Machinability Study of Tool Steel (Din 1.2311) through End Milling

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DECLARATION

I hereby certify that this material, which I now submit for the assessment on the programme of study leading to the award of Master of Engineering is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

Signed: ________________________ ID No.: _______________

Date: __________________

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ABSTRACT

This research presents an investigation of the machinability assessment when end milling tool steel (Din 1.2311) BHN 300. The tool steel is a pre-hardened steel and it is widely used for molds or dies in the injection moulding industry. It is also classified as AISI grade P20 mold steel.

The objective of this assessment is to generate reliable machining data in terms of tool life, cutting force and surface finish in relation to cutting speed, feed rate and depth of cut. During this research, cutting tests were carried by using the both the design of experiment and one-variable-at-a-time experimental techniques.

Various cutting tools were used for the different tests including uncoated high speed steel, coated high speed steel, uncoated cemented carbide and coated cemented carbide. The results of these tests were plotted as graphs in order to assess the differences between the different tools.

From these machinability assessment tests, a cutting speed, feed rate and depth of cut range for the material can be determined and the optimum cutting conditions chosen, including economic production rate or maximum production rate for the end milling process.

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CHAPTER ONE

INTRODUCTION

The main reason for the continued interest in the definition and assessment of machinability is the problem of specifying the cutting conditions for an optimal economic utilization of the resources. In general, where process planners specify machining conditions, it will usually be found that they refer to data of a very generalized nature. This is typified by that provided in the handbooks of cutting tool and other manufacturers, or to 'in-house' handbooks complied by company personnel or from the parent company abroad. The generalized data is thus either very comprehensive or so imprecise that it can at best indicate only a 'starting point' for machining. The absence of any but the vaguest indication of expected tool life also lessens its practical usefulness in situations that demand complete control.

The basic aim of machinability testing is the provision of reliable machining data to ensure optimum production capacity from the expensive DNC and CNC machines. The conventional method of developing machinability data under laboratory conditions, is to undertake actual machining tests over a wide range of cutting conditions in order to optimize the processes over these conditions. Cutting force, tool life and surface finish tests are usually carried out to assess the machinability characteristics of a given work material.

The end milling process is widely employed for the manufacturing of tool steel molds and dies for the injection molding industry. However, most research concerned with machining tends to deal with the turning process, while the milling process has received little attention due to the complexity of the process.

The injection molding industry places a heavy demand on end milling processes due to the shape complexity of the molds and dies, and also due to the accuracy required in the finished dimensions. The market is increasingly moving towards near-net shape workpieces which reduces the requirement for roughing operations and large depths of cut. Increasingly high surface integrity and close dimensional tolerances are required which requires tools to have lower wear rates and much tighter specification of tool dimensions. Improvements in machine tool rigidity with lower chatter levels and increased machine tool power has led to increasing use of cemented carbides.

The main goals of this machinability study are as follows;

a) Assessment of different cutting tool materials in terms of tool life for the end milling process. Tool life tests were conducted in accordance with the International Standard ISO 8688-2 for end milling.

b) Development of optimum conditions for the process, in terms of tool life. These include cutting speed, feed rate and depth of cut.

c) Optimization of the machined surface roughness under different cutting conditions.

d) Optimization of the cutting forces produced under different cutting conditions.

The scope of this project are as follows;

<u>One-variable-at-a-time experiments</u>

Tests	**Cutting Tools**
Cutting Force Tests	Uncoated High Speed Steel
Tool Life Tests	Uncoated High Speed Steel
	Coated High Speed Steel
	Uncoated Cemented Carbide
	Coated Cemented Carbide

<u>Design of Experiment</u>

Following the one-variable-at-a-time tests one cutting tool from each material group was selected to be used for the design of experiment tests.

Tests	Cutting Tools
Tool Life Tests	Coated High Speed Steel
	Coated Cemented Carbide
Surface Finish Tests	Coated High Speed Steel
	Coated Cemented Carbide

Chapter Review

Chapter 2 reviews the literature used during the project and covers a general introduction on machinability studies, tool materials including high speed steel, cemented carbide and coatings used for cutting tools. It also focuses on the methods of assessing machinability such as tool life, cutting force and surface finish testing.

Chapter 3 gives a general overview of machinability and includes the factors which influence machinability. It also covers the end milling process and gives an assessment of the workpiece material that was used for the tests. The selection of various cutting tool materials and their applications have also been discussed in this section.

In Chapter 4 covers the different methods of assessing machinability. The wear on cutting tools is discussed, as is the method of tool life testing that was carried out along the guidelines of ISO standard. This chapter also discusses the method of assessing machinability by using both cutting force tests and surface finish tests, including the machining parameters which affect the surface finish of the material.

The experimental equipment that was used are described in Chapter 5, including the specifications of the different cutting tools that were used during the research. This chapter also covers the specifications of the equipment that were used for the cutting force, tool life and surface finish tests. The different experimental procedures that were used are also covered in this chapter.

Chapter 6 covers the results from the one-variable-at-a-time experiments. The cutting force tests were the first tests that were carried out. The effects of cutting speed, feed rate and depth of cut on the cutting force while using uncoated High Speed Steel end mills are presented, with the values being shown in plots. The range of the cutting variables for these tests were chosen from the Machining Data Handbook [1]. The results from these tests provided a guideline for the subsequent tool life tests in this chapter. Following the completion of the cutting force tests, the effects of cutting speed, feed rate and depth of cut on the tool life were examined. These tests were conducted using both uncoated and coated High Speed Steel cutting tools, and uncoated and coated cemented carbide cutting tools. Once again the effects of these machining parameters are plotted as graphs. The results from these tests were used to decide which tools from each group had the best performance. With one tool from each group being used in the design of experiment tests.

In Chapter 7 the development of machinability models using the method of Response Surface Methodology is discussed. The experimental results of the design of experiment tests for both tool life and surface finish are presented. Following this mathematical models of tool life and surface finish based on response surface methodology are given. The end result of this method is the formulation of an equations for both tool life and surface finish with respect to cutting speed, feed rate and depth of cut. These equations are then used to plot response contours of tool life and surface finish across the range of cutting conditions used in the tests. As an aid to the selection of optimum cutting conditions, contours of metal removal rate are also shown.

Finally, in Chapter 8 the conclusions and recommendations from this research have been discussed.

CHAPTER TWO

LITERATURE SURVEY

2.1. Machinability

The term machinability is used to describe the ease with which a material is machined under a given set of cutting conditions. If a material is said to be more machinable than another, it could mean that a longer tool life is achievable with one over the other or that less power is required to machine that material and it could also be that a better surface finish is produced when machining that material. Other considerations of machinability are cutting temperature, chip formation, dimensional accuracy or operator safety including noise levels. [1]

Barrow [2] stated that the measurement of machinability is difficult for a variety of reasons. The machinability of a metal is not only a function of the metal's own metallurgical properties, such as hardness, microstructure and the chemical composition, but also a function of the type of machining process, the size and shape of cut, the cutting tool, cutting fluid and the nature of engagement of tool with work (continuous or intermittent, "entrance" and "exit" conditions etc.). However it is important to note that machinability is only applicable to a particular set of circumstances under which the observations are made. For example, material A may be better than material B in regards to tool life under a certain set of circumstances whereas material B may be better than material A in regards to cutting forces under a different set of conditions.

Reen [3] stated that the three most important factors to be considered are surface finish, tool life and power consumption. While Trent [4] concluded that cutting force, chip formation, surface finish, and tool life are all important factors to be considered when machinability rating materials.

Sandvik define machinability as the ability of a work material to be machined.[5]

It was stated by Ernst [6] that the machinability of a metal is a complex term which involves finishability or the ease of producing a good surface finish and also the effect of it's abrasiveness on the tool during cutting.

Machinability has been described by Boulger [7] as the removal of chips with the combination of good tool life and surface finish.

Boston [8] defined machinability of a metal as the obtainment of longer tool life, better surface finish, lower power consumption, better chip breakdown, improved uniformity of dimensional accuracy and lower overall cost when compared to other materials under the same cutting conditions.

A range of machinability tests have been developed, often to assess specific cutting conditions, whilst others are used for more general machining assessment. Sometimes machinability data is expressed in the form of a single index such as a "standard" material being rated as 100% with others materials having values which are in relation to it. [9] The ratings can be dependent on the type of test such as the Volvo "flycutting" milling test. Here the tests have index values on a "100 scale". In general a machinability test assesses the speeds and feeds which are varied by trial and error and with specified constraints. [1]

Cuttability tests, also called ranking tests are adaptable to several different cuttings operations. The test measures how much material can be cut in a given length of time and under a given feeding force, other conditions being fixed. Three possible cutting tests are as follows: [10]

1. Drilling test, in which the depth of penetration is measured in a specified time under a constant feed pressure. Materials are compared on the basis of their relative depths of penetration.
2. Turning test, in which the length of travel of a turning tool subjected to a constant feeding force is measured after a given time of cut.
3. Sawing test, in which the measure of machinability is the time or number of strokes required to cut off a certain cross section with a hacksaw subjected to a given feeding load.

Colwell and McKee, although their research was more of a general nature and not limited to machinability testing, concluded that the relative machinability of five materials studied was about the same for a sawing test as for a turning test. Other than inferences of this sort, these type of tests are not taken seriously by most researchers. [10]

2.2 Tool Material

Of the many factors affecting any machining operation, the cutting tool-while small and relatively inexpensive, is one of the most critical. The cutting tool material, tool geometries, toolholders and cutting conditions all affect the machinability relationship between the work and the machine. This section mainly deals with the materials that are used as cutting tools and the coatings that are deposited onto these tools.

2.2.1 High Speed Steel (HSS)

Since the beginning of this century, HSS has been an essential class of cutting tool employed by the metalworking industry. The original HSS was not invented, but rather discovered from experiments on air-hardening tool steel grades. In 1898, Taylor and White of Bethlehem Steel Co. experimented with high-temperature heat treatments on steels containing 1.85% carbon, 3.8% chromium and 8% tungsten. Through these experiments they expected to show that high-temperature heat treatments of tool steels would be deleterious to the cutting efficiency of the tool. Instead, they found that with austenitizing temperatures higher than 1010 °C, cutting efficiency actually increased. However, they did not understand the reasons for this improved cutting performance.

In 1904, J.M. Matthews of Crucible Steel Co. was issued a patent covering the addition of vanadium to tool steels. This led to the development of the best known HSS, containing 18% tungsten, 4% chromium and 1% vanadium. This popular HSS is called 18-4-1 or T1. Six years later, data by O.M. Becker showed an increase of 600% in efficiency for tools made from these vanadium HSS's when compared to the plain carbon steel tools. Following further research, it was found that increasing the vanadium content resulted in an increase in wear resistance. however, the carbon content also had to increased to attain a cutting tool with sufficient hardness. Then in 1912, research conducted in Germany showed that the addition of 3-5% cobalt further improved the performance of HSS by increasing the hot hardness. Further research concentrated on the affect of cobalt content, which has led to the introduction of grades containing 12% cobalt.

During the 1930's, following the discovery of large deposits of molybdenum ore, research was conducted on the affect of molybdenum on the performance of HSS tools. This led to the introduction of several molybdenum HSS compositions by leading steel companies and toolmakers, including grades which are now known as M1 and M7 by the Cleveland Twist Drill Company that are in popular use today. The outbreak of World War 2 and the subsequent lack of raw materials to the United States resulted in the further development of the molybdenum grades of HSS. The end of the war and the subsequent resumption of world trade permitted the further exploration of molybdenum grades of HSS. This resulted in the development of M30 series of HSS's and subsequently the M40 series during the 1960's. Of the dozens of grades of M30 and M40 HSS's only M33 and M42 are still popular today. [11]

An examination of the HSS market today shows that the molybdenum based grades dominate the marketplace, with M1, M2, M7, and M10 grades being the four most important grades. [10]

In the 1970's, powdered metallurgical processed tools were developed. The superior homogeneity and uniform hardenability of the powder metallurgy (PM) material gives more consistent wear over the entire edge of the cutting tool. Because forging of PM cutting tool is not necessary, enrichment of the carbide phase is possible resulting in better hot hardness and a significant gain in performance. Also, the finer grain size achievable with PM tools results in tougher tools which have better resistance to edge chipping. [12]

2.2.2 Cemented Carbide

The first successful tungsten carbide tools were brought to the United States from Germany in 1928. These tools consisted of finely ground tungsten carbide particles sintered together with cobalt binder. However, early work with these materials was hampered by their brittleness and tendency to chip, resulting in catastrophic failure. Gradually during the thirties, tools of greater shock resistance were produced but carbide tools were only used for turning cast iron and non-ferrous metals due to the greater tendency for steel to cause tool face cratering. Then in 1938, it was found that the addition of titanium and tantalum carbides reduced the tendency of a carbide tool to crater when machining steels. The net result of all of this is that there are two types of sintered tungsten carbide; one for machining grey cast iron, non-ferrous metals and abrasive non-metals (ISO K-type) and another for machining ferrous metals (ISO P-type).

During the 1960's there was a gradual improvement in the quality of carbide cutting tools. Carbide tools were made less brittle by reduced particle size and improved binding and sintering techniques. At the same time a number of systems for classification of cemented carbides were introduced. They were the U.S. (unofficial) 'C' system which is based on performance, the British Hard Metal Association (BHMA) system which is based on properties, the International Standards Organisation (ISO) system which is based on application and the Russian system which was based on the composition of the tool. [11]

2.2.3 Coated High Speed Steel

Hedenqvist et al [13], carried out an investigation by organizing published information about significant mechanical and chemical properties of TiN coatings for high speed steel tools. They stated that the thermal conductivity is probably the most interesting parameter regarding TiN coatings. They reported that TiN is often considered to play the role of a thermal barrier, protecting the heat-sensitive HSS substrate from thermal softening. However from their research they discovered that the thermal conductivity of TiN differs little from that of HSS A simple temperature distribution analysis was performed using finite element analysis. The results showed that the maximum equilibrium temperature of the substrate is reduced by less than 5 °C by the addition of a TiN coating of 5 μm thickness. This clearly demonstrates that the substantial temperature decrease reported by Milovic et al.[13] do not rise because TiN acts as a thermal barrier but can be explained by changes in the contact conditions.

The mechanical properties of the TiN coating and the HSS substrate are somewhat different. The is Young's modulus of TiN is considerably higher than that of HSS, indicating a stiffer behavior. As most ceramics, the Young's modulus of TiN is expected to decrease with increasing temperature. This mismatch in thermal expansion between TiN and HSS is of importance since it may cause thermal stresses which can influence the performance of the coating. The hardness of the coating is the mechanical parameter that is most commonly discussed. For HSS, the room temperature hardness is strongly dependent on the heat treatment. For cutting tool applications, the hot-hardness, i.e. the hardness at elevated temperatures is of great importance. For HSS there is a continuous moderate decrease in hardness with increasing temperature up to the tempering up to the tempering temperature (approximately 600 °C). Above this point the decrease is relatively steep. The hot hardness of TiN is rarely quoted in literature, however it has been shown by Münz [13] to be constant for temperatures up to and above 600 °C.

The solubility C of a coating material in a given work material is related to the free energy of formation ΔG for the coating as;

$$C \; \alpha \; e^{\Delta G} \qquad (2.1)$$

Thus the relatively high ΔG value for TiN (-320 kJ mol^{-1}) corresponds to a high chemical stability, indicating a high resistance to solution wear. Theoretical calculations of the solution wear resistance of a number of coating materials indicate that this is one of the major advantages of TiN.

In most cutting applications, the adhesion of the coating to the substrate is of utmost importance, because of the large shear stresses that are present at the tool workpiece interface. Insufficient adhesion of the hard and brittle TiN coating will lead to spalling and thus the life time of the tool will not be improved by the coating. Recent *in situ* scratch testing in a scanning electron microscope has shown that TiN adheres remarkably well to the HSS substrate.

The concept of hardness or load-carrying capacity of a coating-substrate composite is rather complex. Low and localized loads may be carried by the coating itself, with no need for support from the substrate. Therefore the relevant strength of the composite is the strength of the coating. However as the load is increased above a critical level, the substrate is also deformed and the strength considered is that of the composite. In the upper temperature ranges, where thermal softening occurs, the substrate will lose much of its load-carrying capacity, whereas the TiN coating will be relatively unaffected. Hence, the substrate is unable to carry the load transmitted via the coating and this causes the brittle coating to fragment.

The contact conditions at a cutting edge are of vital importance for the resulting cutting and thrust forces. They also determine the chip shape and the appearance of the machined surface. In machining, the chip is deformed by shear deformation in three shear zones; primary shear, secondary shear and tertiary shear. The length of the primary shear zone is determined by the undeformed chip thickness and the shear plane angle, while the secondary shear zone is determined by the length of contact. The properties of the tool having the most influence on the contact length and therefore secondary shear are the chemical activity, which influences the adhesion to the chip and the thermal conductivity, i.e. the ability to keep the contact zone at a low temperature by transporting the heat into the bulk of the cutting edge. A special feature which further complicates the contact conditions and chip formation is known as the dead zone (DZ) phenomenon. DZ is the general term for the group of phenomena caused by the tendency of work material to become stagnant at the tip of the cutting edge, thus acting as a 'flow divider' for the work material splitting into chip and cut surface.

From cutting tests, it was found that the presence of the TiN coating generally seems to restrain the initiation of the internal cracks necessary for the formation of the built-up edge (BUE) classes of DZs and further to reduce the overall size of the BUE. The difference in DZ behavior is primarily due to the shorter contact length that is produced with TiN tools. This is explained by the chemical solubility of TiN in metals, resulting in a low adherence between rake face and chip. These changes influence the cutting performance of the tool by resulting in a better surface finish of the cut surface and of the tool side of the chip, lower cutting and thrusts forces and more beneficial chip shapes by a tighter curl. The shorter contact length of TiN coated tools results in a lower shear force in the secondary shear zone and consequently to a reduced thrust force. Moreover, it can be shown that a reduced shear force in the secondary shear plane leads to a higher shear plane angle and thus reduces the overall cutting forces produced. The lower cutting forces obtained for TiN coated HSS tools results in less heat generation and consequently lower cutting edge temperatures, thus reducing the of temperature dependent (diffusion) tool wear.

Fenske et al [14] studied the performance of Titanium Nitride and Carbide coatings that were deposited by the physical vapour deposition process to characterize the coating properties and analysed the effect of process parameters on the coating properties. The research involved the characterisation of the chemical, microstructural and mechanical properties of the coatings. He also conducted research on the cutting performance of these tools. The research involved the application of two PVD processes: high-rate reactive sputtering (HRRS), which was developed by W.D. Sproul, and the activated reactive evaporation (ARE) process developed by R.F. Bunshah. The substrate material that was used for the tests was high speed steel, grade T-15 inserts.

In the study described here, the HRRS coatings were deposited at temperatures below 300°C, while the ARE coatings were deposited at temperatures ranging from 350 to 550°C.

With the HRRS technique, shown in figure 2.2.3a, energetic plasma ions sputter individual atoms on the sputtering target. These individual atoms are then transported through the plasma and deposit on the substrates. A nitrogen or carbon rich gas is used to form the plasma, the sputtered atoms (titanium) react with the active plasma species to form carbide or nitride coating on the surface of the substrate.

For the ARE process, shown in figure 2.2.3b, the metallic atoms are formed by thermal evaporation with an electron beam evaporation source. The evaporation is carried out in a partial vacuum of reactive gases similar to those used in the HRRS process. A separate electrode is used to generate a plasma between the evaporation source and the substrate to 'activate' the reaction of the metallic and reactive gases.

Fenske carried out a characterization of ARE deposited coated inserts to determine how process parameters such as deposition temperature and gas pressure influenced the microstructure and chemical composition of the coating., which in turn, critically influence the micro-hardness and chemical stability of the coating and hence the abrasive wear and chemical diffusion wear rates respectively. The chemical composition of the coatings was determined by Auger microanalysis. The results of the microanalysis indicted that all of the deposited coatings were of high purity when compared to coatings deposited by the chemical vapour deposition (CVD) technique.

High-Rate Reactive Sputtering Process

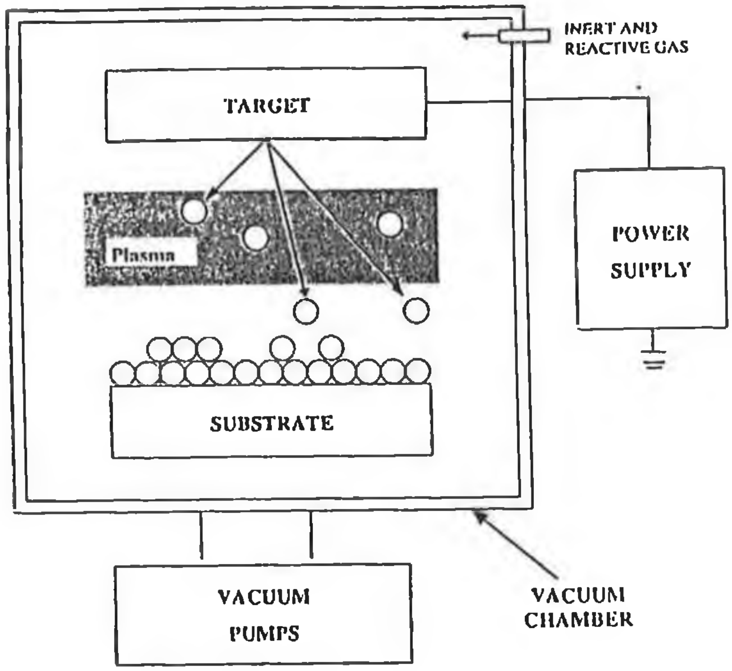


Figure 2.2.3a, Schematic Diagram of HRRS process [14]

Activated Reactive Evaporation Process

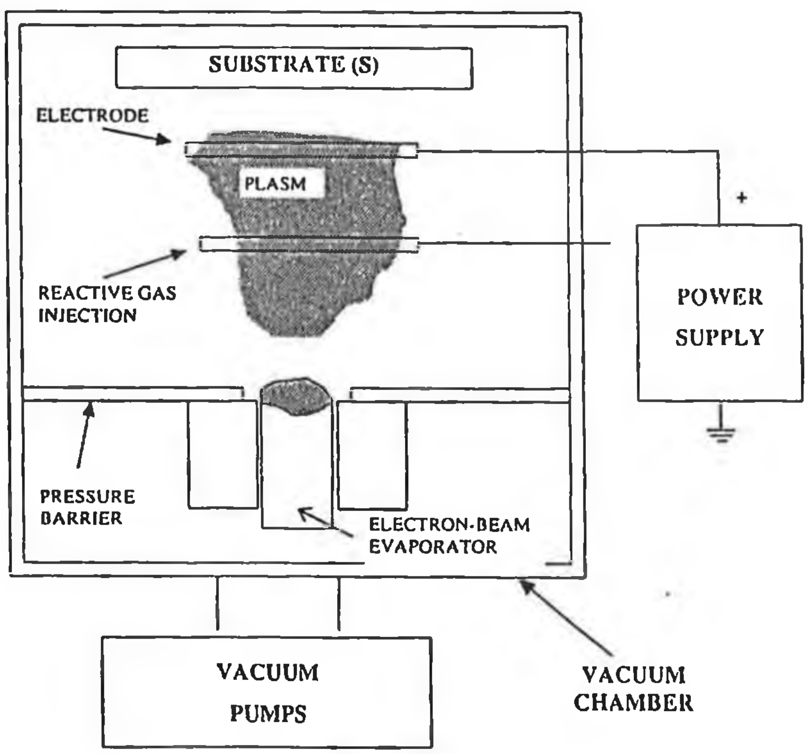


Figure 2.2.3b, Schematic Diagram of ARE process [14]

Both scanning and transmission electron microscopy provided useful information on the microstructure of the coatings. Scanning electron microscopy (SEM) showed that the microstructure is columnar, with column widths ranging from 100-400 nm and column lengths extending in height through the entire thickness of the coating (approx. 5000 nm). While transmission electron microscopy (TEM) of the columnar coatings reveals that the columns observed in the SEM are actually aggregates of much finer columnar grains. The TEM analysis of the coatings also indicated that the coatings were extremely dense and contained no detectable grain boundary porosity with either coating process. A qualitative comparison of the columnar grain sizes for both the HRRS and ARE coatings showed the ARE to be the finer of the two, which can be attributed to the substrate bias used in the HRRS process.

