface finish is an important index of machinability because performance and service life of the machined component are often affected by its surface finish, nature and extent of residual stresses and presence of surface or subsurface micro-cracks, if any, particularly when that component is to be used under dynamic loading or in conjugation with some other mating part(s). Generally, good surface finish, if essential, is achieved by finishing processes like grinding but sometimes it is left to machining. Even if it is to be finally finished by grinding, machining prior to that needs to be done with surface roughness as low as possible to facilitate and ecenomize the grinding operation and reduce initial surface defects as far as possible.

The variation in surface roughness observed with progress of machining of medium carbon steel by the SNMG insert at a particular set of cutting velocity, ,feed rate and a constant depth of cut of 1 mm under high-pressure coolant conditions have been in shown Fig. 2.6. As same combination of cutting speed and feed are used for measuring tool wear, and tool life and surface roughness, surface roughness for a definite combination is obtained by averaging the chronological readings surface roughness as shown in Fig. 2.6

Like the approach adopted to develop the tool life model, surface roughness model was developed from same combination of cutting speed and feed. After performing ANOVA to check the validity of the proposed first order model was evaluated which was subsequented by determining interaction and quadratic effects. As ANOVA (Table 3.3) suggested, the first order model proved adequate to ensure the accuracy of the model. Again, a subsequent set of tests were carried out to determine the amount of difference between the model-predicted and test results (Table-3.5). This was graphically presented in Fig. 3.3. The amount of error is reasonably within the acceptable limit which proved the model to be appropriate.

Chapter-5

Conclusion

Based on the analytical and experimental investigation, the following conclusions can be made:

- The scope of this study is to investigate the effect of high-pressure coolant in turning performance in terms of surface roughness and tool life in order to develop a mathematical model which can be used to predict the quality of the product and the useful life of the tool. The extent of effect of machining parameters like speed and feed is quantified by the use of a well applied statistical method namely response surface methodology.

- Application design of experiment methodology reduces the number of experiments needed to developed the model and therefore, reduces redundancy of expenditure and effort can be avoided. This method is easy to adopt and apply in any process characterisations and optimizations.

- As part of applying response surface method, regression analysis was employed to find the parameters so that proposed first order model to fit experimental results. This was followed a performing analysis of variance, ANOVA, the adequacy of the model was verified.

- ANOVA also shows that the interaction between the independent variables are insignificant compared the regression effect. However, as the ANOVA table indicates the presence of quadratic and interaction, though in small amount, a second or higher model may be employed in development of statistical model.

- A subsequent second set of tests were carried out to measure the deviation between the predicted and actual machining performance. This experimentation shows that the surfaca roughness model is more accurate as the predicted result deviate from the actual results by at most 12%. The amount of error is fairly acceptable for machining performance. The tool life model, on the other hand, can also be considered to predict tool life. Here the amount of error is 16% at best which can be considered to be reasonable and the model can be considered accurate.

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