Micro-hardness measurements were obtained on a number of coated inserts that were sectioned transversely to the rake face after undergoing tool life tests. The data was taken at a distance of approximately 0.6 mm from the cutting edge which corresponds to the bottom of the crater. The micro-hardness of the tool far away from the crater was approximately 1100-1200 kg/mm² ,while the hardness in the crater decreases to around 700-800 kg/mm² for an uncoated tool and 850-1000 kg/mm² for a coated tool. Thus they all underwent the same degree of softening, with the uncoated tool deteriorating by the most.

Hedenqvist et al, concluded that a unique combination of sufficient adhesion to the substrate, high hot hardness, high wear resistance (including both abrasion and diffusion) and an ability to improve the contact conditions at the cutting edge, were the main reasons for the improved performance of TiN coated cutting tools. [13]

The flowchart shown below in figure 2.2.3c displays the complex relationships between the coating properties, complex mechanism and the resulting tool performance of TiN coated HSS cutting tools.

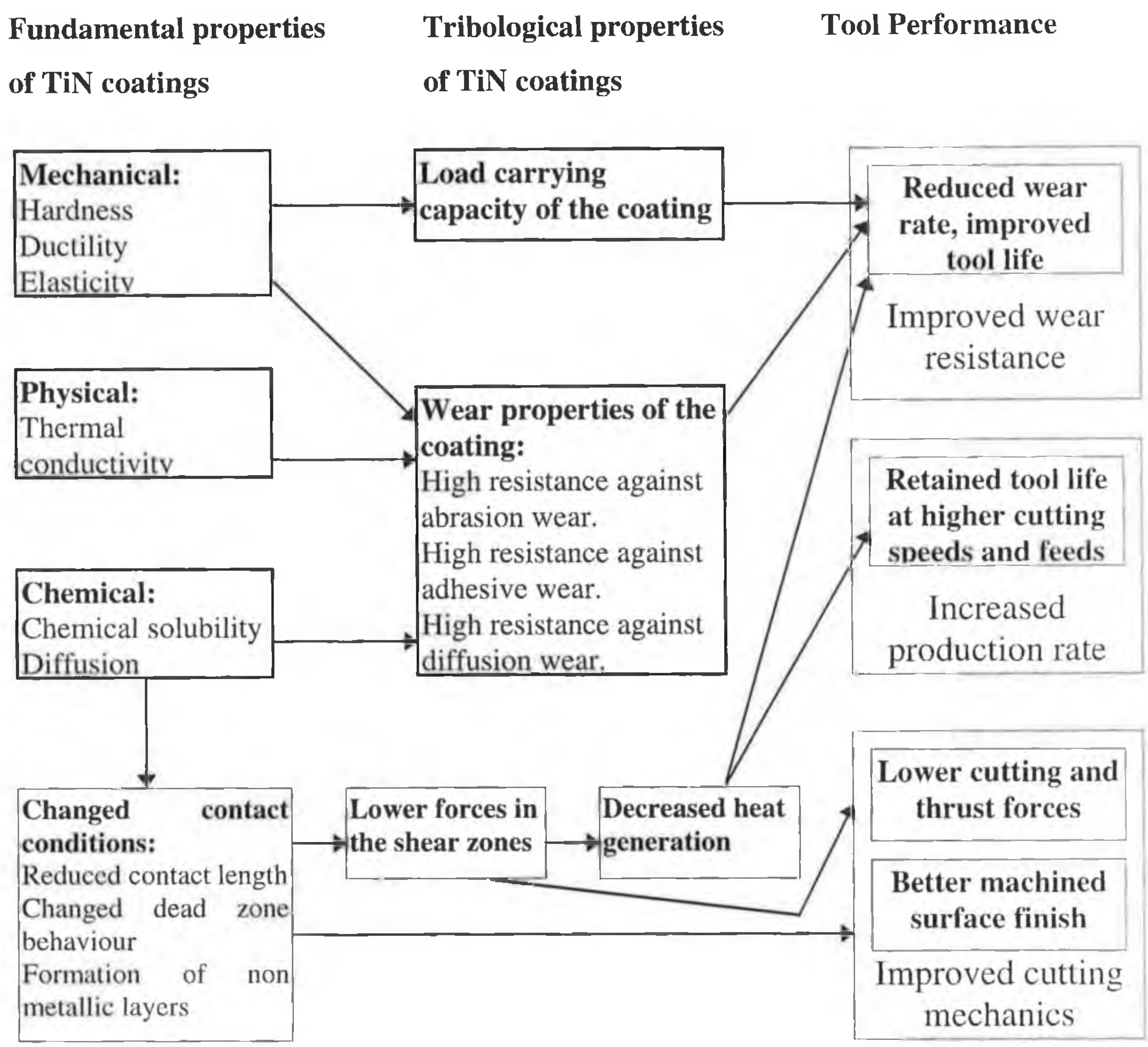


Figure 2.2.3c, Cutting parameters influenced by TiN coating [13]

Posti and Nieminen [15] stated that there is a remarkable variation in the experiences reported of the use of HSS tools with TiN coatings. They noted that the cutting conditions and the properties of the coatings seem to affect the wear rate of the coated tools.

They stated that the chemical composition of the coating and in particular the amount of free titanium present, determines the wear resistance of the tool. Titanium on its own is not as hard as titanium-nitride, so when the amount of free titanium in the coating decreases the hardness and therefore the abrasion wear resistance of the coated tool increases. They also reported that the chips produced by uncoated tools have a different form and poor surface quality when compared with TiN coated tools.

2.2.4 Coated Cemented Carbide

Numerous studies have been carried out on the benefits of using the PVD process over the CVD process for producing inserts for use in milling.

Klaphaak [16] concluded that titanium-nitride (TiN) coatings produced by physical vapour deposition (PVD) are more beneficial than chemical vapour deposition (CVD) produced coatings for cemented carbides.

He stated that, generally CVD coatings are thicker than PVD coatings. This increased thickness is advantageous only when improved abrasive wear resistance is the primary requirement of the coating, as is the case in high-speed semi -finishing of steel. PVD coatings are generally smoother than CVD coatings, providing friction-reducing surfaces that enable easier cutting at lower power levels. Another benefit of PVD coatings on sharp carbide tools designed for finishing, is the enhanced quality of the finished surface.

The PVD process does not produce the hard, brittle material called Eta that often occurs in carbides beneath CVD coatings. Eta forms during CVD coating at about 1000°C. It is especially detrimental to both the strength and shock resistance of thin sharp edges. On the other hand, PVD coatings are deposited at around 500°C which is below the temperature at which Eta is produced and as a result carbon does not diffuse from the carbide substrate into the coating.

Yamagata and Nomura carried found that PVD coated cemented carbide tools have no degradation in their transverse rupture strength (TRS) up to a 6 μm coating thickness, but in the case of CVD coated tools, as the coating thickness increases a corresponding reduction in the TRS is observed. They also found that with PVD, the TRS strength of the coated specimen is equal to the uncoated specimens strength. Whereas for CVD the TRS of the coated specimen is lower than that of the uncoated specimen. They noted that through lowering of the deposition temperature of CVD coatings, the TRS can be improved, as can be seen in figure 2.2.4a. They attribute this to a finer grain structure and lower tensile stress in the coating. [17]

Transverse Rupture Strength vs. Deposition Temperature

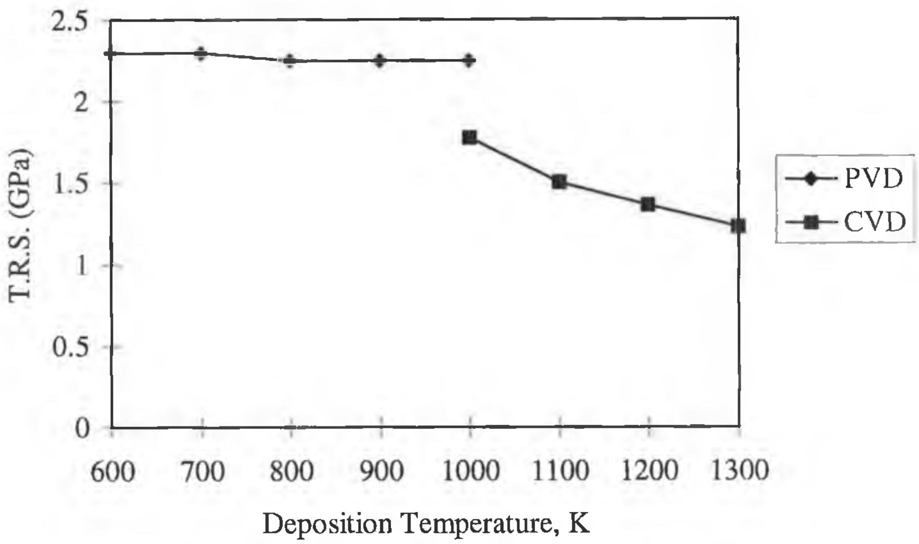


Figure 2.2.4a, Effect of Deposition Temperature on Transverse Rupture Strength [17]

Critical Load vs. Deposition Temperature

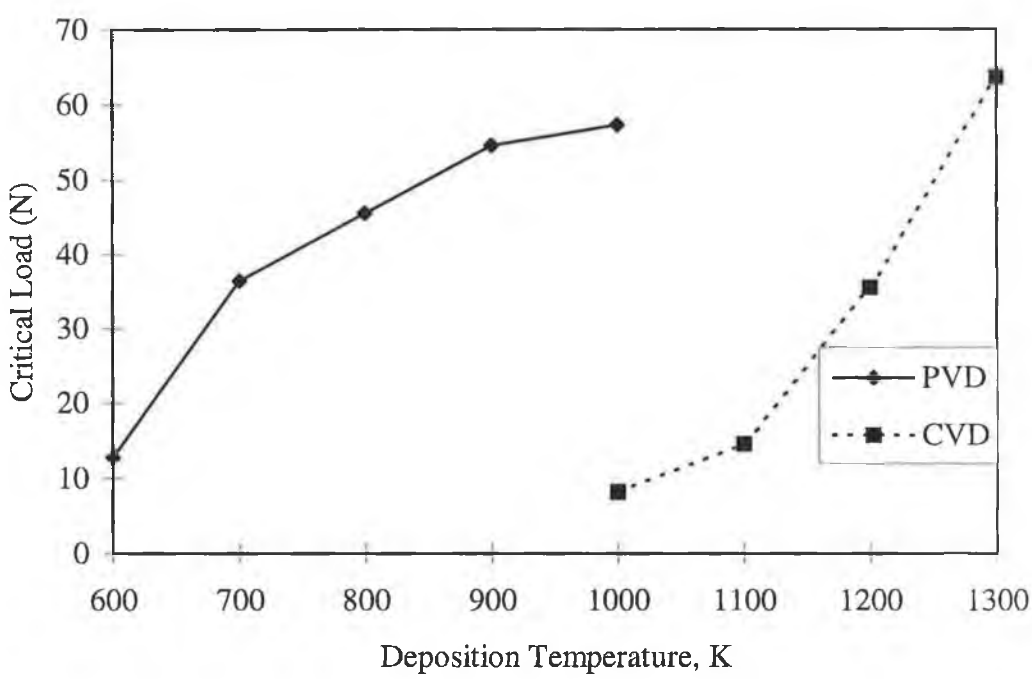


Figure 2.2.4b, Effect of Deposition Temperature on Critical Load [17]

However decreasing the deposition temperature also has the effect of reducing the adhesive strength of the coating-substrate interface as can be seen in figure 2.2.4b. However, PVD coatings obtain equivalent adhesive strength at a much lower deposition temperature than CVD coatings. They have been able to enhance the adhesive strength of the PVD coated carbide without causing a degradation in the toughness of the substrate.

They also reported that the residual stress in the CVD coating is tensile and increases with rises in deposition temperature. The stress generated in the tungsten-carbide (WC) phase at the surface is compressive. On the other hand, larger compressive stress, about 2.0 GPa can be measured in the PVD coating. In the WC phase the stress is also compressive but lower that that of the coating. They explained the TRS of CVD and PVD as follows;

As mentioned earlier, with PVD the structure of the coating is extremely fine grained and is under compressive stress of approximately 2.0 Gpa. Since the coating is tough, the substrate would rupture before the coating. This is the reason that the TRS of the coated specimen conforms with the TRS of the uncoated specimen. In the case of CVD, since the grain size of the coating is enlarged and the coating is subject to tensile stress, it ruptures under lower strain ahead of the substrate. Then stress is concentrated at this point in the coating and the substrate is destroyed.

2.3 Tool Life

2.3.1 Tool Wear

In general, a tool reaches the end of its useful life through many modes of degradation, some of which are gradual while others are catastrophic. It is obvious that catastrophic failure is not an acceptable failure mechanism for most cutting processes. This type of failure through either plastic deformation or brittle fracture of the tool material will only occur when the gradual wear of the tool has reached excessive proportions. The assessment of tool life criteria under plastic deformation and brittle fracture is currently being investigated by ISO. As a result, tool life criteria based predominantly on gradual tool wear are the currently accepted standard. [18]

Wear processes usually occur on the flank and rake faces of the cutting tool. However, flank wear is usually recommended as the criterion for tool life. With a particular width of flank wear land being taken as the criterion for tool failure.

Colding [19] states that crater wear is also important in determining tool life when a work material produces long and continuous chips. The tougher the material the more important it is the rake wear in determining the life of the tool. The rake wear is also considered important when high cutting speeds and feed rates are used in machining the tough material.

Opitz et al [20] noted that the physical properties of the work materials influencing the rate of crater wear could be summarised for similar work materials by their shear strength. Moreover the cutting speed for a given tool life with respect to crater wear varies exponentially with the shear strength of the work material. The slope of the exponential curve is determined by the chemical composition of the work.

Yellowley was of the opinion that in general, cutting tools wear steadily on both their flank and rake faces. He stated that while crater wear has often been used as a criterion for tool life, it has been realized in both the areas of industry and research that the stipulation of reliable limits for crater wear and measurement of actual crater wear are difficult. Also, the advent of higher alloyed tool material has meant that even at high cutting speeds the mechanism of tool failure is attributable to flank wear and not to crater wear. [21]

McGoldrick and Hijazi assessed the tool life in end milling by investigating the amount of weight loss of the tool occurring during machining. This is a measure of the total wear of the tool that occurs. However, this method is not as practical as it cannot distinguish between flank wear and rake wear on the tool. [22]

ISO recommends that a certain width of flank wear land (VB) is the most commonly used criterion for both HSS and cemented carbide end mills. They also recommend that a certain depth of face wear is sometimes used as a criterion. Catastrophic failure criterion can occur inadvertently and should not be used as a primary tool life criterion.

2.3.2 Tool Life Equations

A lot of research in the field of cutting tools and tool life has dealt with the development of equations for tool life. Indeed, although it is not entirely necessary to express tool life data in the form of a mathematical equation, it is nonetheless a very useful aid in machinability assessment. Most tool life equations are expressed as a function of a machining cutting condition such as cutting speed, feed rate or depth of cut. Some equations are based on other machining variables such as temperature.

In 1907, F.W. Taylor [23] developed equations for tool life based on cutting speed, feed rate and depth of cut for use in turning. In the case of milling these equations still hold, but because of the complexity of the milling process they are not as accurate and their application is reduced.

$$\mathbf{VT^n = C} \qquad \mathbf{(2.2)}$$

where, N = exponent constant, T = tool life, C = constant V = velocity

One of the inherent faults of Taylor's equations and curves are that they assume that the relationship between log v and log T is linear, i.e. n is a constant. Several investigators found that the Taylor equation was not capable of covering the full range of cutting conditions. They explained that the exponent "n" of the Taylor equations is a special case which occurs in certain conditions. [24]

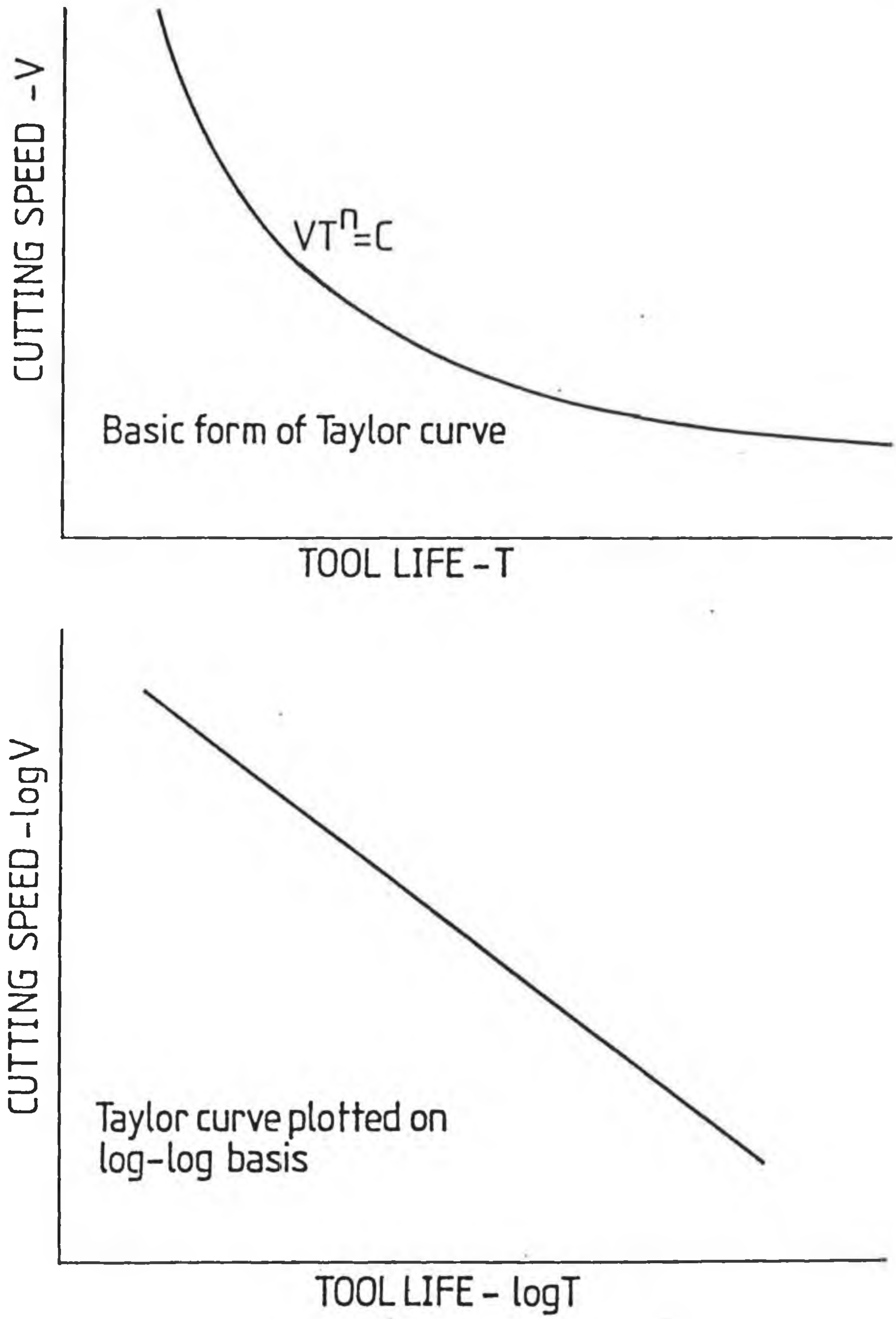


Figure 2.3.2a, Taylors tool life curves [9]

Pilafidis conducted a literature survey on tool life, based on 140 tool life curves obtained from published literature for various machining processes including end milling, face milling and turning. He found that the values for "n" varied with workpiece material, tool material and the machining process. As a result of his study, Pilafidis concludes that the values of "n" should not be made in terms of discrete values but rather in terms of ranges when "n" fluctuates for specific types of process and workpiece-tool material combination. It has also been shown that "n" fluctuates considerably when machining high strength alloys, machining at high metal removal rates and when machining under conditions where prolonged tool life is obtained. [25]

Sabberwal and Fleischer developed an equation for the effect of temperature on tool life performance in material cutting processes. They have shown that the relationship between tool life and absolute temperature to be as follows: [26]

$$T\,\theta^{n2} = C_{13} \qquad (2.3)$$

Where C13 and n2 are constants depending on the material and cutting conditions. The magnitude of index "n2" has been reported as high as 20.

2.3.3 Tool Life Performance

Posti and Nieminen [15] noted that the flank wear rate of TiN coated HSS tools is lower than that of uncoated tools. When examining the tools with the wear in the primary wear stage, the contact area on the rake face of the uncoated tool is observed to be larger than that on the rake face of the TiN coated tool. They stated that the hardness, the chemical stability and the inertness of the coating are the reasons for the improved performance of the coated tool.

Fenske et al, studied the performance of TiC and TiN coated HSS tools while machining steel 1045. He noted that the performance of the coated tools was more a function of the coating adhesion and substrate properties than of the wear behavior of the coating itself. He also stated that this is contrary to coated cemented carbide tools, where because of the excellent high temperature strength of the carbide substrate, it is not necessary to consider plastic deformation as an additional wear (or failure) mechanism. [14]

He hypothesized the wear processes that were supposed to have occurred during the cutting tests as follows. During the initial stages of cutting the tool chip slides across the coated insert. The temperature is sufficiently low during the initial stage that the substrate is not softened and the coated tool can support the loads imposed by the cutting process. However, with time, the heat generated in shearing the workpiece and in sliding friction that occurs between the workpiece and coating, softens the substrate to such an extent that the coating and underlying substrate cannot support the cutting loads. At this point the coating fractures as the substrate is plastically deformed. The fractured coating is eventually transported away with the moving tool chip, leaving the underlying substrate exposed to both the chip and heat. The heat generated continues to soften the substrate and consequently the region of softened substrate expands to areas under the regions of coating that are still intact. Eventually, the substrate under the coating cannot support the cutting loads and the tool fails.

Yamagata and Noumra [17] found that when compared with CVD coatings, PVD coated cemented carbide inserts have a much superior edge toughness. Also for both PVD and CVD, at lower deposition temperature edge toughness is superior. In the cutting tests the PVD coated inserts (when compared to uncoated cemented carbide) exhibit a slight reduction in edge toughness and further as the PVD temperature increases, this tendency slightly increases. These results demonstrate that in milling of steel, edge breakage of the PVD coated tools (similar to the CVD coated tools), seems to originate from rupture in the coating.

They concluded that at high speeds and low feed rates the CVD tool excelled over PVD coated tools, in terms of both flank wear resistance and crater wear resistance. At high speeds and high feed rates, PVD tools are superior over CVD tools due to their excellent adhesive strength, good wear resistance and superior edge toughness. Furthermore they stated that in actual machine shop use, where machine rigidity and performance may not be as good as a test laboratory and where edge toughness is most important, the application of CVD coated tools is reduced.

2.4 Cutting Forces

Cutting force tests are used as a method to assess the machinability of a given work material. These forces are measured by using a dynamometer. It has been shown by various researchers that cutting forces are in significant in affecting machining parameters such as the temperature produced, power required, vibration in the cutter and the surface finish that is produced.

In the past, a considerable amount of work, both analytical and experimental, has been published on the determination of the power requirement during the milling process.

Tlusty and MacNeil studied the cutting mechanisms and the total force system in end milling. They showed that in steady state machining, the variation of cutting force will vary with the angle of flute engagement of the workpiece. [27]

Yellowley [21] used an analog force model by considering both flank and rake force conditions to express the average values of force, torque and specific power. He stated that specific power is a unique function of mean chip thickness.

Koneigberger and Sabberwal [28] considered that cutting forces depend on the area of cut taken by each tooth. In milling, the size of cut taken by each tooth will depend on the undeformed chip thickness and depth of cut. Assuming a circular path they developed the following expression for face milling as:

$$\mathbf{F = K_s A_a F_z \sin W} \qquad \textbf{(2.4)}$$

Where K_s - specific cutting pressure which is a function of chip thickness,
A_a axial depth of cut, F_z feed per tooth and W is the angle of rotation of the cutter in the workpiece.

Martellotti considered the path of the cutter as trachoidal and then proceeded to derive expressions for the chip thickness, length of the tooth path and radius of the curvature. The assumption of a circular tooth path is a close approximation to the trachoidal form and the simpler expressions obtained are of greater value. [29]

Kline et al developed a mechanistic model of the cutting force system in end milling in which cutting force is assumed to be directly proportional to chip area. The model is called a mechanistic model because the chip load and the cutting forces are computed based on the cutter geometry and the cutting conditions. The end milling process is examined by dividing the end mill into axial segments. In this model the equations which relate the elemental chip loading to cutting forces. [30]

$$\mathbf{DF_t = K_t\, D_z\, T_c} \qquad (2.5)$$

$$\mathbf{DF_r = K_r\, Df_t} \qquad (2.6)$$

Where Dft - elemental tangential force, Dfr - elemental radial force on a flute, Dz - thickness of the axial disk, Tc - chip thickness, Kt and Kr - constants.

Boston and Gilbert studied the influence of rake angles on the power required in milling, by means of a wattmeter which recorded the gross power input to the machine. The net power at the cutter could be calculated after the efficiency of the machine had been measured by means of a pony brake. [8]

Man Liu and Steven have attempted to develop an expression for the frictional force on the rake face of an end mill cutter based on mechanics of cutting assuming cutting an equivalent oblique cutting model. But they have taken data for equivalent oblique cutting from classical orthogonal cutting. They developed the following expression for frictional force: [31]

2.5 Surface Finish

Due to the inherent configuration of end milling, it has a larger machining error than other types of milling, that is, the end mill has a long hold shaft and miller which can be easily deflected by cutting forces. Therefore it is important to study the cutting process of end milling for reducing the amount of machining errors. [10]

In general, the machining errors on the finished surface of workpiece can be classified into two distinct types. One is location error which is defined as the distance between the desired surface and the actual surface of the workpiece. The other is the surface waviness error which is defined as the peal-to-peak value of actual surface. Superposition of these two errors is defined as the shape error. [10]

Martelloti [29] was probably the first person to carry out detailed research into the surface roughness produced when milling. He considered the milling path to be trachoidal and derived the following formula for surface roughness for slab milling.

$$\mathbf{R_a = \frac{f^2_z}{32(R \pm (f_z * z/\pi))}} \qquad \textbf{(2.7)}$$

Where R_a - surface roughness in CLA, f_z - feed per tooth, R - radius of cutter, z - number of teeth in the cutter.

The National Twist Drill & Tool Company [32] carried out extensive research on the surface roughness produced by the plain and end milling processes. They studied the affect of the depth of cut, the number of teeth, runout, cutter diameter and the mode of milling on the surface irregularities. This study covers the problems of feed rate and cutter rigidity. They recommended the use of the shortest cutter shaft length as possible. They developed an equation for the surface roughness produced while using the plain milling process and assuming a circular tool path.

$$\mathbf{R_a = f^2_z / 32R} \qquad \textbf{(2.8)}$$

where R - radius of the cutter, f_z - feed rate of cutter.

Shaw and Nakayama [33] stated that the roughness of machined surfaces is due mainly to the following three factors; geometric conditions, inaccuracy of tool motion and point of separation of chip from workpiece. The first factor includes feed marks, the depth of which may be easily calculated for a given feed and tool geometry.. Inaccuracy of tool motion due to chatter may be a major factor when machining difficult-to-machine materials, as a result of the large cutting forces involved. Discontinuous and inhomogenous chip formation is a particularly troublesome case where vibrations of the system may result. More rigid and powerful machines are then called for.

Brittle materials frequently crack below the level of the tool point leaving behind a rough surface that contains many points of high stress concentration that may prove to be troublesome in fatigue and in stress corrosion cracking of the part in service. Any changes that may be made to increase the shear angle (decrease the strain in the chip) will prove helpful in preventing roughness due to sub-surface fracture of the workpiece during cutting. The effect of built-up edge (BUE) on the surface roughness of the part is similar to the aforementioned problem of brittle materials. This is due to the irregular shape of the BUE and to the fact that it leaves behind strain hardened debris on the machined surface. Certain difficult-to-machine materials are particularly from the viewpoint of BUE (austenitic stainless steels, high temperature alloys and tantalum). However there are several methods of reducing the amount of BUE forming, including using cutting fluid to prevent chip-tool adhesion, changing machining conditions to promote discontinuous chip formation and increasing the chip-tool interface temperature to the point where the chip material recrystallizes. However the last method has the effect of increasing the amount of temperature dependent tool wear, namely diffusion wear, which results in a reduction of the tool life. [11]

Ema and Davies have researched the effects of different helix angles and machining conditions on surface finish during end milling. They studied the effect of cutting speed, feed rate and depth of cut on surface finish. They found that end mills with small helix angles produced the worst surface roughness. This is a direct result of the chatter that occurs and also the reduction of the period when the cutting edge engages with the workpiece material during down milling. [34]

Elbestawi and Sagherian studied the effect of vibration on surface error while end milling thin walled sections. The metal removal rate is reduced because of machining vibration which results in out of tolerance components. The vibration can either be forced or self-excited, which is more commonly known as chatter. The surface errors in the workpiece are the result of both the dynamic and static deflection of the workpiece and tool. [35]

The effects of cutter and workpiece deflection on surface errors have been studied by Fuji et al. who showed that the machined surface is generated by an envelop generated from the projected curvature of a helical tooth end mill cutter. The envelop is approximated by a locus of vertex of helical tooth. Using the data of measured cutter and workpiece deflection, it was possible to accurately predict the surface error profile. [36]

CHAPTER 3

MACHINABILITY OVERVIEW

3.1 Introduction

Machinability is the characteristic or behaviour of a material when it is being cut. It has been suggested that the word "machinability" was first used in the 1920's and referred specifically to the speed/tool life relationship [9]. Now machinability is defined in a number of different ways. However, in general machinability can be defined as an optimal combination of the following factors;

- Small cutting forces,
- High metal removal rates,
- Low tool wear rates,
- Good surface finish,
- Good surface integrity,
- Accurate and consistent workpiece geometrical characteristics,
- Good curl or breakdown of chip,

The main reason for the continued interest in the definition and assessment of machinability is the problem of specifying the cutting conditions for an optimal economic utilisation of the resources. In general, where process planners specify machining conditions, it will usually be found that they refer to data of a very generalised nature. This is typified by that provided in the handbooks of cutting tool and other manufacturers, or to 'in-house' handbooks compiled by company personnel or from the parent company abroad. [9]

The generalised data is thus either very comprehensive or so imprecise that it can at best indicate only a 'starting point' for machining. The absence of any but the vaguest indication of expected tool life also lessens its practical usefulness in situations that demand complete control.

In this study the machinability of the material by the end milling process is assessed by investigating the following parameters:

(1) Tool life

(2) Cutting forces

(3) Surface finish

3.2 Factors Influencing Machinability

The machinability characteristics are defined by a number of independent factors, such as the cutting conditions, workpiece properties and the tool properties.

Cutting Conditions;

- Cutting Speed,
- Feed Rate,
- Depth of Cut,
- Cutting Fluid,

a) Cutting speed,

This is the most important variable in the cutting operation, as it directly affects the tool wear rate, surface finish cutting forces and the type of chip formed. At low speeds the material behaves in a brittle manner, with discontinuous chips and low tool wear rates, however it also results in a poor surface finish. High speeds result in continuous chips and improved surface finish but on the downside can cause high tool wear rates and the tool life is low. Therefore there has to be a trade off between good tool life, surface finish and chip formation. The major effect of speed is on tool wear rates, so efforts must be made to balance these factors to attain the most desired conditions.

b) Feed rate,

This is similar to cutting speed in that it influences cutting forces, tool wear rates and surface finish, but to a lesser extent. An increase in feed rate results in an increase in cutting forces, tool wear rates and a poor surface finish. The surface finish produced is a direct function of the feed rate.

c) Depth of cut,

This has a significant effect on the cutting forces produced. In that a small increase in the depth of cut results in a significant increase in the cutting forces produced but only has a small effect on the tool wear rate and a negligible effect on the surface finish produced.

d) Cutting fluids,

This has two effects as it acts as both a coolant and a lubricant. In continuous operations its presence results in increased tool life as it removes the swarf and reduces the temperature in the cutting zone. In intermittent operations it can cause thermal cyclic loading, which can result in thermal fatigue failure. [18]

Workpiece Factors

Machinability is all about efficient ways and means of machining a workpiece. The workpiece is the central figure of a machinability study. The workpiece factors which influence machinability are;

Microstructure,
Chemical Composition,
Physical Properties,
Work Hardening Properties,

a) Microstructure,

Metals of similar microstructure generally have similar machining properties, however even small changes in microstructure can greatly affect machinability. The machinability of a piece of metal can differ due to inclusions or different grain structure, i.e., between core and surface (due to varying cooling rates). For good tool life the grain structure must be uniform.

b) Chemical Composition,

Alloying elements have a strong influence on machinability, e.g., sulphur, lead and phosphorus improve it, whereas chromium, vanadium, nickel and molybdenum all reduce machinability. Hard abrasive carbides also reduce machinability.

c) Physical Properties,

The most significant factors, affecting machinability, related to the workpiece are the physical properties. The hardness of the material is a significant factor in determining the machinability. Hardness is determined by composition, structure and heat treatment. The ductility of similar metals are related, so it is possible to predict from data obtained whether a metal is readily machinable and whether a good surface finish can be produced. As hardness is related to strength, it also gives an indication of the cutting pressure required.

d) Work Hardening Properties,

The physical, and any heat treatment, must be known as they both have a considerable effect on machinability.

Tool Properties

Another important area that affects machinability is the properties of the tool being used. This includes the tool material and the tool geometry. [10]

Tool Material,

Tool Geometry,

a) Tool Material,

A cutting tool material must be hard and tough. It must also possess good wear resistance as well as good mechanical and thermal shock resistance. It also must have the ability to maintain its properties at the elevated temperatures experienced during machining.

b) Tool Geometry,

Properly chosen tool angles enhance tool life and make possible the machining of a greater quantity of workpieces in a given unit of time, i.e., greater production rates. The cutting forces, power consumption and surface finish all depend on the tool angles. The rake angle has the largest influence on tool life. The tangential cutting force is greatly influenced by the rake angle.

The tool material and geometry selection are vital as they can often be the difference between success and failure of the machining operation.

Finally, the type and age of machine that is used will affect machinability. An older or less rigid machine may cause the age-old problem of vibration or 'chatter'. Chatter is manifested in imperfections on the surface of the workpiece and may result in an increase in tool wear rates.

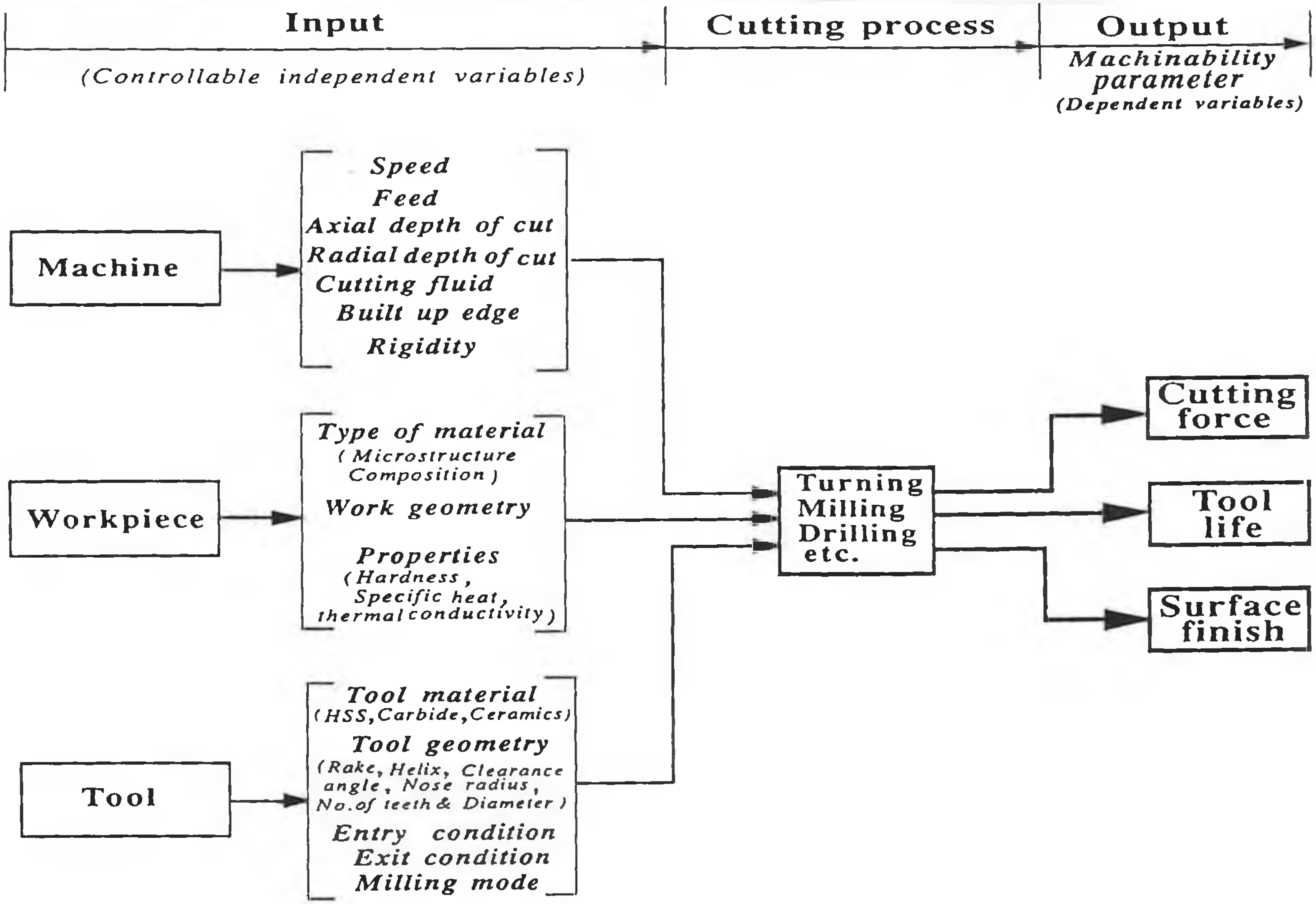


Figure 3.2a, Factors influencing machinability of materials [9]

3.3 Milling Process

Milling is one of the most universal and at the same time one of the most complicated machining methods. The number of factors effecting the machining result in milling, are considerably more than in turning, for example. However, the material removal rate in milling is high and the possibilities of obtaining a good finish are excellent.[5]

Milling is a process for producing flat and curved surfaces using multi-point cutting tools. There are three basic types of milling cutters, plain mills, face mills and end mills. However, for this investigation the end milling method was studied.

The milling process is distinguished by a tool with one or more teeth that rotate about a fixed axis while the workpiece is fed into the tool. The process is further distinguished from other metal cutting operations by the chips that are produced. These are generally short, discontinuous segments, which is a direct result of the geometry of the tool. The undeformed chip thickness in milling varies from one end to the other. While the maximum chip thickness may occur at either end or the middle of the chip, depending on the mode of milling used. The regular chip discontinuity that is associated with milling leads to non-steady-state cyclic conditions of force and temperature. As a tooth engages the work, it receives a strong shock followed by a varying force. At the same time the tool tip is relatively cool as it enters the work, is heated as the chip is formed and cools while awaiting the next engagement. This cyclic loading is detrimental to tool life, while the thermal cycling can cause thermal fatigue failure of the workpiece. The cyclic variation of force can provide the necessary energy to excite a natural mode of vibration in any part of the machine. Such vibrations can result in a poor surface finish and reduced tool life. [10]

As a result of the vibration in milling it is particularly important that the work be rigidly supported and that the machine be in good mechanical condition. Cutters should be mounted on large arbors and the arbor supported close to the cutter to further ensure a rigid system. This is more important when using cemented carbides inserts which operate at higher speeds and feeds than HSS. [18]

An end milling cutter has teeth on its end as well as its periphery, hence the name and is used to produce slots and surface profiles. It closely resembles face milling in the manner in which it is presented to the work but it is usually a lot smaller. In use, its axis of rotation is perpendicular to the surface produced. Although it is called an end mill, most of the cutting is done by the teeth on the periphery of the cutter. [10]

Classification of milling process

According to ISO 8688-2 (end milling) [18], the end milling process when using a standard end mill cutter with a straight shank can be classified as follows;

(1) ar = D, slot milling

(2) aa > ar, milling where the periphery is predominantly used.

(3) aa < ar, milling where the end teeth of the tool are predominantly used.

Another type of classification that is used is known as the immersion ratio. This is the width of cut that the end mill takes compared to the width of the end mill. Common immersion ratios include full immersion, where the width of cut equals the diameter of the cutter (ar = D) and half immersion where the width of cut is half the diameter of the cutter (ar = 1/2D). [5]

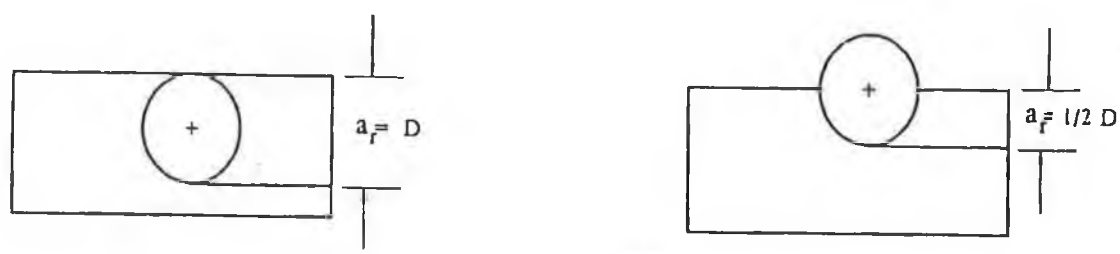


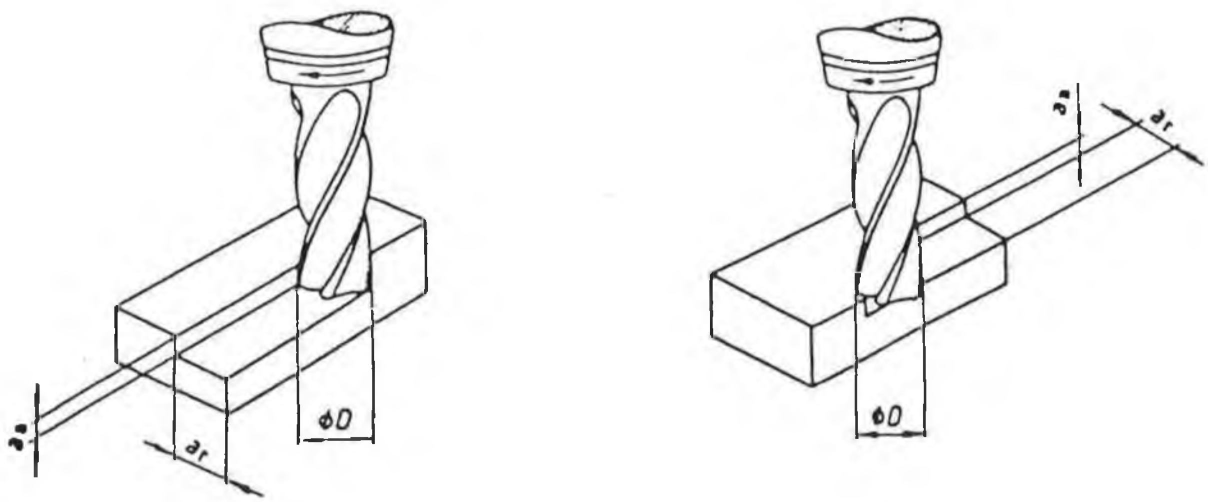
Figure 3.3a Common immersion ratios [5]

Mode of Milling

A basic consideration when milling, is the direction of approach of the cutter to the workpiece. Up milling (or conventional milling) occurs when the milling cutter rotates against the feed direction of the workpiece, while down milling (or climb milling) occurs when the cutter rotates with the direction of the workpiece.

In up milling (figure 3.3b), the chips starts thin and increases to a maximum chip thickness on exit. There is a burnishing effect before the cut starts. The cutter and workpiece tend to separate as a result of the cutting forces. The length of the burnishing is therefore a measure of the workpiece rigidity as well as the machine stability.

In down milling (figure 3.3c), the chip starts at its maximum thickness and decreases to a minimum on exit. In up milling the cutting forces tend to push the cutter away from the workpiece, whereas in down milling the cutting forces act to pull the cutter into the workpiece. For down milling there are two important criteria that must be met. Firstly, it is essential that the table feed mechanism of the machine is free of play or is equipped with a backlash arrestor. Secondly, the relationship between the teeth and the cutting depth must be that one tooth is in cut at all times. [10]



Up milling

Down milling

Figure 3.3b, Differences between (I) up- and (II) down-milling. [5]

Chip Geometry

The geometrical quantities of interest in the milling operation are; maximum undeformed chip thickness (tm) and undeformed chip length (l) which gives an indication of the time of contact per tooth. The actual shape of an undeformed milling chip is rather complex as the cutting edge travels in a trachoidal path. Martellotti [29] developed equations for calculating the chip geometry in milling.

$$tm = \frac{v}{Nn} = f \tag{3.1}$$

$$l = \tfrac{1}{2}(D\,\psi) \tag{3.2}$$

$$\psi = \sin^{-1}(2m/D) + \sin^{-1}[2(w-m)/d] \tag{3.3}$$

where,

v -

N - speed of the cutter, r.p.m. n - number of teeth

f - feed per tooth D - cutter diameter

Cutting Tool Angles

The more important angles present on a cutting tool are rake angle, clearance angle and helix angle. The rake angle affects the power requirements and the chip formation. The larger the positive angle the lower the cutting forces that are produced. Tough sticky materials such as light alloys require a larger rake angle than brittle materials, such as cast iron. However, the shock loading to which milling cutters are subjected limits the maximum useful rake angle. Negative rake angles are used when the strongest cutting edge is required, such as when machining hard and abrasive materials. They are also frequently used in cemented carbide cutters to provide a greater wedge angle for increased shock resistance and strength.

However, this has the effect of increasing the energy consumed per unit volume and increasing the temperature at the tool point.

The clearance angle is designed to provide clearance between the tool and the workpiece and is sometimes divided into a primary and secondary clearance angle. It decreases the friction between the two surfaces. Ductile materials such as copper need a larger clearance angle than hard materials. Flank wear develops at a slower rate when using a larger clearance angle.

The wedge angle is determined by the rake and clearance angles and greatly influences the strength of the tooth. To avoid fracture, cemented carbide inserts are often reinforced by rounding the cutting edge or providing a negative primary land.

The helix angle brings the cutting edge progressively into cut, providing the cutter with a "quieter" run. It also gives rise to an axial force component. This force will tend to pull or push the cutter out, or towards the spindle depending on whether the helix is right or left hand. [11]

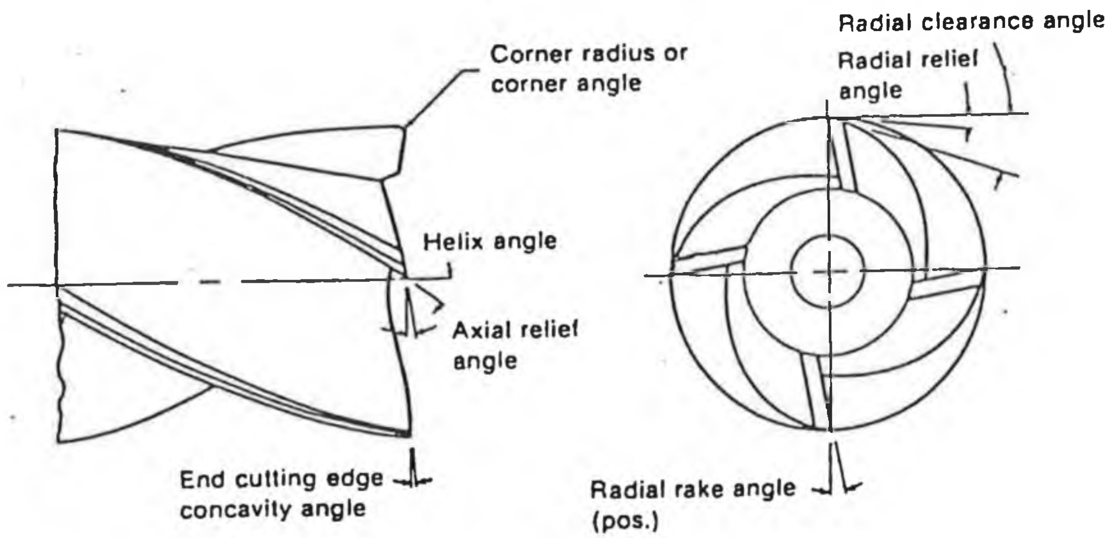


Figure 3.3c, Geometry of an end mill [9]

3.4 Workpiece Material

3.4.1 General Classification

The material used for the test is tool steel (Din 1.2311), which is similar to mold steel (AISI P20). Mold steels, also called P group steels, contain chromium and manganese as principal alloying elements. Type's P20 and P21 are normally supplied heat treated to 30 - 36 HRC (280-320 HB), a condition in which they can be readily machined into intricate dies and molds. Because these steels are pre-hardened no subsequent high-temperature heat treatment is required, therefore distortion and size changes are avoided. However, when used for plastic molds, type P20 is sometimes carburized and hardened after the impression has been machined. All group P steels have low resistance to softening at elevated temperatures. Plastic molds often require massive steel blocks up to 750 mm thick and weighing as much as 9 metric tonnes. Because these large blocks must meet stringent requirements for soundness, cleanliness and hardenability, electric furnace melting, vacuum de-gassing and special deoxidisation treatments have become standard practice in the production of group P steels. In addition, ingot casting and forging practices have been refined so that a high degree of homogeneity can be achieved. [37]

3.4.2 Chemical Composition

The chemical composition of the workpiece is broken down as follows;

Table 1 The composition of the workpiece material

Element	Composition %
Iron	96.0
Carbon	0.4
Manganese	1.5
Chromium	1.9
Molybdenum	0.2

The alloying elements that are present in the tool steel provide additional hard abrasive particles that improve wear resistance, they also provide higher hardness (hot-hardness) and greater strength at elevated temperatures. However the addition of manganese tends to make the material more brittle (decrease the strain to rupture), while both manganese and chromium increase the tendency of the material to strain harden.

3.4.3 Heat Treatment

Tool steels are the steels that are used to form and machine other materials and they are therefore designed to have high hardness and durability under severe service conditions. With few exceptions, tool steels must be heated treated to develop specific combinations of wear resistance, resistance to deformation or breaking under high loads and resistance to softening at elevated temperatures.

The two most common methods of heat treating mold steel is to case harden by carburizing or pre-harden the steel (or partially machined mold or die) to about 30-40 HRC, finish machine and use at this hardness level. Nitrided molds have proved successful in some instances, but nitriding is not extensively used. Before P20 is nitrided it must be pre-hardened to approximately 300HB using the method outlined below. This sequence will ensure freedom from carburization or decarburization.

The steel is pre-heated to between 870 -900°C for approximately 1 hour (higher temperatures may impair polishability). It is then hardened at 815°C for 15 minutes and finally quenched in oil. Following this treatment the steel is ready to be machined and it requires no further high-temperature heat treatment.

3.4.4 Physical Properties

Although this material would not be immediately classified as a difficult to machine material, it is nonetheless a very hard material to machine. It has the following characteristics;

- Brinell hardness ~ 290 and 320 HB
- Tensile strength ~ 1000 N/mm^2.
- Density ~ 7.85 g/cm^3
- Thermal Expansion ~ 12.8 µm/m (425 °C), 13.7 µm/m (540 °C), 14.2 µm/m (650 °C)
- Resistance to thermal softening ~ Low, typically undergoing large reductions in hardness at moderate temperatures.

Except for special grades, the composition and heat treatments of most steels are selected to provide very high resistance to plastic deformation. This course of action leaves the metal with very little ability to absorb deformation; in other words, it leaves the metal very brittle.

The pre-hardened condition imposes large forces on the cutting tool and may result in tool fracture and high cutting temperatures. As a result feed rates and cutting speeds must be reduced. Hard materials require rigid machine tools that are stable at high energy levels.

3.4.5 Machining Characteristics

The most economical way to make a plastic mold is to machine pre-hardened steel (usually 275-325 HB) for service without further heat treatment. Machinability for most operations is reasonably good at this hardness level and the cost of further heat treatment is eliminated. At a hardness level of 275 -325 HB a high-speed end mill can be operated at about 18 m/min (60 sfm) and at a feed rate of about 0.13 mm/tooth, although this is somewhat less if the cutter lacks rigidity. When carbides are used, the feed will be roughly the same, but the speed can be increased to around 73 m/min (240 sfm).

For molds used in molding plastics that contain abrasive fillers, mold hardness must be higher to attain acceptable mold life. Under these conditions one of three procedures is followed. The first involves machining the P20 in its unhardened state (180-210 HB) to its finished size. After machining, the mold is carburized and hardened so that the surface is approximately 60 HRC and the core is 50 HRC. However, when molds are too intricate to withstand the carburizing treatment without excessive distortion, a second procedure is sometimes used. The pre-hardened steel is completely machined and then gas nitrided for 30 hours. The third machining procedure is also used for plastic molds that are too intricate to carburize in the finished machined condition. The fully annealed stock is rough machined to within about 1.6mm of finish surface, then hardened to 45 -50 HRC. After heat treatment, the mold is finished machined using carbide cutters.

3.4.5 Applications

All group P steels have low resistance to softening at elevated temperatures. Group P steels are almost exclusively used in low temperature die casting dies and in moulds for the injection moulding of plastic It is recommended for use in casting zinc alloys, except for long production runs (1 million shots). It is not recommended for use in molds for the injection molding of nylon, which requires a harder steel.

Tool steel (Din 1.2311) or Mold steel (P20) is recommended for use in the following:

- Injection molding of thermoplastics,
- Blow molding of general thermosetting plastics and thermoplastics,
- Extrusion of general thermosetting plastics and thermoplastics,
- For moulds with complex shapes such as automobile or household parts,
- For large moulds such as large automobile parts.

3.5 Tool Material

At present, a wide variety of hard cutting tool materials are industrially used depending on the cutting conditions and work material. They are high speed steel (HSS.), cemented carbides, cermets, ceramics, sintered cubic boron nitride (CBN) and sintered diamond. Furthermore each of these materials is manufactured in different grades to satisfy the particular application requirements. The properties and cutting performance of these materials are constantly being improved and new grades are developed one after another. This has led to a very large and diversified marketplace from which the manufacturing engineer has to choose the most suitable cutting tool.

3.5.1 Material Selection

In general the most satisfactory tool will usually be the one corresponding to the minimum total cost of performing a required operation to the specified accuracy. This total cost includes the following: [9]

- Initial tool cost including tool holding cost.
- Tool grinding cost.
- Tool Life.
- Metal removal rate.
- Labour cost as influenced by cycle time, machine, operator and labour cost.

The best tool will not necessarily be the one that gives the longest life; such factors as grindability, metal removal rate and surface finish play important roles in the selection of the best tool material for a particular operation. With the increased use of computer numerically controlled (CNC) machines, reliability and predictability of performance are of greater significance than ever before and these items must be given greater weight in selecting tool materials for such application. [38]

Due to intense competition between tool manufacturers, a great amount of research and development has gone into developing new and improved tool materials. This has resulted in new end-milling cutters being constantly introduced into the workplace. These cutters are rapidly replacing high speed steel as the preferred tool in many applications. The reason for this being that higher speeds and consequently higher metal removal rates are possible with these new cutters. These cutters are able to utilise the greater stability of modern CNC machines better than HSS cutters can. Another reason for the continued decline in the use of HSS is the large volume of difficult-to-machine work material such as super alloys, high silicon aluminium alloys and hardened steels that are being handled today. However the development of HSS is still ongoing with improvements being made in chemical composition and advancements in surface coating of HSS tools. [39]

A general observation that may be made is that there is a need for a wide spectrum of cutting tool materials. The three most important properties of a cutting tool are high-temperature physical and chemical stability (HTS), abrasive wear resistance (AWR) and resistance to brittle fracture (RBF). A given tool material is generally not outstanding in all three categories, i.e. as a material is made more refractory (high HTS), it becomes more brittle (low RBF)or if it is made more abrasion resistant (high AWR) it also becomes more brittle (low RBF). This is true not only when comparing different classes of tool material such as HSS, cemented carbide and ceramics but also when comparing different compositions within a given class such as different grades of cemented carbide. In general, as a tool material becomes more brittle, it becomes more important to avoid the low-speed range where an unstable built-up edge (BUE) tends to form. If a ductile metal, such as mild steel, must be machined in the built-up edge speed range, then it may be necessary to use HSS instead of a cemented carbide or ceramic tool to avoid chipping of the cutting edge. [11]

The major classes of tool material can be listed in order of increasing hardness and decreasing toughness, as is illustrated in figure 3.5.1a shown below. As this list is descended, the strain at fracture decreases. All of these materials except the last one have a two-phase structure - a softer continuous phase separating very hard particles. Initially the spacing of the hard particles is sufficiently great so that Young's modulus of elasticity corresponds to that of the continuous phase, a solid solution of iron in the case of HSS. However, beginning with the cemented carbide, the hard particles are so close together that Young's modulus approaches that of the carbide particles instead of the cobalt binder phase. In the case of ceramics, polycrystalline diamond and cubic boron nitride (CBN) the space between the hard particles is essentially that corresponding to crystal boundaries. In the case of the ceramic no binder material or sintering aid is employed, the only difference in chemistry in the crystal boundaries being that due to the very small impurity content.

1. High speed steel
2. Cast alloy
3. Cemented carbides
4. Cermets
5. Titanium carbides
6. Ceramics
7. Polycrystalline diamond and cubic boron nitride
8. Single crystal diamond

Figure 3.5.1a, Toughness and hardness of tool materials. [11]

3.5.2 High Speed Steel

Since the beginning of the twentieth century, HSS has been an essential class of cutting tool material, which is used by the metalworking industry. H.S.S.'s are basically high alloy steels designed to cut other materials efficiently, despite the extreme heat generated at the cutting edges of tools during machining. It is the most widely used tool material for low or medium cutting speeds.

Composition of HSS

Carbon is one of the most important alloying elements in HSS because it is required for heat treatment response. The carbon level, which varies from 0.75 to 1.50%, must permit the HSS to be quenched to a full martensitic structure and must provide sufficient excess carbon for the formation of the alloying carbides. In the completely annealed state, very little carbon is in solution in the matrix of HSS Usually, most of the carbon is combined with the alloying elements to form complex carbides. Cobalt is added to the high speed steel to improve its performance. The high speed steels with cobalt generally contain 5 to 12% Co. The addition of cobalt provides greater hot hardness and wear resistance but results in a somewhat lower toughness. Other alloying elements present in HSS tools are; tungsten and molybdenum, which promotes hot hardness and increases wear resistance and chromium which provides the ability to harden HSS by increasing carbide solubility during heating for hardening and promotes scaling resistance. [11]

Advantages of HSS

In general, HSS containing cobalt can be treated to a hardness level of 63 to 68 Rc. Above 68 Rc HSS tools tend to be too brittle for most applications. It is also capable of maintaining a high hardness at elevated temperatures. This hot hardness property of HSS is related to its composition and to a secondary hardening reaction, which is the precipitation of fine alloy carbides during the tempering stage of the heat treatment process.

HSS also possesses a high level of wear resistance due to the high hardness of their tempered martensite matrix and the extremely hard refractory carbides distributed within its martensitic structure. HSS tools possess an adequate degree of impact toughness and are more capable of taking the shock loading of interrupted cuts than carbide tools, which is the reason for their continued widespread use in milling operations. The toughness of HSS can be increased by adjusting the chemistry to a lower carbon level or by hardening at an austenizing temperature lower than that usually recommended for the steel, thereby producing a finer grain size. Tempering at a temperature range between 593 °C to 649 °C will also increase the toughness of HSS. However this has a downside, because increasing the toughness of the tool has the undesirable effect of decreasing both the hardness and wear resistance of the tool. [10]

Limitations of HSS

The most significant factor affecting the use of HSS and its primary limitation is speed/metal removal rate, typically suffering plastic deformation at relatively low speeds. Another limitation of HSS is that the hardness of these materials falls off rapidly when machining temperatures exceed about 540 °C to 600 °C. This requires the use of lower cutting speeds than those used with carbides and cermets cutting tool materials.

It has been found that cobalt grades are not particularly advantageous when cutting the readily machinable materials. They are however, most beneficial for machining steels having a hardness level above 300 BHN (Brinell hardness number) and for the more difficult to machine metals such as titanium and nickel base high temperature alloys.

A processing factor that affects the use of HSS is the tendency of the carbide to agglomerate in the centres of large ingots. This can be minimised by remelting or by adequate hot working. However if this agglomeration is not minimized, then physical properties can be reduced and grinding becomes more difficult.

Applications of HSS

Despite the increased use of carbides and other cutting tool materials, HSS is still employed extensively - some estimate its use for about 60% of all metal-cutting operations. Most drills, reamers, taps, end mills and gear cutting tools are made from HSS. It is usually preferred for operations performed at low cutting speeds; on older, less rigid machines with low horsepower and when good surface finishes are required on workpieces. It is often best for tough, interrupted-cut operations on difficult-to-machine materials such as heat-treated steels, titanium alloys and high-temperature materials. Reasons for the continued high usage of HSS tools include it's relatively low cost and easy fabrication, good wear resistance and toughness, and versatility as it is suitable for use on virtually all types of cutting tools.

3.5.3 Cemented Carbides

Cemented carbides belong to a class of hard, wear resistant, refractory materials in which the hard tungsten carbide (WC) particles are bound together, or cemented, by a soft ductile metal binder, namely cobalt (Co). These materials were first developed in Germany in the early 1920's in response for a die material having sufficient wear resistance for drawing tungsten incandescent filament wires to replace the expensive diamond dies then in use. Although cemented carbide was first used as a die material, its application has changed since then with approximately 50% of all carbide production being used for metal-cutting applications.

Cemented carbides must be manufactured by the powder metallurgy process since the carbide melts at such high temperatures. The production process consists of a sequence of steps in which each step must be carefully controlled to obtain a final product with the desired properties, microstructure and performance. These steps include:

1. Processing of the ore and the preparation of the tungsten carbide powder.
2. Preparation of the other carbide powders.
3. Production (milling) of the grade powders.
4. Compacting or powder consolidation.
5. Sintering
6. Post-sinter forming.

Tungsten powder is first produced by hydrogen reduction of chemically purified ore. Reduction conditions can be altered to control the grain size of the tungsten metal which is then carburized by mixing with carbon and heating in hydrogen at high temperature (ranging from 1400 to 2650 °C). The grain size of tungsten carbide so produced can range from 0.4μm to 7μm. Fine control over the carbide grain size can be exerted during the next stage of the process, which involves adding fine cobalt powder and wet milling all of the constituents that make up the final powder, together with a lubricant that aids pressing. Small amounts of vanadium, tantalum or chromium carbides are frequently added to inhibit grain growth. After milling, the powder is dried, ideally by spray drying, which produces free flowing spherical aggregates of powder. Pressing to shape is followed by sintering at some 1500 °C in vacuum, during which porosity is reduced from 50% in the pressed compact to less than 0.01% by volume in the final product. This low porosity is due to the fact that there is liquid present during sintering, and hence the extent to which the carbide is wetted by the molten binder metal and dissolves in the binder is important in producing a pore-free product with good cohesion between the hard particles and the binder. [13]

Tungsten carbide is wetted most easily and dissolves most in the iron group metals and therefore forms sintered cemented carbide with the best mechanical integrity. However, those very properties that make tungsten carbide easily sinterable and tough, also cause it to dissolve most readily in iron. Cemented carbide grades that contain only tungsten carbide and cobalt can only be used for machining non-ferrous alloys and cast iron (the chips from which fracture easily and so do not remain in contact with the tool long enough to cause dissolution wear). Tools that are used for cutting steels require additions of titanium carbide (TiC) or tantalum carbide (TaC) which are less soluble in hot steel. These additions have the downside effect of reducing both the hardness and the strength of the material. However even with these so-called mixed crystal grades, wear by virtue of dissolution of the tool material in the chip is the process that limits tool life at high speeds. One approach to this problem has been to develop grades based on titanium-carbide or titanium nitride with essentially a nickel-cobalt alloy binder. These materials can be used for moderate to high speed finish machining of steel both in milling and turning and in Japan they account for more than 15% of all inserts and are currently becoming popular in Europe and the United States. [40]

Classification of Cemented Carbide

In 1964, the International Organisation of Standardisation (ISO) issued ISO Recommendation R513 that deals with the "Application of carbides for machining by chip removal". In the ISO system, all machining grades are divided into three colour coded groups based on their application; P, M and K. The P group (blue colour), which are high alloyed tungsten carbide grades, are recommended for cutting materials with long chips such as carbon steels, alloy steels, tool steels and ferritic steels. The M group (yellow colour), which are also alloyed tungsten carbides but which contain less tungsten carbide than the corresponding P series, is used for cutting materials with medium chips such as austenitic stainless steel, nickel-based super-alloys and ductile cast iron. The K group (red colour), are straight tungsten carbide grades and are recommended for cutting non-ferrous alloys, grey cast irons and non-metals. Each grade within a group is assigned a number to represent its position from maximum hardness to maximum toughness. P-grades are rated from 01 to 50, M-grades from 10 to 40 and K-grades from 01 to 40 grades. Examples of chemical compositions and properties of cemented carbides for machining is shown in table 3.5.4a.

Table 3.5.3a, IS0 carbide grade system. [10]

ISO grade	Composition % WC TiC TaC Co	Hardness HRA	Transverse rupture strength MPa	Compressive Strength MPa	Modulus of rigidity GPa
P10	60 18 14 08	92.0	1,900	4,600	530
P20	72 10 10 08	91.5	2,000	4,800	540
P30	71 08 12 08	90.5	2,300	5,000	560
P40	79 06 04 11	89.5	2,300	4,700	540
M10	75 06 13 06	92.5	2,000	5,000	580
M20	80 04 08 08	91.5	2,300	4,900	570
M30	71 08 12 09	91.0	2,300	5,000	570
M40	72 05 05 12	89.0	2,800	5,000	540
K01	89 04 02 05	93.5	1,900	6,300	630
K10	92 xx 02 06	92.0	2,400	6,200	635
K20	94 xx xx 06	90.5	2,800	5,300	620
K30	93 xx xx 07	90.0	3,200	4,900	580

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P20	72	10	10	08	91.5	2,000	4,800	540
P30	71	08	12	08	90.5	2,300	5,000	560
P40	79	06	04	11	89.5	2,300	4,700	540
M10	75	06	13	06	92.5	2,000	5,000	580
M20	80	04	08	08	91.5	2,300	4,900	570
M30	71	08	12	09	91.0	2,300	5,000	570
M40	72	05	05	12	89.0	2,800	5,000	540
K01	89	04	02	05	93.5	1,900	6,300	630
K10	92	xx	02	06	92.0	2,400	6,200	635
K20	94	xx	xx	06	90.5	2,800	5,300	620
K30	93	xx	xx	07	90.0	3,200	4,900	580

As can be seen from the table, the group P grade carbides contain a large amount of TiC and TaC that increases crater wear resistance. The content of additive carbides is medium in the M grade carbides and the K grade carbides are basically composed of WC-Co though some of them contain a small percentage of TaC as a grain growth inhibitor. The grades with a lower class number have a higher hardness, higher TiC-TaC content, a lower TRS and low Co content. The hardness and the TiC-TaC content decrease, while the TRS and Co content increase as the class number increases. The small number grades are used for light to finish machining. The cutting speed is high but the feed rate and depth of cut are low because they have high wear resistance but possess poor edge chipping resistance. The higher number grades are used in medium to heavy cutting, or rough cutting. They cannot be used at high speeds because of low hardness and poor wear resistance but high feed rates and depths of cut are permissible because of their superior edge toughness. They are also used in interrupted cutting such as milling.

Now micro-grain cemented carbides are available that have grain sizes of less than 0.5 micro metres compared to 2-3 micro metres in normal tools. The advantage of micro-grain carbides is their increase in strength without a reduction in the hardness of the tool. When hardness is the same, micro-grain carbides have a higher strength and a lower density than normal carbides. They possess superior wear and chipping resistance at speeds of less than 50 m/min. They are available in both inserts and solid end mills. They have a higher metal removal rate and longer tool life than high speed steel. [10]

Physical and Mechanical Properties

The hardness of cemented carbides is affected by both the level of porosity and microstructure. For straight tungsten-carbide cobalt (WC-Co) alloys of comparable tungsten carbide grain size, hardness and abrasion resistance decrease with increasing cobalt content. Also for a given cobalt content, hardness increases with decreasing grain size. In cemented carbides, hardness is measured by the Rockwell A-scale diamond cone indentation test (HRA) or the Vickers diamond pyramid test (HV). Typical values for cemented carbides used in machining applications range from 88 to 94 HRA or 1100 to 2000 HV. A true indication of the resistance to plastic deformation in metal cutting can only be obtained by measuring hardness at the elevated temperatures produced during cutting. It has been found that the hardness of cemented carbides decreases monotonically with increasing temperature.

One of the unique properties of cemented carbides is their high compressive strength. The compressive strengths of cemented carbides are greater than those of most other materials, with typical values ranging from 3.5 to 7.0 GPa. The ductility of cemented carbides is generally low at room temperature, so there is little difference between their yield strength and their fracture strength. At higher temperatures, however, these materials exhibit a small but finite amount of ductility. Measurement of yield strength is therefore more appropriate at elevated temperatures. High temperature yield strength is typically measured at 0.2% offset strain. Like hardness, the compressive yield strengths of cemented carbides decrease monotonically with increasing temperature, with the rate of decrease depending on the composition and microstructure. As is the case for metallic materials, fine-grain alloys tend to lose their yield strengths more rapidly with increasing temperature than coarse-grain grades, although at room temperature the former can exhibit higher yield strengths.

The most common method of determining the fracture strength of carbides is the transverse rupture strength test. In this test, a rectangular test bar is placed across two sintered carbide support cylinders and a gradually increasing load is applied by a third carbide cylinder at the midpoint between the supports. Transverse rupture strength is determined from the dimensions of the test bar, the distance between the supports and the fracture load. There is a good correlation between transverse rupture strength and milling performance. This can be attributed to the fact that during milling the tool is subjected to tensile stresses as it leaves the cut, and a material with a high transverse rupture strength should be able to resist fracture under these conditions.

The modulus of elasticity, or Young's modulus varies inversely with cobalt content. However, unlike the hardness and compressive strength, the modulus of elasticity is independent of tungsten carbide grain size. The modulus of elasticity of cemented carbides is higher than that of any other commercially available except diamond and cubic boron nitride. As a result, cemented carbides have elastic moduli of two to three times those of cast irons or steels.

The thermal conductivity of WC-Co alloys is important in machining applications because the ability of the tool to conduct heat away from the tool/workpiece interface has a definite effect on tool performance. For modulus of elasticity, thermal conductivity decreases with increasing cobalt content and is unaffected by tungsten carbide grain size. The addition of titanium carbide has the effect of considerably reducing the thermal conductivity. [11]

Cutting tools are subjected to thermal shocks during interrupted cutting operations such as in milling. Resistance to thermal shock is therefore an important property that determines tool performance in milling. As of yet, no laboratory test has been devised to measure the resistance of a cutting tool to thermal shock. However, empirical parameters have been suggested that can be used to evaluate tool materials for their probable resistance to thermal shock. A commonly used parameter is $\sigma k/E\alpha$, where σ is the transverse rupture strength, k is the thermal conductivity, E is Young's modulus of elasticity and α is the coefficient of thermal expansion. In general, the higher the value of $\sigma k/E\alpha$, the better is the thermal shock resistance of the material. [11]

Tools and Toolholding

Early carbide metal-cutting tools consisted of carbide blanks brazed to steel holders or milling cutters. Tools that became dull were re-sharpened by regrinding. Clearance angles, cutting-point radii and other features could also be ground into tools to suit particular cutting situations. Special chip-breaker grooves designed to curl and break the chips generated in metal cutting were also ground into the early tools. Although these early carbide metal-cutting tools provided significant increases in metal-cutting productivity, certain disadvantages have become apparent. Regrinding changes the size of the tool; therefore the tool/workpiece relationship must be altered every time the tool is re-sharpened. Maintaining consistent geometry is difficult with reground tools and as a result part quality can suffer. Further because the brazed joint could only withstand a limited range of temperature, the selection of usable carbide grades and the cutting conditions were restricted. This restriction due to temperature also meant that vapour deposition coating technologies could not be employed to brazed tools.

However during the 1950's, the now-familiar indexable inserts were introduced. These so-called throwaway inserts resemble brazed tools except that the carbide is mechanically secured in the holder rather than brazed. A popular holding method involves a screw with a tapered head that passes through a conical hole in the insert and forces it into the holder pocket. Consistency and ease of replacement are the main advantages of indexable insert tooling. Consistent positioning of the cutting edge from index to index simplifies machine tool set-up and thus helps ensure uniform product quality. Another advantage of indexable inserts is that when a cutting edge wears, a fresh edge can be obtained by simply rotating (indexing) the insert. The use of indexable inserts also eliminates labour costs for regrinding and allows a wider selection of carbide grades to be used, as well as permitting coating of the insert.

Indexable inserts are available in both positive and negative geometries depending on the application. Negative-rake inserts have excellent resistance to breakage and are suited to difficult operations involving interrupted cuts. Negative-rake inserts can also be used on both sides, effectively doubling the number of available cutting edges per insert. Although positive rake inserts can only be used on one side, they cut with lower cutting force, reduce the possibility of distorting the workpiece and produce better surface finishes. Indexable inserts also feature chip-breaker grooves to control chip formation. These grooves often aid in producing lower cutting forces. In fact, advanced chip-control geometries can give negative-rake inserts the force-reducing capabilities of positive rake designs. [10]

3.5.4 Coatings for Cutting Tools

Coatings such as titanium nitride (TiN), titanium carbide (TiC), titanium-carbo-nitride (TiCN), hafimum nitride (HfN) and aluminium oxide (Al_2O_3) are deposited on metal cutting tools to increase tool life and achieve higher metal removal rates than are possible with uncoated tools. [4]

An important development in the production of coated cutting tools and especially carbide tools occurred in the 1960's, when laminated tips were produced that consisted of a base material with a sintered layer coating of a more hard, resistant ceramic material. This development not only enabled higher cutting speeds in steel machining but also reduced diffusion wear on the tool. Although metal cutting productivity increased with the use of these laminated tools, the thermal expansion mismatch between the substrate and the surface layer caused thermal stresses during metal cutting, which caused the laminate to spall (or peel) during use. Further development of laminated cutting tools resulted in the introduction of a thin layer (~5 μm, or 200 μin.) of a hard TiC coating to cemented carbide tools by a process known as Chemical Vapour Deposition (CVD). The impetus for this development came from the Swiss Watch Research Institute, where vapour-deposited TiC coating had been used on steel watch parts and cases, to combat wear on these components. [39]

The CVD process is one which in some ways is similar to the gas carburizing process. In the process a reactant atmosphere gas is fed into the processing chamber where it is decomposed at the surface of the workpiece, liberating one material for either absorption or accumulation at the workpiece. A second material is liberated in gas form and is removed from the processing chamber, along with atmosphere gas, as a mixture referred to as off-gas. In the case of coating cutting tools and in particular titanium carbide, coatings are formed by the hydrogen reduction of titanium tetrachloride ($TiCl_4$) in the presence of methane (CH_4) or some other hydrocarbon and hydrogen (H_2). The deposition temperatures range from 900 °C to 1100 °C depending on the substrate material. Although the process can be carried out at atmospheric pressure, reduced pressure (0.1 atm) is used to improve uniformity of deposition over the parts being coated. The reaction is:

$$TiCl_4\,(g) + CH_4\,(g) + H_2\,(g) \leftrightarrow TiC\,(s) + 4CHl\,(g) + H_2\,(g) \qquad (3.4)$$

During the TiC deposition process, a secondary reaction often occurs in which carbon is taken from the cemented carbide substrate:

$$TiCl_4\,(g) + C\,(s) + 2H_2\,(g) \leftrightarrow TiC\,(s) + 4HCl\,(g) \qquad (3.5)$$

The resulting surface decarburization leads to the formation of a weak (brittle) eta (η) phase and to associated substrate microporosity at the coating-substrate interface. Also, if insufficient carbon is supplied from the gas atmosphere, the substrate can become carburized by the diffusion of carbon to the interface to form titanium carbide. The early coated tools were particularly notorious in this regard and showed inconsistent performance during interrupted cuts. Such performance inconsistencies have now been largely eliminated by a number of metallurgical and processing innovations that have resulted in coatings with greater thickness uniformity, better adherence to the substrate, more consistent morphology and microstructure, with minimum interfacial η phase and associated porosity. [41]

During the 1970's CVD coatings evolved from the single-layer TiC coatings to multilayer hard coatings comprising various combinations of TiC, TiCN, TiN and Al_2O_3. Multilayer coatings, through a combination of properties, suppress diffusion wear, flank wear, built-up edge wear and extend the range of application. A variation of the multilayer coatings employs multiple alternating layers. [5]

Another advancement in CVD coated tools came in the late 1970's with the introduction of cobalt-enriched tools. As was already mentioned earlier, early coated tools were prone to catastrophic fracture when they were applied at higher feed rates or in intermittent cutting operations. One solution to the problem is to improve fracture toughness of the substrate by increasing its cobalt content. Unfortunately, this approach results in decreased deformation resistance, which can cause tool tip blunting.

The high temperatures employed during CVD coating ensure good adhesion of the coating to the substrate (cemented carbide). However, this coating adhesion can be adversely affected by stresses caused by the thermal expansion mismatch between the substrate and the coating. This mismatch is highest for TiN coatings and lowest for TiC coatings, where the thermal expansion coefficients of the coating materials are higher than those of the substrate material. As a result, hard coatings on cemented carbide substrates are in residual tension at room temperature. In certain cases, the stresses may be relieved by transverse cracks that form in the coating. These cracks do not affect coating adhesion but they may initiate tool fracture in interrupted cutting operations in which the cutting edge is subjected to fatigue-type loading. Residual tensile stresses are most severe at tool corners, so to minimize their effect and to reduce the formation of η phase, which tends to develop to a greater extent at sharp tool edges, CVD tools are honed before coating.

In the 1980's yet another major advancement in coating technology occurred with the introduction of Physical Vapour Deposition (PVD). In this process the coating is deposited in a vacuum by condensation from a flux of neutral or ionized atoms, where the metal species are derived from a variety of sources including electron-beam evaporation, magnetron sputtering and arc evaporation. In the ion plating variations of the PVD process, the flux of atoms is activated by an electrical glow discharge plasma, and the charged species are accelerated towards the substrate by applying a negative bias potential on the substrate. For hard coatings, the evaporated or sputtered metal species (titanium, aluminium etc.) are evaporated or sputtered and are made to react with the gaseous species (N2, NH3, CH4, etc.) introduced into the vacuum chamber. Because PVD coatings are produced at low pressures (10-3 to 10-2 torr), the atoms and molecules have long mean free paths and undergo fewer collisions, making PVD coating a line-of-sight deposition technique. This necessitates moving the tool fixtures during tooling to ensure uniformly thick coatings on both the rake and flank face of tools. [10]

A number of factors make PVD coating more attractive than CVD coating:

- Because of the lower deposition temperatures involved, PVD coating can be used to coat HSS cutting tools that could not be coated by using the CVD technique. This is because the deposition temperatures used in CVD coating are above the melting point of HSS
- The lower deposition temperatures of PVD coating prevents the formation of eta (η-phase) and produces crack free coatings with finer grain sizes.
- The coatings are smoother and thus generate less frictional heat during machining.
- PVD coating introduces compressive residual stresses that are beneficial in resisting crack propagation into the coating.
- PVD coatings can be applied uniformly over sharp cutting edges. A sharp edge is desirable in a cutting tool as it leads to lower cutting forces, reduced tool-tip temperature and finer workpiece surface finishes.
- For cemented carbide cutting tools, the PVD coating preserves the transverse rupture strength of the carbide substrate, whereas the CVD process generally reduces the transverse rupture strength by as much as 30%. This is due to the presence of interfacial η-phase and/or residual tensile stress in the CVD coating.

Benefits of Coatings

In general, coatings increase the wear resistance of cutting tools, including abrasion wear, adhesion wear, diffusion wear and friction wear resistance's. The coating also reduces the amount of heat generated by reducing the friction between the workpiece and toolface. This reduction in temperature results in a decrease in the temperature dependant wear on the cutting tool. The reduction in friction also results in lower cutting forces between the workpiece and tool. The coating is more thermally and chemically inert than the substrate material and is more resistant to thermal wear (diffusion wear). It also maintains its hardness level (hot hardness) at the elevated temperatures found at the tool-chip interface found during machining. This means that it is more resistant than an uncoated tool, to both abrasion and adhesive wear mechanisms and results in extended tool life.

3.5.5 Coated High Speed Steel

Coated high speed steel tools have titanium nitride (TiN), titanium carbide (TiC) or titanium carbo- nitride (TiCN) as the coating material. Both conventional and cobalt alloyed HSS tools are coated. In milling, a TiC coating is preferred at low speeds where the wear is mainly due to mechanical abrasion, whereas TiN is preferred at high speeds where thermal wear is dominant. TiCN is a balance between the two and is used at medium speeds where both thermal wear and mechanical abrasion are evident.

Care must be taken in the application of coatings to prevent spalling and peeling, and the deposition temperature must be low enough to prevent over-tempering of the HSS substrate or microcracking. Obtaining uniform coating thickness is difficult to achieve and therefore the process must be carefully monitored.

The coated cutting tools are more chemically inert and have better thermal stability than their uncoated counterparts. They also possess higher hardness at elevated temperatures than the uncoated tools. The toughness (hardness and ductility) of TiN coatings increases with increasing temperature in the cutting zone during machining. It has often been said that the TiN coating yields lower forces, this is due to the shorter contact length that results in a lower shear force in the secondary shear zone and consequently to a reduced thrust force. The lower shear force in the secondary shear zone leads to a higher shear plane angle and thus also reduces the cutting forces. A reduction in cutting forces means that less heat is generated in the cutting zone and consequently that the temperature dependent wear is reduced. It also results in improved surface finish of the workpiece due to a reduction in tool vibration. [10]

Coated HSS is used for the same applications as uncoated HSS and yields the advantage of a smooth wear resistant coating, longer tool life and increased cutting speeds and therefore a higher metal removal rate and better surface finish.

The specification and chemical compositions of uncoated and coated tools are usually identical. This is because coated cutting tools are basically standard cutters that have been surface coated. Therefore the only difference between the two types of tools is the coating.

3.5.6 Coated Cemented Carbides

Carbide inserts coated with wear-resistant compounds for increased performance and longer tool life represent the fastest growing segment of the cutting tool sector, with more than 60% of metal-cutting inserts currently sold having vapour deposited coatings. Coated carbides consist of a cemented carbide inner core with a coating of either TiC, TiCN, TiN or aluminium oxide (Al_2O_3) on the outside. If Al_2O_3 is used then an intermediate layer such as TiC is required to increase the adhesion strength.

As well as improvements in single layer coatings, there have also been advances in the applications of multi-layer coatings. These coatings provide good wear characteristics for machining both steels and irons. When combined with specially designed cobalt-enriched substrates, these coatings can also add a new dimension to tool life improvement, especially for interrupted cuts. In these applications the impact strength of the cobalt-enriched substrate works as a partner with wear resistant coatings.

The use of coated carbide inserts has permitted increases in machining rates that are considerably higher than those used for uncoated inserts. Many people consider the development of coated carbide tools to be the most significant development in cutting tool materials since the introduction of cemented carbides in the 1930's. [11]

Advantages of Coated Carbides

A general rule for most cutting tool materials is that toughness (impact resistance) decreases as the wear resistance increases. Conversely, as toughness increases, the wear resistance decreases. While it is impossible to alter the general shape of the curve depicting the relationship, it is possible to obtain a more favourable disposition of the curve. A thin layer of a hard, stable, high temperature material metallurgically bonded to the surface of a proper high-strength substrate improves wear resistance and provides longer tool life for the inserts.

The resistance, especially thermal wear resistance of coated carbides is remarkably better than uncoated carbides and the tool life is prolonged several times by coating. Coated carbides basically have both advantages, they have the wear resistance of ceramics and the strength of carbides. They also provide better abrasion resistance, crater resistance and edge build-up resistance, and they are used at higher cutting speeds than those used with uncoated tools. They give superior cutting performance in high speed and high feed rate. Ceramics on their own cannot withstand the conditions because of chipping and cemented carbides wear rapidly.

The increase in productivity capability is the most important advantage of using coated carbide inserts. With no loss of tool life they can be operated at higher cutting speeds; while longer tool life's can be obtained when tools are operated at the same speed. Coated inserts also provide greater versatility, as fewer grades are required to cover a broader range of machining applications, because the available grades generally overlap several of the classifications for uncoated grades. This simplifies the selection process and reduces inventory requirements. [10]

Limitations of Coated Carbides

Despite their obvious advantages, coated carbides are not suitable for all applications. For example, they are generally not suitable for light finishing cuts, including precision machining of thin-walled workpiece. They should also not be used in for machining workpieces containing surface sand or scale, inclusions or imperfections or workpiece with very poor surface finishes. Also, they are not as suitable as uncoated carbide inserts for machining some non-ferrous metals and non-metallic materials.

Coated carbides inserts are slightly higher in cost than their uncoated counterparts. However, a cost analysis should be carried out to determine whether the increased productivity or tool life benefits of coated tools, offset their cost premium.

Applications of Coated Carbides

The main factors influencing the cutting performance of coated carbides are the coating thickness, the coating material, the coating method and the substrate material. In milling, the best coating thickness is 2 micro metres because too thick a coating and micro-chipping occurs due to repeated shock on the cutting edge. The tool life of Al_2O_3 is shorter than those of TiC and TiN because micro-chipping is likely to occur in the Al_2O_3 layer since it is weak in both mechanical and thermal shocks.

A TiC coating gives longer tool life at low speeds were wear is mainly due to mechanical abrasion, Al_2O_3 coatings give longer tool life at high speeds were thermal wear is dominant as is shown in figure 3.5.6a.

Thermal wear resistance

<---------------------

Al_2O_3 - TiN - TiC - TiCN

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Abrasion wear resistance

<----------------------

Cutting speed

Figure 3.5.6a Wear resistance of Coatings [9]

The combination of coating and grade of carbide for the substrate must be properly selected to optimise the toughness vs. wear resistance relationship for various machining applications. The first coated carbides had substrates made from conventional steel cutting grades of tungsten carbide. Since then, new substrates tailored to the specific coating and application have been developed. Important requirements for the substrate material are maximum compressive strength, high toughness, good high-temperature strength, and resistance to both heat and thermal shock. Some wear and crater resistance, to supplement that of the coating is also desirable. Substrates used for coated inserts often do not require costly additives, such as tantalum carbides, which are almost always used in uncoated inserts for machining steel. [9]

3.5.7 Other Tool Materials

Another tool material that was considered was Cubic Boron Nitride (CBN). This contains cubic boron nitride (CBN) and a binder. The percentage of CBN depends on the application. A medium CBN content, approx. 70%, is used for cutting hardened carbon steels and die steel. A higher CBN content will generally result in an increase in the chipping resistance. As a result of my investigations it was found that CBN was very expensive and had poor regrindability. It is not extensively available in end mills and is mainly used for machining hard to machine materials in turning. At this moment in time CBN has a very limited application area. As a result of the investigation it was decided that CBN would not be researched. [42]

CHAPTER 4

MACHINABILITY ASSESSMENT

4.1 Introduction

The criteria for judging the ease of working of a metal vary from one machinability study to the next. Some machinability studies may only use one criteria for determining the machinability rating of materials, while others might use five or six different variables. The most frequently used criteria for judging the ease of cutting are as follows;

1. Life of the cutting tool between re-sharpening, expressed in various terms, tool life tests.
2. Magnitude of the tool forces, machining work or power consumption, cutting force tests.
3. Quality of the surface finish produced on the work, surface finish tests.

The three general criteria; tool life, cutting forces and surface finish relate in general terms to the cost of machining operations as carried out in the shop and can be given numerical values. It would seem logical then that these three quantities should have become the most commonly accepted measures of machinability for shop use. Historically however, tool life is usually the dominant criterion in determining the machinability and controlling the cost of the operation. The use of tool life tests can be supported by the fact that the life of the tool is one of the most important economic considerations in a machining operation and a comparison of alternatives (tools, work materials or cutting fluids) is justifiable on economic grounds. [43]

4.2 Wear on Cutting Tools

As with most things in life, cutting tools wear with use. This wear will ultimately lead to either the tool being reground or replaced entirely. This is because normal loads on the tool wear surfaces are high and also because the cutting chips and workpiece that apply these loads move rapidly over these surfaces. The loads on the tool wear surfaces produce friction between which increases the temperature and as a result increases the chemical and physical wear processes on the tool, thus further increasing the tool wear. These high forces and motions are necessary in order to remove unwanted material from the workpiece, hence they are part of the process and must be accepted. Therefore tool wear must be considered as an economic factor in the machining operation. The costs associated with tool wear can be minimized if the cutting process is planned and controlled, based on sound knowledge of the wear processes involved in the operation. [5]

Wear Surfaces

Figure 4.2a shows how a sharp tool may wear due to velocities and forces imposed on it by the cutting action. Along the rake surface, the motion of the chip and the high normal stress produce a wear scar known as crater wear. This can result in a poor surface finish being produced. While along the clearance surface, the tool motion and high normal stress have increased the area of contact between the tool and work, producing flank wear. This results in a decrease in the diameter of the end mill. Flank wear is the easiest of the two to measure and is thus used as a parameter of tool life. The location and size of these wear surfaces play an important role in determining the useful life of a cutting tool. [10]

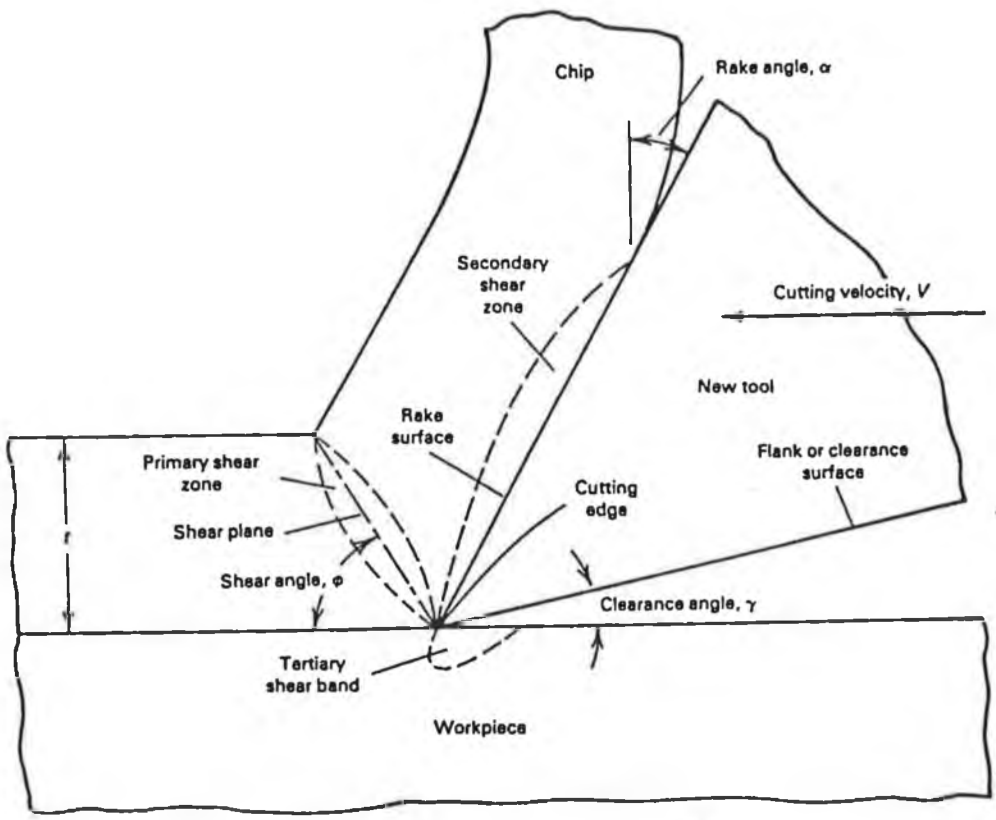

Figure 4.2a, Typical wear surfaces [10]

The combination of both the flank and crater wear leads to a deterioration of the surface finish and could produce out-of-tolerance dimensions on machined parts. It also leads to a decrease in the angle between the rake surface and the clearance surface. This geometric change results in a weakened cutting edge and may cause sudden edge fracture.

Figure 4.2b shows how the wear processes change the geometry of an end milling tool.

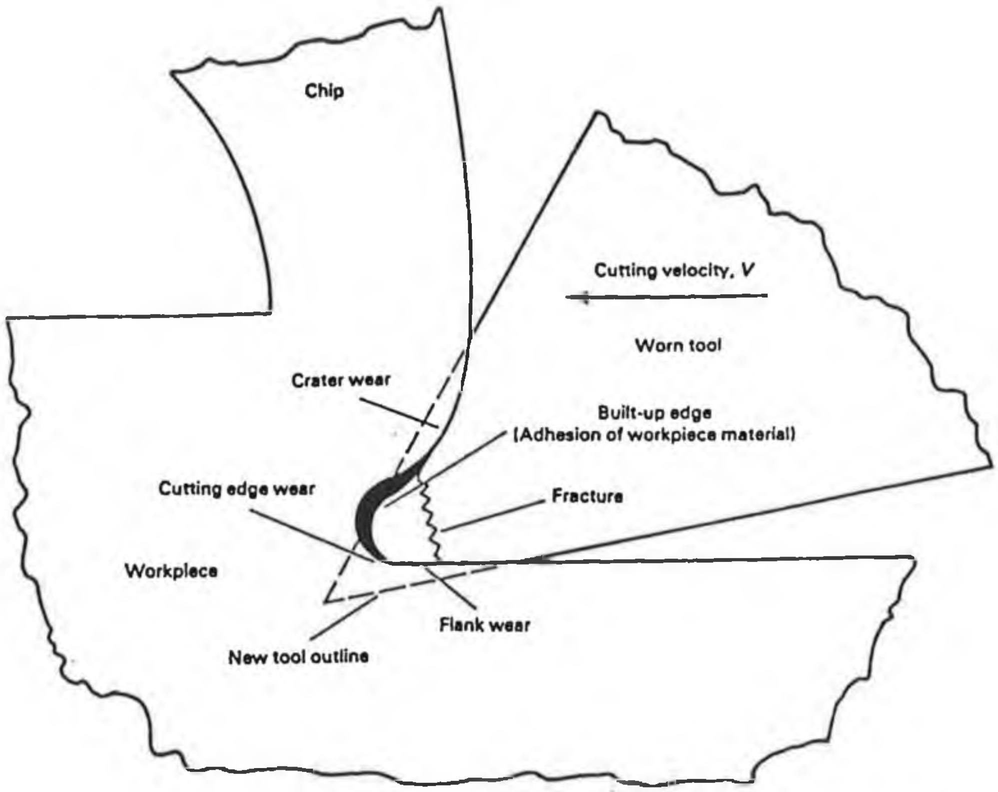

Figure 4.1b, Flank and crater wear on an end mill. [10]

Figure 4.2c shows the approximate distribution of the stresses present on tool wear surfaces. The normal stresses, σn, are caused by the normal forces acting along the rake surface, the cutting edge and the clearance surface. In addition to the normal stresses, there are also shear stresses acting on the tool. Shear stresses, τ, act along the surface of the tool and are associated with the sticking and sliding shear processes. In the sticking zone the chip tends to adhere to the workpiece and periodically separate along shear fracture planes within the metal, leaving adhered material on the tool or within the tool, which subsequently causes tool wear. The presence and size of this sticking zone is dependent on the magnitude of the normal force and the frictional conditions along these surfaces. Sizable amounts of material can build up over a period of time, this material is known as built-up edge and can significantly alter the geometry of the cutting tool. The sliding zones have friction forces and associated surface shear stresses that vary according to the normal force and the coefficient of friction. Both the surface roughness of the cutting tool and the lubrication conditions present, affect the magnitude of these surface shear stresses. [10]

Normal stresses can become very high and exceed the strength of the tool causing fracture of the cutting edge. The magnitude of the stress in the cutting region varies with time and the associated variations in the load, may create a fatigue failure environment for the tool.

σ_n = normal stress

τ = shear stress

τy = material yield stress

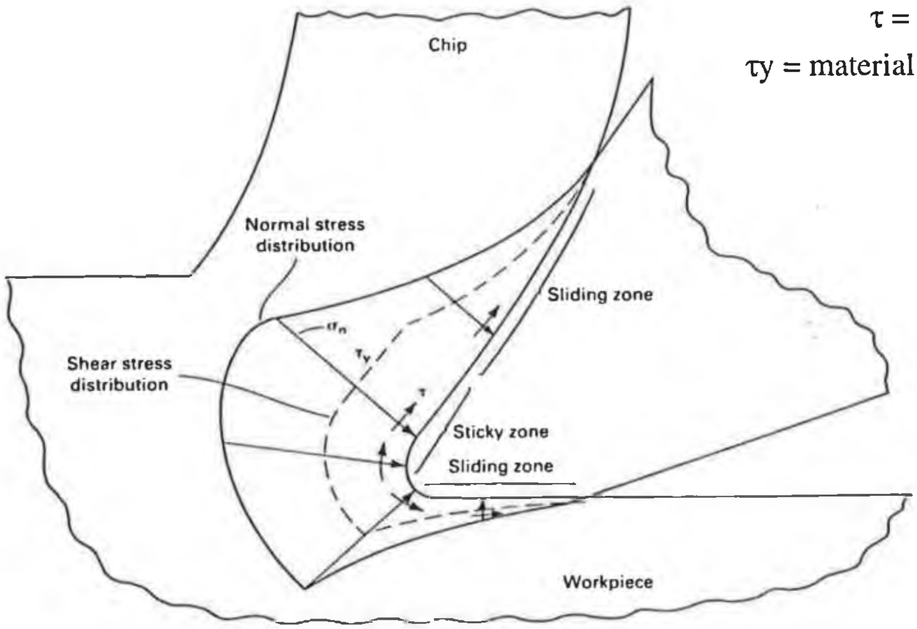

Figure 4.2c, Typical wear surfaces [10]

Cutting Temperatures

The term "cutting temperature" as used in this discussion refers to the temperature at the tool/chip interface. The temperatures produced during cutting are dependent on the cutting velocity (the relative velocity between the clearance surface and the work), the chip velocity (which is the relative velocity between the chip and the rake surface of the tool) and the shear stresses on the wear surfaces. The magnitude of these two velocities and the shear stresses at the interfaces determines the amount of thermal energy released per unit of contact area. This is the magnitude of the amount of thermal energy released. The difference between the thermal-energy release rate and the thermal energy dissipation rate determines the temperature of the material and the tool in the wear zones. Thermal energy dissipation is a function of the thermal conductivity properties of the tool and workpiece materials. Additionally, workpiece size and specific heat determine workpiece heat capacity; to a lesser extent, surface area plays a role in convective and radiative heat transfer to the surrounding air. Most of the mechanical energy expanded in metalcutting in transformed into thermal energy. About 75% of this heat is carried away from the tool/chip interface by the chip; the remainder is divided between the workpiece and the tool. [11]

The tool/chip interface temperature is not uniformly distributed along the path of chip contact with the tool face. The peak temperature, with a sharp cutting tool, is located a short distance from the cutting edge. The crater formation which is initiated at the point highest temperature, is due to the non-uniform temperature distribution. The rate of crater formation depends upon the interface temperature as an exponential function. [10]

An increase in the cutting speed or feed rate results in an a significant increase in the overall cutting temperature and the temperature in the cutting zone. While an increase in the depth of cut results in a significant increase in the overall cutting temperature produced, it only results in a negligible increase in the temperature of the cutting zone (tool/workpiece interface). This can be attributed to the fact that the size of chip produced increases and therefore the proportion of the overall temperature transmitted to the chip and the workpiece increases. The net effect is that the rise in the cutting zone temperature with increasing depth of cut is small when compared to both cutting speed and feed rate. [44]

Wear Types

In general, the wear that occurs on a cutting tool may be classified into several different types as follows;

I) Adhesive wear,

II) Abrasive wear,

III) Diffusion wear,

IV) Corrosive wear,

Depending on the operation, work material, tool material and specific cutting conditions; the overall wear of the tool can be predominantly one type of wear or it might be a combination of a few different types. In the end milling process, the most dominant types of wear are diffusion and abrasion, with negligible amounts of either adhesive wear or corrosive wear.

I) Adhesive wear,

Adhesive wear occurs when direct contact is made between the workpiece and cutting tool surface's. The mating surfaces then form strong bonds, if these bonds are stronger than the local strength of the material, a particle may transfer from one surface to the other. After this has occurred several times a loose fragment may be formed and leave the system as a wear particle. If the particles removed are very small (sub-microscopic) then the process is known as attritious wear. While if the particles are visible under a microscope, the process is known as galling. Adhesive wear is affected by the environment in the cutting zone, with adhesive wear becoming more severe as oxygen content decreases, because a protective oxide layer is unable to form. Metallurgical factors decrease the adhesive wear of cutting tools at temperature (hot hardness).

An extreme case of adhesive wear, sometimes called continuous wear, occurs in high speed steel cutting tools used in demanding metal cutting applications. Tool temperatures in the crater can approach 700 °C and direct contact with the chip causes alloying elements (usually carbon and chromium) to diffuse out of the tool steel and into the chip. Adhesive wear of this kind is known as seizure. The solutions to this problem are to reduce the cutting speed, coat the tool with a hard ceramic material, or improve the lubrication and cooling. [1]

II) Abrasive wear,

Abrasive wear is experienced whenever a hard phase is rubbed against the cutting tool. The hard phase can be inclusions or impurities embedded in a softer phase, such oxide inclusions are found in steel or aluminium, or it can be in a liquid carrier such as the contaminants in coolants or lubricants. The amount of abrasion present is dependent on the hardness of the cutting tool material. The abrasion of a cutting tool material results in the addition of hard particles to the wear debris, thus causing more abrasion. We should expect the performance of these abrasive particles giving rise to abrasive wear to resemble that of abrasive grains in a grinding wheel. Part of the action in each case will cause metal removal and part will be associated with rubbing and friction causing further abrasion. [1]

III) Diffusion wear,

Diffusion wear occurs when the atoms of a metallic crystal lattice move from an area of high atomic concentration to an area of low concentration. This process is dependent on the temperature at the interface between the tool and the chip, and at the interface between the tool and the workpiece. It also depends on the atomic bonding affinity of the tool and workpiece materials, and the chemical solubility of the tool material. Transport by diffusion depends on the concentration gradient of the diffusing species. Secondary shear flow on the tool face plays an important role relative to all aspects of diffusion transports.

Diffusion wear is often accompanied by the decomposition of a component of one of the sliding surfaces. For example, in cutting a ferrous alloy with a tungsten carbide tool at high cutting speed (high temperature), there is a transformation from α-iron to γ-iron on the surface of the chip. The γ-iron has a strong affinity for carbon, the tungsten carbide crystals in the surface of the tool decompose and the carbon that is released diffuses into the surface of the chip. The increased carbon concentration strengthens the surface of the chip which in turn increases the wear rate.

Research on this type of tool wear is very difficult to carry out since it is not possible to duplicate all conditions except by use of a cutting test and this will involve other types of wear in addition to diffusion wear. While non-cutting tests; which involve placing different work materials next to the tool material at constant temperature for long periods of time, are non-realistic as they involve conditions far different from those present during cutting. They differ from actual cutting, in that there are no freshly generated surfaces, no high local deformation strains, there is an absence of realistic temperature and concentration gradients, and they involve temperatures that are too low and times that are too long. [1]

IV) Corrosive wear,

Corrosive wear is not usually a major cause of excessive wear, but it can become the most important wear mechanism for steels at high temperatures or during plastics processing. Wear proceeds by the corrosion of the fresh, exposed steel tool, followed by rupture of the corrosion film by the workpiece and corrosion of the newly exposed surface. This form of wear can normally be controlled by proper lubrication, higher chromium content of the cutting tool or by coating the tool. [1]

Wear Mechanisms

Studies have shown that a particular wear mechanism depends on the contact stress, temperature, the physical and chemical properties of the contacting materials, and relative velocities at the wear interface. For a particular set of contacting materials, wear mechanism maps have been used to identify the ranges of normal pressure and velocity that result in a particular wear mechanism. From figure 4.2d it can be seen that there are 4 main classes of mechanism; Seizure, Melt wear, Oxidation/diffusion-dominated wear and Plastically-dominated wear. Temperature is not a mapped variable, however it does have an effect on the pressure (normal stress), velocity and size of wear surface, as was mentioned earlier. The dashed lines in the figure mark possible boundaries that could be used to define a safe operating zone. [10]

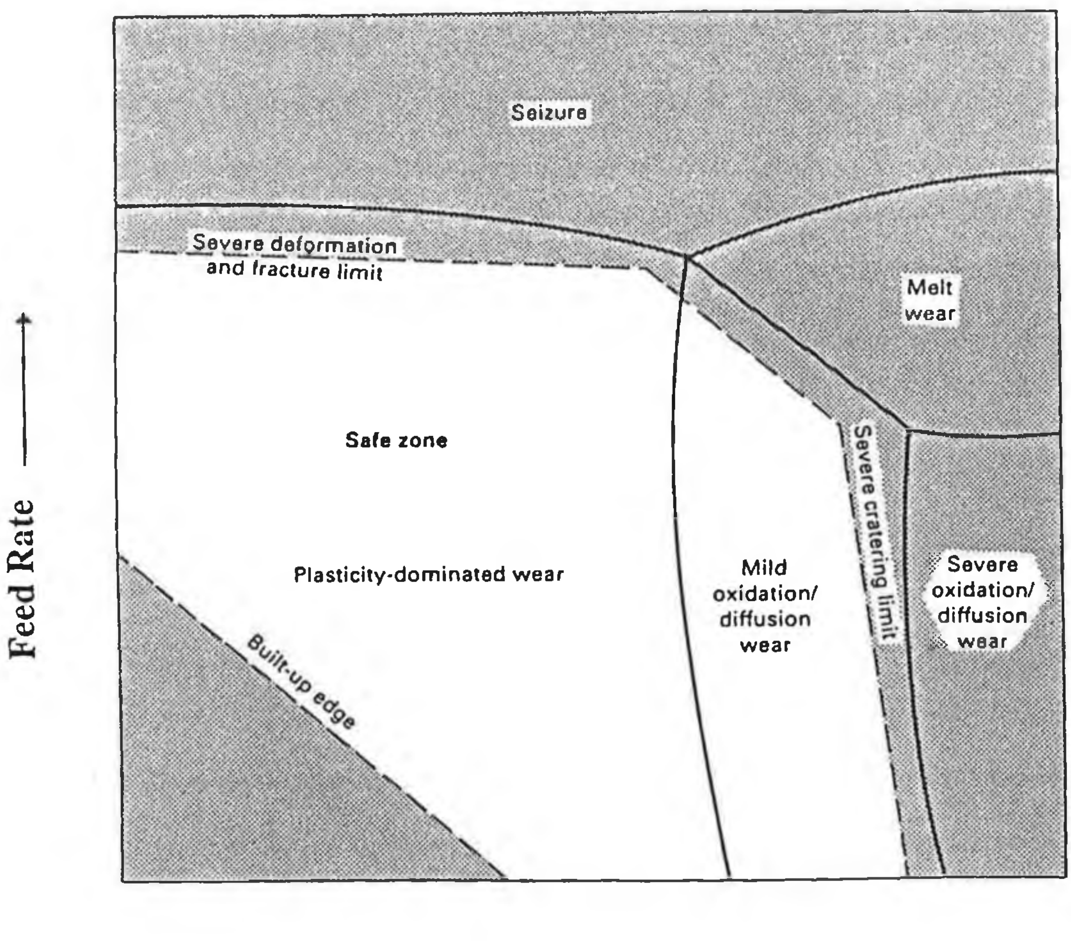

Figure 4.2d, Wear mechanism maps and safe operating regions for cutting tools. [10]

1) Initial Wear Mechanisms

In this period the wear rate is decreasing with machining time. The two materials in contact have surface roughness irregularities in the form of protrusions or asperities. At the interface, asperities from the two materials touch, defining tiny contact areas. The total area of these contact points is a fraction of the projected area of the contact surface. In these areas the stresses and heat are intensified and this results in the partial removal of the asperities due to seizure accompanied by asperity fracture or melting. As these asperities are removed, the initial surface roughness is altered and the contact area increases. If the force conditions remain unchanged, pressure decreases and active wear mechanisms change due to plasticity and/or mild diffusion wear. This initial wear period creates short visible wear surfaces. [10]

2) Steady-State Wear Mechanisms

In this period the wear rate is constant with machining time. Conditions of velocity and normal stress that continued to cause seizure and melting would soon cause complete failure and must be avoided. Assuming that such conditions do not exist, the wear surfaces will become progressively larger. If the wear mechanism is plastically dominated, small particles of material mechanically deform and fracture away from the wear surface. This is known as abrasion wear and can occur on any wear surface. It is the most common wear process along the clearance or flank surface of most cutting tools. As was stated earlier, normal stress and temperature may vary over the wear surfaces so that a wear mechanism that dominates in one area may not dominate in another. Again, as was discussed earlier, the maximum tool surface temperature occurs a short distance from the cutting edge on the rake surface of the tool. Due to the very high temperatures, wear in this area is dominated by the diffusion wear process and is called crater wear. The high temperature and pressure in the region cause atoms to move from the tool to the workpiece or chip with the wear taking the shape of a crater, hence the name crater wear. In hard cutting tool materials, such as ceramics or carbides, which commonly experience high cutting velocities, diffusion wear processes may be responsible for much of the wear.

The built-up edge (BUE) condition shown in figure 4.2d, affects the wear process in two ways. Near the cutting edge, the higher pressures may cause particles of work material to adhere to the cutting tool in the sticky zone (which is shown in figure 4.2c). If the shear forces due to chip movement are high enough, the bond will be temporary and the adhered material will fracture away from the tool surface. When the built-up edge fractures, small particles of tool material may be removed with it. This is then a wear process associated with conditions in the safe zone just outside the BUE line. The second effect occurs when the BUE is not fractured away by the chip motion, but instead remains to alter the geometry of the cutting edge. The presence of the BUE changes the shear angle, causing instabilities in the chip-forming process as well as damage to the machined surface. The damage to the machined surface is due to the presence of a dull cutting edge which causes a poor surface finish to be produced by the cutting tool. The lubricating characteristics of cutting fluids are helpful in eliminating the BUE condition. However, the presence of a BUE is not always detrimental, as for rough cuts the presence of a stable BUE can be beneficial by providing an intermediate layer between the tool surface and the workpiece.

Wear can also occur as chipping along the cutting edge. Such chipping more commonly occurs when the cutting edge intermittently removes material as is the case for milling. This results in cyclic impact and thermal loading of the cutting edge which can result in the initiation of small cracks and than cause these cracks to propagate, leading to tool chipping.

The abrasion, diffusion, adhesion and chipping wear processes that occur at operating conditions within the safe zone shown in figure 4.1d cause the initial wear surfaces to gradually wear. This surface life period is known as the steady-state wear period and is the most important wear period as it ultimately leads to the tertiary wear period and tool failure. Control of this wear period results in extended tool life.

3) Tertiary Wear Period

The period of steady-state wear eventually enlarges the wear surface to a critical size that triggers the tertiary or accelerated wear period. The pressures and velocities on these enlarged surfaces begin increasing the temperature so that diffusion and local seizure or melting conditions cause rapid destruction of the tool. In the tools that have a hard, wear-resistant coating such as titanium carbide, wear through this coating exposes the less resistant core material, resulting in accelerated wear. This accelerated wear damages the surface of the workpiece and may necessitate repairing or scrapping of the part. Therefore it is imperative that a tool change is made before the wear reaches the tertiary wear period.

4.3 Tool Life Testing

One of the problems associated with machinability testing is the variability in results from seemingly minor test conditions. The logical answer to this problem is to standardise test conditions. A number of groups have worked to develop a standard test procedure which could be used for machinability testing and in particular tool life testing. However, it is the International Standards Organisation (ISO) who developed standards which are now widely accepted as the international testing method. In 1977, the ISO issued a standard method for tool life testing with the ISO Standard 3685-1977, "Tool-Life Testing with Single-Point Turning Tools". Then in 1989, they issued ISO Standard 8688-1989, "Tool-Life Testing in Milling", which has two parts; part 1 - face milling and part 2 - end milling. [18]

The standard covers many aspects of milling including;

1) Scope and field of application

The ISO standard specifies three types of end milling tests suitable for use as, slot milling (where the tool is totally immersed in the workpiece), face milling in which the tool periphery is predominantly used and end milling in which the end teeth of the tool are predominantly use.

The standard considers only conditions concerned with testing that result predominantly in tool wear.

2) Workpiece Material

The ISO standard states, that in principle testing bodies are free to select work materials according to their own interests. However, in order to increase the comparability of results between testing bodies, the use of one of the reference materials is recommended. Information concerning the work material such as grade, chemical composition, physical properties, microstructure and any heat treatment carried out must be reported. The hardness of the workpiece shall be determined on one end of each test piece, over the cross-section of the piece. The deviation in hardness within one batch should be as small as possible. A realistic value for the deviation is ± 5%.

3) Cutting Tool

As is the case for work material, testing bodies are free to select the tool material according to their own interests. However in order to increase the comparability of results between testing bodies, the use of a reference tool material and tool specification is recommended. In tests were the tool geometry is not a test variable it is recommended that the specifications laid down by ISO be used. While in tests were the tool geometry is a test variable, all the tools shall be manufactured together in the same batch of steel from the same charge (heat) and using the same heat treatment.

In order to avoid regrinding problems it is recommended to use only new cutting tools for the tests. However, if the effects of regrinding are being investigated, the diameter of the tool should not be reduced below 90% of the original tool diameter, and for such tests the actual diameter should be reported in the test report.

4) Cutting Conditions

In cases where the cutting speed, feed rate and axial depth of cut are the test variables, all data shall be clearly specified. It should be noted that the cutting conditions shall be chosen to be compatible with the cutting tool, the machine tool and the clamping device, in order to obtain reliable test data. The cutting condition data for the particular work material should be referenced from the Machining Data Handbook. Although these values are mainly used as a guideline or starting point for the cutting tests, it is recommended that they are not deviated by a considerable amount.

5) Tool Wear

In practical workshop situations, the time at which a tool ceases to produce workpieces of the desired size or surface quality usually determines the end of useful tool life. The period up to the instant when the tool is incapable of further cutting may also be considered as the useful tool life. However, the reasons for which tools may be considered to have reached the end of their useful tool life will be different in each case depending on the cutting conditions, etc. In order to increase reliability and comparability of test results, ISO have defined the total cutting time of the tool as a specified value of tool-life criterion. They have defined the types of tool deterioration which occur during machining and have specified values for each type of deterioration, that determine the end of useful tool life. Each type of deterioration will progress or occur in a variety of ways depending on the cutting conditions. Where more than one form of deterioration becomes measurable, each should be recorded and when any one of the deterioration phenomena limits have been attained, the end of tool life has been reached.

As was just mentioned, their are several types of tool deterioration which can occur in machining, depending on the cutting conditions. However, in milling it is the wear on the flank of the tool which is normally specified as the limiting criterion for tool life. For end milling the following end points are recommended:

- Uniform wear: 0.3mm averaged over all teeth on the tool.
- Localized wear: 0.5mm maximum wear on any tooth on the tool.

Flank wear measurement is carried out parallel to the surface of the wear land and in a direction perpendicular to the original cutting edge, e.g. the distance from the original cutting edge to that limit of the wear which intersects the original flank.

In cases where none of the recommended criteria apply, it may be possible to obtain meaningful data by using one of the following criteria.

- A certain depth of the face wear is sometimes used as a criterion.
- Chipping (CH) is a criterion which may be used.
- When chipping occurs it is treated as localized wear using a VB3 value equal to 0.5mm as a tool end point.
- Chipping (CH) in a very heavy form and flaking (FL) are forms which are exceptionally used as criteria.
- However, catastrophic failure (CF) which can occur inadvertently should not be used as a primary criterion for the tool life end point.

When there is evidence of built-up edge (BUE), or other debris material on the surface of the cutting tool, such observations should be reported since accurate measurement of the wear may be impeded by such deposits. Although mechanical devices for the removal of deposits are not recommended, it is permitted to remove BUE by using a soft material such as a 'thumb nail', piece of plastic or wood, with a minimal risk of damaging the cutting tool.

6) Procedure

The procedure generally adopted in tool life tests is to compile flank wear versus time curves. This is done by measuring the teeth on the tool under a toolmakers microscope, at regular time intervals until the average flank wear on the tool is 0.3mm or the wear on any tooth exceeds 0.5mm, as recommended by ISO 8688-2. Figure 4.2b shows a typical graph of flank wear against machining time. It can be seen that there are 3 distinct stages to the wear curve. These are initial wear, steady-state wear and tertiary wear mechanisms discussed in section 4.1.

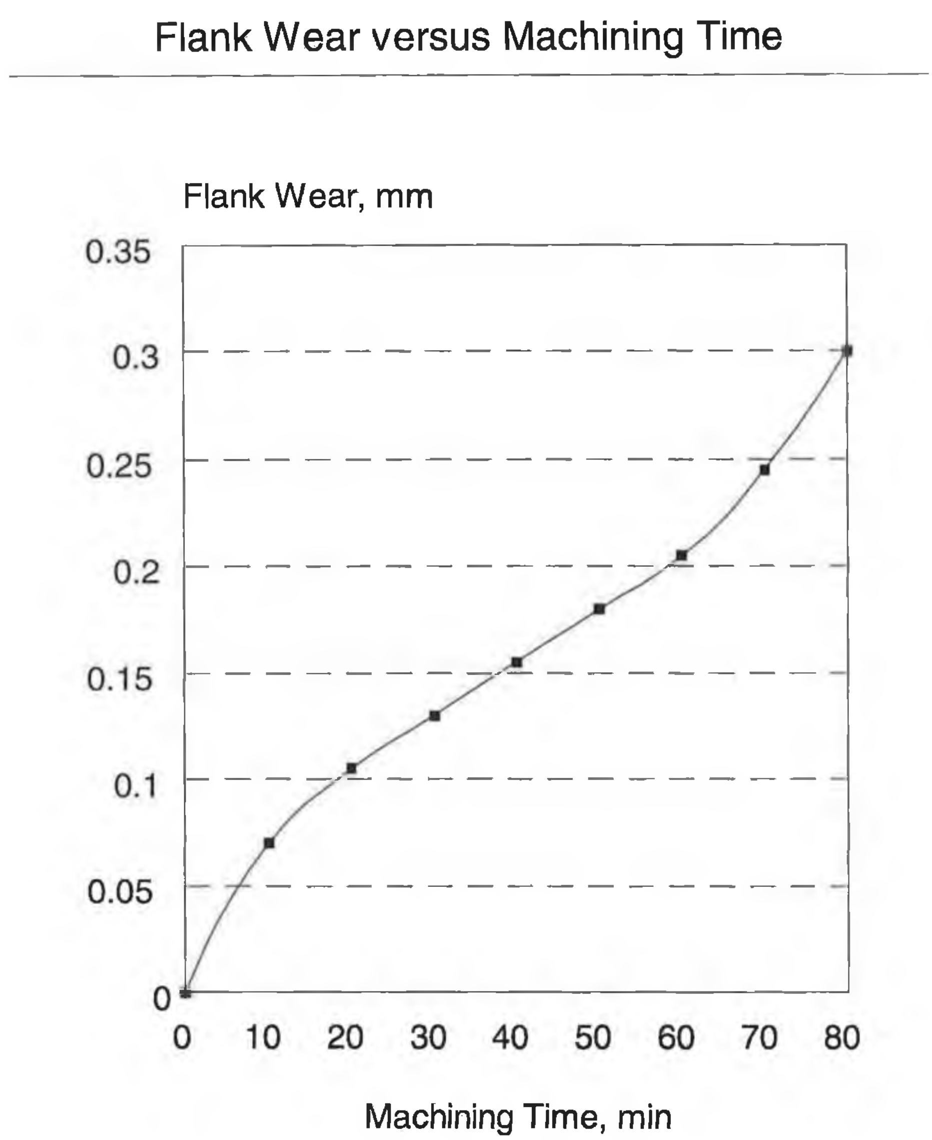

Figure 4.3a, A typical tool wear curve [18]

4.4 Cutting Forces

Another method of determining the machinability characteristics of a given work material is to carry out cutting force tests. A knowledge of these forces is useful for a variety of reasons. For example, knowledge of the power requirements and the forces acting on a cutting tool is desirable in both the design and selection of machine tools. In the general case, the force system acting on a cutting tool is three dimensional, with the resultant force on the tool being made up of three components (with one component coming from each axis). However, it must be noted that the magnitude of the forces in metalcutting is small when compared to those encountered in metal-forming processes such as extrusion, wire drawing or forging. This is due to the small area being cut at any one instant; the forces measured are normally in the magnitude of a few hundred Newton's. [10]

Cutting Force Measurement

Cutting force measurements are measured by using an instrument known as a dynamometer. These instruments have evolved in such a way that they are capable of measuring forces at the cutting tool with great precision and accuracy. The desirable characteristics of a metalcutting dynamometer include rigidity, sensitivity, lack of cross sensitivity and hysteresis.

Rigidity and sensitivity are the two primary requisites of a cutting tool dynamometer. The dynamometer must be rigid to prevent any significant tool deflections affecting the normal cutting operation, yet it must be flexible or sensitive enough to measure force variations with time. To assure the complete transmittibility of the cutting force, the natural frequency of the dynamometer should be at least 4 to 5 times higher than the maximum exciting frequency to which the cutting tool may be subjected. Cross sensitivity occurs when occurs when the application of a force in one direction causes the dynamometer to record readings of apparent force in other perpendicular directions. If this mutual interference of the force-measuring elements occurs, a set of simultaneous equations must be solved to determine the force components and to prevent unnecessary complication of the data. Therefore considerable care must be taken in the design of the dynamometer to prevent cross sensitivity from occurring. A cutting force dynamometer should also have linear calibration characteristics and not exhibit hysteresis. Hystersis is an effect that is characterized in

In the range up to 3.2 μm R_a, the machining cost increases with the fourth root of the finish according to:

$$MC = \frac{157.4}{\sqrt[4]{AA}} \quad (\%) \qquad (4.1)$$

For cast, sawed and rough-turned surfaces and for rougher half of semi-finished surfaces. While for finished, ground, and honed surfaces, the machining cost increases inversely with the smoothness of the finish, as shown by:

$$MC = \frac{6700 \ (\%)}{AA} \qquad (4.2)$$

Although figure 4.5b is labeled for turning operations, a similar pattern applies to milling operations.

It is obvious that the lowest cost is achieved when an as-received surface of a bar, casting, forging or stamped part is used. As operations are added the machining cost increases. Therefore the product designer is responsible for accurately assessing the functional requirements of the surface and specifying the least costly surface that will function properly. While manufacturing engineers are responsible for efficiently planning the tooling and processing that will yield the required surface finish at the lowest manufacturing cost.

4.5.1 Machining Parameters affecting Surface Finish

Surface finish is affected by many variables in the cutting process, including the machine tool, cutting tool, cutting conditions, cutting fluid and the workpiece itself.

Machine Tool Considerations

Each machine tool process has an inherent ability to produce surface texture. With milling usually producing surfaces in the range of (3.17-12.7 μm) R_a. When specialized techniques are used, this roughness can be reduced to 1.01 μm R_a or less. The machine tool factors which have an influence on the surface finishes produced are as follows; [10]

I) Machine tool rigidity

The effect of machine tool rigidity on surface finish is particularly apparent on the waviness of the surface produced. The machine tool must rigidly support the workpiece and cutting tool in relation to each other and it must be designed, built, and maintained to minimize tendencies to vibrate and telegraph vibrations from the driving elements and adjacent machines into the workpiece and cutting tool. It must also have sufficient power and rigidity to effectively handle the cutting forces which are present in machining operations. Design of the machine tool need not necessarily be massive, although a heavy mass is usually beneficial. Dynamic and static forces acting within the system must be understood and properly considered. Vibration damping capacity and elastic properties of structural materials and designs are also important.

II) Machine tool drives

The machine tool drive must be sufficient to maintain set cutting speed and feed rate; otherwise waviness may be introduced into the surface texture. Except for special machine tools designed, built and used to perform a single operation on a single workpiece with one tool material, machine tool drive and control systems need to effectively provide for operation over a range of cutting conditions. This is usually considered to be a requirement for optimum productivity, but it is also important in relation to surface finish. The softer the workpiece material, the higher the cutting speed required to minimize development of a built-up edge on the cutting tool. This is particularly true of carbide tools when relatively soft, continuous-chip materials are machined.

III) Installation

Proper installation of machine tools is required to minimize problems in producing consistent surface finish. Vibration from other sources may be transmitted from the surface on which the machine is mounted, or the mounting surface may act as a sounding board to receive, reinforce and return to the machine tool its own vibrations. These vibrations often appear as chatter in the surface texture. The machine tool also requires solid support to avoid shifting the tool relative to the workpiece during cutting. Such shifting may result in dimensional variation and waviness.

IV) Maintenance

A machine tool in good condition may produce satisfactory surface finish today, but after having being used for a period of time may yield less than satisfactory results. New machines and rebuilt machines usually wear-in as bearing surfaces settle. Relatively minor maintenance is usually required to restore satisfactory results when timely corrective action is taken. Usually, a good preventative maintenance program extends total satisfactory life of the machine tool, while at the same time maintaining a good level of surface finish. Proper preventative maintenance programs include maintaining proper adjustment of bearings, slides and shaft supports. Looseness in these elements may appear as chatter or waviness in the workpiece.

Lubrication is an essential element in proper maintenance. Machine tools are recognized to consist of an engineered group of elements which act together with a film of lubricating material that separates working surfaces. Whenever this film is removed, erratic movement occurs. This erratic movement may adversely affect surface finish.

Workpiece Considerations

Workpiece material composition, metallurgical structure, physical properties (whether the material is cast or cold worked), inclusions in the material, and workpiece design all affect surface texture. It is usually not practical to select, for any given part, workpiece material that inherently yields the desired surface texture. Workpiece material is selected based on a wide variety of considerations which may affect part performance. Very low-priced raw material may cost an inordinate amount to process.

Maintaining consistent surface texture requires that the workpiece material be as consistent as practical in composition, metallurgical structure, and physical properties. Variations in these factors may require changes in tooling in order to produce parts of consistent quality (including both surface texture and dimensional tolerance). In the case of steel, carbon content is one of the most important considerations. When carbon content is less than 0.10%, the material machined is prone to rapid development of built-up edges on the cutting tool. This usually results in the production of a rough surface finish on the workpiece. When such steel does develop BUE, the problem can be handled by increasing the rake and relief angles and/or increasing the cutting speed.

The main workpiece factors which affect the surface finish produced during machining are as follows; [10]

I) Workpiece hardness

Very low hardness and high ductility also require the use of increased rake and relief angles and increases in cutting speed. The machine tool used and the design of the part may be of such a nature that sufficient speed cannot be applied to eliminate the production of a built-up edge. In this case, increasing the hardness of the workpiece may provide a situation in which the surface finish becomes satisfactory.

Inclusions in the workpiece may help or hinder the production of desirable surface texture. Usually, inclusions that serve as aids to chip formation are helpful. Inclusions that are abrasive promote rapid wear on the tool which is reflected in deterioration of surface texture.

II) Metallurgical consistency

As was mentioned earlier, consistency in metallurgical structure and physical properties of the workpiece material are important. For instance, the effect of material inconsistency is apparent when the end of a relatively large diameter of bar stock is faced. Near the centre of the bar the surface finish is often much rougher than it is near the outside diameter. This difference in finish is caused by a number of factors. It is common to find that, as the centre of the tool is approached by the tool, the work material becomes softer. To produce the same or similar surface finish on the workpiece, relief or rake angles on the tool should be increased (which is quite impractical) or cutting speed should be increased (which is practical). Sufficient speed increase is often required to compensate for the reduction in the hardness. However, it must be noted that there is reasonable limit to which the speed may be increased.

III) Workpiece design

The various elements of the cutting tool (nose radius, rake angles, cutting edge angles and relief angles) have considerable impact on surface finish. However helpful changes in tool geometry may be, workpiece design may not permit taking advantage of such changes. Parts should be designed to permit as large as possible female corner radii if smooth surface finish is required. The workpiece must be stiff enough to resist deflection due to the use of relatively large nose radii and/or reduced end cutting edge angles which produce smoother surface finish. Thin, large diameter flanges and shafts with large length-to-diameter ratios are particularly difficult to machine with cutting tools designed to produce smooth surface texture. This is because these tools usually impose high radial pressures.

Cutting Tool Material

Cutting tool materials play an important role in surface finish. The following cutting tool materials are discussed in this section; [10]

I) High speed steel

Various types of high speed steel tool materials yield very similar surface finish. With HSS tools it is normal to increase rake angles to obtain high shear angles in the chip. These materials have relatively high edge strength to resist chipping when rake angles are increased, but they do not have the ability to successfully resist softening due to cutting temperatures generated when cutting speed is increased to the values needed to reduce the chip shear angle. Coated HSS tools produce a better surface finish than uncoated tools under the same cutting conditions. This can be attributed to the lack of a built-up edge on the surface of a coated tool and also due to the lower cutting forces that are obtained with coated tools. The reduction in cutting forces reduces the amount of tool vibration (chatter), which results in improved surface finish.

II) Cemented carbide

Carbide tool materials, and in particular titanium carbide, have lower edge strength than HSS but they have excellent temperature resistance. Therefore, cutting speed can be increased to the point that the chip shear angle and built-up edge are reduced and surface texture is improved. The composition of carbide tools can affect the surface texture produced with significant changes apparent when machining steel. It is not necessarily true that measured surface roughness will differ greatly, but appearance of surface texture varies with changes in carbide tool composition. As was the case for HSS cutting tools, coated cemented carbide tools produce a better surface finish than their uncoated counterparts. Again the coated tool produces less tool vibration due to the lower cutting forces and also their is less built-up edge on the coated tool.

Cutting Tool Geometry

The geometry of the cutting tool has a significant affect on the surface finish produced during machining and in particular, the shear angle, relief angle and nose radius have the greatest effect on the machining surface.

I) Shear angle

The shear angle in metalcutting operations should be as large as is practically possible. Increasing shear angle reduces the cut chip thickness as compared to the uncut chip thickness, reduces cutting forces and helps reduce the formation of built-up edge on the cutting tool. The shear angle may be increased by changing the tool geometry, increasing the cutting speed or, increasing the lubricity of the cutting fluid. Changing the shear angle is best accomplished through changing of a combination of elements since each element has limiting considerations. For example, tool geometry is usually changed to increase the shear angle by increasing the rake angle. However increasing the rake angle has the negative effect of reducing the strength of the cutting edge and also reduces the ability of the cutting edge to conduct heat away from the cutting area. Increasing the cutting speed also increases the shear angle; however this also has the effect of increasing the cutting temperature which causes a reduction in the tool life of the cutter. Increasing the lubricity of the cutting fluid reduces the fluid's cooling capacity.

II) Relief angle

Relief angles are important in producing desirable surface finish on the tool. Relief must be sufficient to assure that the workpiece does not rub against the relief surfaces of the tool. Many times however, too little allowance is made for elasticity in the piece or loss in relief due to advance of the cutting tool into the work. Relief must be sufficient to permit debris (breaking off of particles from the built-up edge) to be freed as quickly as possible in their passage over the tool edge and past the finished workpiece surface.

III) Nose radius

The selection of nose radius is critical to the surface finish of the component. A large nose radius is generally chosen for rough machining whereas the smallest possible radius is selected for finish machining. A large nose radius is also recommended for machining of brittle materials which produce discontinuous chips.

CHAPTER FIVE

EXPERIMENTAL SET-UP

5.1 Introduction

In this chapter the experimental facilities and procedures that were used in assessing the machinability have been discussed. The details of the machines/equipment, cutting tools and work material have been described. The experimental procedures that were used during the tests have also been described in this section.

5.2 Cutting Tools

Two different types of cutting tool were used for the tests, they were high speed steel (HSS) and cemented carbide. Both the HSS and the cemented carbide tools were used for the tool life and surface finish tests, but only HSS tools were used in the cutting force tests. Both uncoated and coated tools of HSS and cemented carbides were used.

Table 5.2a. Cutting Tools used for Machinability Tests

Cutting Tool	Cutting Force	Surface Finish	Tool Life
Uncoated HSS	1	2	2
Coated HSS	-	3	3
Carbide	-	2	2
Coated carbide	-	2	2

The numbers in the table indicate the number of different manufacturers that were used for each test, for example, tools from three different manufacturers were used for the tool life tests using HSS cutters.

(a) High Speed Steel

The uncoated high speed steel cutting tools that were used where Clarkson and Strassmann. In order to try and avoid variations in machining due to differences cutting tools, tools with similar specifications were chosen. However, due to manufacturer preferences, some variations between the cutting tools is present. The specifications of these tools are shown below

The coated high speed steel cutting tools that were used where Clarkson. Strassmann and Kestag. Coated tools are basically uncoated tools which have been coated following manufacture. Therefore the only differences in the specifications of these tools is the coating material.

Table 5.2b. Specifications of HSS cutting tools [46-48]

Tool Manufacturer	Shank type	Cutter Diameter	No. of teeth	Cobalt content	Tool Coating
Clarkson	Weldon	25 mm	5	8 %	Uncoated
Strassmann	Weldon	25 mm	5	5 %	Uncoated
Clarkson	Weldon	25 mm	5	8 %	TiN
Kestag	Weldon	25 mm	5	8 %	TiCN
Strassmann	Weldon	25 mm	5	5 %	TiN

(b) Cemented Carbide

The uncoated cemented carbide tool that were used where Sandvik and Iscar. They both had Weldon shanks, were 25mm in diameter and an insert thickness of around 2.4 mm. The coated cemented carbide tool that were used had the same geometry and dimensions as the uncoated inserts, however they were different ISO grades. The specifications of these tools is shown below.

Table 5.2c. Specifications of Cemented Carbide cutting tools [49-50]

Tool Manufacturer	Insert Grade	No. of Inserts	Insert Length	Nose Radius	Cutting Edges	Tool Coating
Iscar	P30	4	6.16 mm	0.4 mm	2	Uncoated
Sandvik	P30	3	9 mm	0.8 mm	4	Uncoated
Iscar	P40	4	6.16 mm	0.4 mm	2	TiCN
Sandvik	P45	3	9 mm	0.8 mm	4	TiN

5.3 Machines and equipment

The following equipment was used for this machinability study;

1) Milling Machine,
2) Hardness Tester,
3) Toolmakers' Microscope,
4) Surface Roughness Tester,
5) Three Component Dynamometer,
6) Charge Amplifiers,
7) Lightbeam Oscillograph Recorder,
8) A/D (Analog to Digital) Converter,
9) Personal Computer,

Milling Machine

The machine that was used for the machinability tests (tool life, surface finish and cutting force) is a computer numerically controlled (CNC) machine, i.e. a machine that is controlled by a host computer (controller). Machine devices are regulated by the control, based on information supplied by operator interface devices and feedback from various machine devices, the control turns on and off machine outputs and controls machine motion. [51]

Machine Type:	Bridgeport VMC 760 - 20, vertical machining centre
Controller:	Heidenhain TNC 2500C
Horsepower:	12 h.p. continuous rating
	15 h.p. at 50% ED rating
Spindle Working Envelope:	760mm (x-axis), 500mm (y-axis), 480mm (z-axis)
Spindle Speed:	40 - 4000 rpm
Maximum table weight:	250kg
Maximum tool weight:	6kg
Tool carousel:	10 tools

5.3.1 Equipment used in tool life testing

The equipment that was used in tool life testing were a hardness tester, the Bridgeport milling machine described earlier and a toolmakers microscope.

<u>Hardness Tester</u>

The hardness tester that was used in this study can directly measure Rockwell ,Brinell hardness and can measure Vicker's hardness by exemplifying tables. The specifications of the O.M.A.G 206RT hardness tester are as follows; [52]

Pre-load:	10 Kgf (98,07 N)
Test Loads:	60 - 100 - 150 Rockwell (588 - 980 - 1471 N)
	62.5 - 125 - 187.5 Brinell (612 - 1225 - 1839 N)
Tests:	Rockwell HRC A - D - B - F - G - L - M, Brinell
Total Height Capacity:	160mm (215 without bellows)
Max. load of piece:	1000 Kg
Field of Application:	For all metals, hard steel, cast iron, bronze, aluminium.

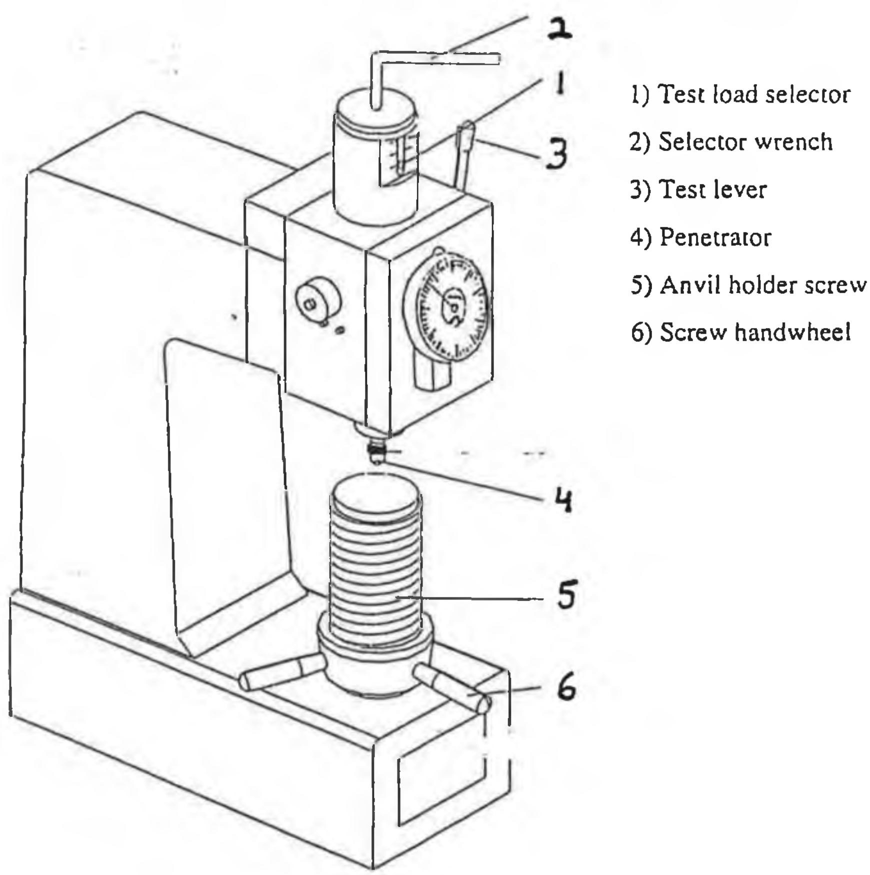

Figure 5.3.1a, Hardness Tester [52]

Toolmakers' Microscope

The toolmakers' microscope that was used for flank wear measurement was a precision optical instrument with the following specifications. [53]

Type: Column supported erect type, TM301

Microscope: Eyepiece optical tube: Vertical tilt angle of 30°

Objective: Magnification = 3x, Working distance = 72.5mm

Eyepiece: Magnification = 10x

Image: Erect image

Maximum height of workpiece: 150mm

Column optical distance: 148mm

Contour illuminator: Adjustable telecentric apeture stop

Light Source: Halogen lamp 6V, 20W

Control Panel: Power switch with pilot lamp

Power Supply: 100, 110, 120, 220, 240 VAC, 50/60 Hz

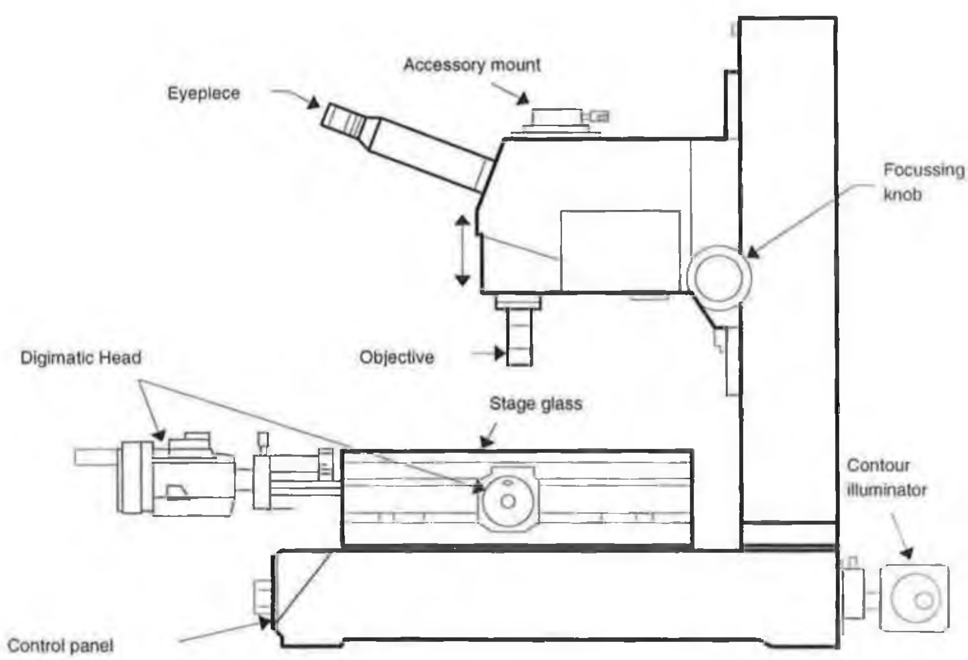

Figure 5.3.1b, Diagram of Toolmakers Microscope [53]

5.3.2 Equipment used in surface finish testing

The equipment that was used for surface finish tests was the Bridgeport milling machine mentioned earlier and a surface roughness tester.

Surface Roughness Tester

Generally, different surface roughness indices i.e. R_a, R_q, R_z can be employed for expressing the surface roughness of a specimen. However, because of its simplicity, the arithmetic average R_a, has been adopted and is widely used. In this study, R_a is used as the measurement for surface roughness. A surface roughness tester was used to measure the surface of the workpiece material. The tester employs the travel of a diamond stylus along a straight line over the surface. These instruments operate by amplifying the vertical motion of a stylus as it is drawn across the surface. Because of the finite radius of the stylus, its path is smoother than the actual surface roughness. The smaller the radius and lower the surface roughness of the tip, the closer is the path of the stylus to the actual surface profile. The tester produces a direct reading of the arithmetic mean surface roughness value. [54]

Waviness of the surface can be eliminated by a frequency cut-off device. A cut-off facility is built in to the surface tester, which is a filtering device that is performed by a frequency dependent electronic filter. It should be noted that a misleading height value could be obtained for the surface if the appropriate value of cut-off length is not selected.

The specifications of the Mitutoyo Surftest 402 are as follows;

Detector:

Detecting method:	Differential inductance type
Stroke:	0.3mm
Stylus Tip:	Diamond
Tip Shape:	Conical of 90°
Tip Radius:	5 µm
Curvature of radius of skid:	30mm

Display Unit:

Display:	Liquid crystal display
Displayable parameters:	R_a, R_q (RMS), R_z and R_{max}.
Displayable range:	(R_a, R_q) $\Rightarrow$ 0.01 - 2.0, 0.1 - 10.0, 0.2 - 50
	(R_z, R_{max}) $\Rightarrow$ 0.1 - 10.0, 0.2 - 50, 1 - 250

Operating Range:

Driving speed:	0.5 mm/s during measurement,
	1.0 mm/s during return.
Detector elevation:	Coarse range ~ 40mm
	Fine range ~ 10mm
Sampling length:	0.25, 0.8, 2.5, 8 and 30mm
Cut-off value:	0.25, 0.8, 2.5mm
Temperature Range:	5 to 40 °C

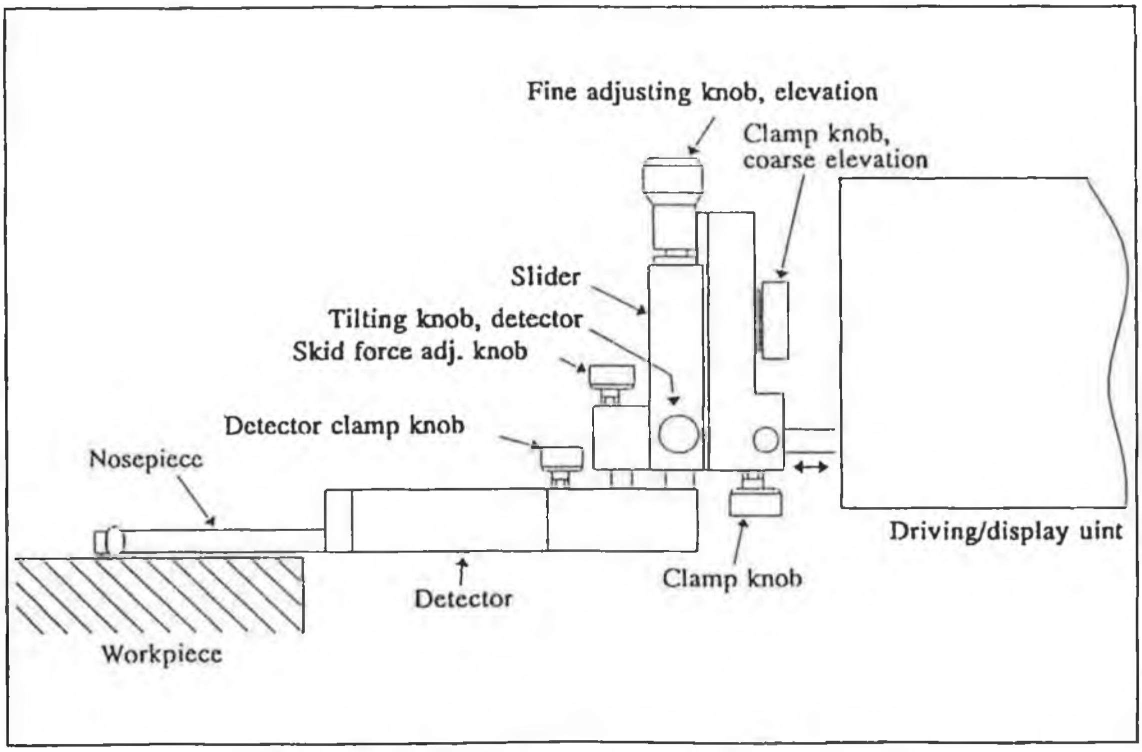

Figure 5.3.2, Diagram of Surface Roughness Tester [54]

5.3.3 Equipment used in cutting force measurement

The equipment that was used for measuring the cutting forces were the Bridgeport milling machine mentioned earlier, a three component type dynamometer, a distribution box, charge amplifiers, a lightbeam oscillograph, an A/D converter, a personal computer with Turbo C version 5.0 and a dot matrix printer. A block diagram of the equipment set-up is shown in figure 5.2.3b.

Dynamometer

The dynamometer is a three component piezoelectric type force measuring transducer. The piezoelectric force measuring principle differs fundamentally from that of previous systems. The transducer measures the three orthogonal components of cutting force and consists of a basic unit and a milling attachment. The basic unit is the main component of the dynamometer and is made up of a stainless steel base plate, a mounting plate with a cooling system and four transducers. The base plate has mounting flanges and on one side, it has a 9-pin Fischer flanged socket. The four 3-component transducers are held under high pre-load in between the base-plate and the mounting plate, where they are shielded both thermally and mechanically. The pre-load is necessary in order to enable tensile forces in the z-direction and cutting forces to be transmitted by frictional contact. [55]

The instrument was calibrated by Kistler Instruments Ltd. (the manufacturers of the dynamometer), who provided all of the calibration data with the instrument. The dynamometer was heated in a furnace overnight to remove any moisture build-up which might have occurred during storage. The a quick check of the calibration was conducted by applying a known load on the dynamometer and measuring the output.

Calibrated Range:		**Sensitivities:**	
F_x	0 - 3,000 N	F_x	-7.87 pC/N
F_y:	0 - 1,500 N	F_y:	-7.91 pC/N
F_z:	0 - 1,500 N	F_z:	-3.58 pC/N

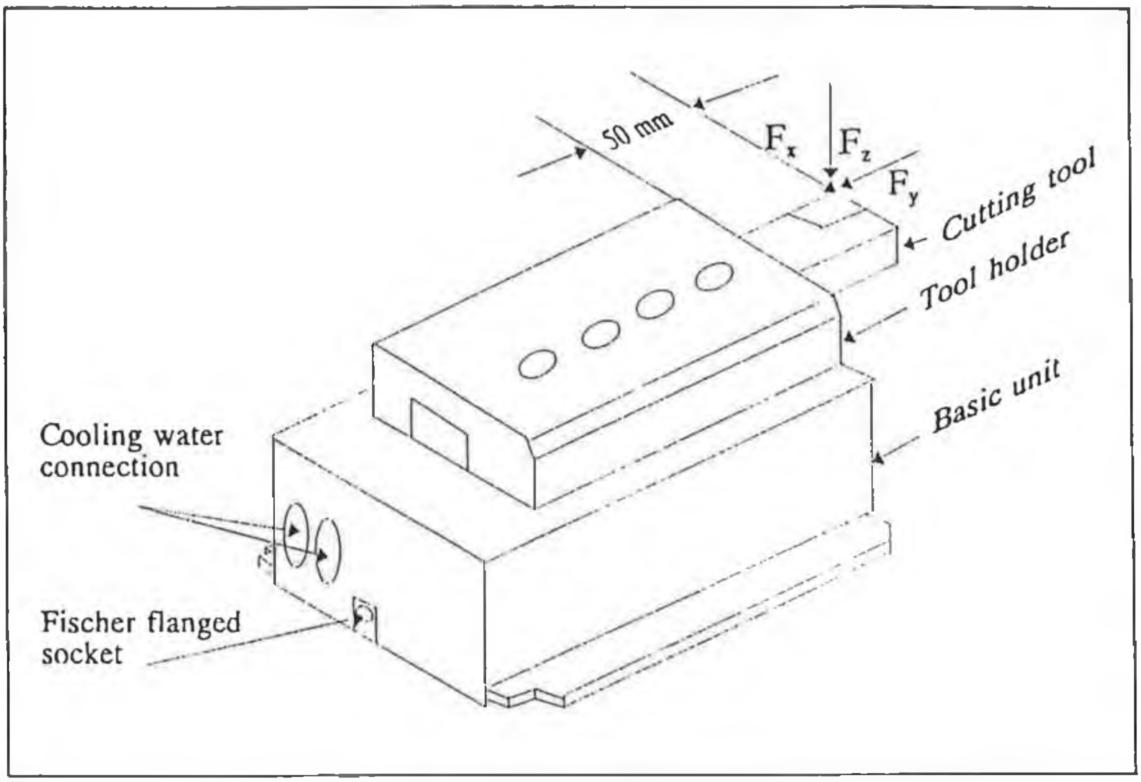

Figure 5.3.3a, Kistler three-component dynamometer. [55]

Distribution Box

The distribution box acts as a connecting link between the dynamometer and the charge amplifiers. The Fx and Fy outputs are led in pairs and the Fz output is led singly to the Fischer socket. From there it is sent down a shielded cable to the distribution box, where the signal is broken down in its three force components signals. From the box, each force component signal is then sent to an amplifier by means of special low noise cables.

Charge Amplifiers

This is a mains operated microprocessor controlled one-channel amplifier, Kistler type 5011. It converts the electric charge yielded by the piezo-electric transducers into a proportional (amplified) voltage signal. The continuous range setting as well as the microprocessor controlled electronics allow for a simple and clearly arranged manipulation. Depending on the magnitude of the cutting forces, the measuring range could be set up in the amplifier through a combination of transducer sensitivity T and scale S. Every channel was adjusted to the number of kN per volt output corresponding to the range with the maximum allowable amplified voltage output being 5V. The amplified signal is then sent to a lightbeam chart recorder and to a personal computer via an A/D converter.

Since milling is a dynamic cutting process, the cutting force fluctuates as a result of chip thickness variation, vibration of the work tool system and the rate of penetration of the cutter teeth into the work etc. To avoid dynamic cutting forces, a low pass filter was used during the tests. This filter only allows certain frequencies in a signal to pass and rejects the others. In other words, the filter transfer function forms a window in the frequency domain through which a portion of the input spectrum is allowed to pass. In this study a low pass filter with Buttersworth characteristic switchable in 8 stages [10 Hz, 30 Hz, 100Hz, 300Hz, 1 KHz, 3KHz, 10 KHz, 30 Khz] was used in the charge amplifiers. The time constant was set at a medium position. The frequency of the amplifier was set by synchronizing with the tooth passing frequency of the cutter (i.e. available frequency of the amplifier ≥ tooth passing frequency). For instance, the spindle speed of the cutter was 200 rpm and the number of teeth was 5, then the tooth passing frequency is [(250*5)/60] equal to approx. 20 Hz. In this case the frequency of the amplifiers was set to 30 Hz, which is the nearest frequency greater than 20 Hz which is available. [56]

Lightbeam Chart Recorder

The chart recorder receives its signals directly from the charge amplifiers. This is a Micro-movements M12-150A direct writing recorder. It uses a low power light source with a high performance optical system together with a servo controlled optical system. The performance of the lamp is optimized by operating it from a regulated supply to eliminate the damage caused by short term overloads and supply fluctuations. In the stand-by mode, the lamp is run below full power and is instantly brought up to full power at the commencement of recording. There is facility for up to 12 channels of information, which can be recorded on the 150mm wide roll of direct print photographic paper.

The principle of operation follows from the ability to reimage a tiny light source as a spot of light for each channel, which can be deflected across the full width of the light sensitive paper, by the mirror of a miniature galvanometer. The resulting record becomes visible after a development period of approximately 1-2 minutes, by the action of ambient light on the photo-sensitive paper. [57]

A/D Converter

The analog to digital converter receives signals from the transducer via the charge amplifiers. The DASH-8 board is an 8-channel 12 bit successive approximation high speed converter, full scale input for each channel is $\pm$ 5 volts with a resolution of 2.44 millivolts and a conversion time of approximately 25 microseconds. The DASH-8 is 12.37cm (5") long and is fitted in a "half" slot of the motherboard of the PC. All connections to the board are made through a standard 37 pin "D" male connector that projects through the rear of the computer. The base address of the DASH-8 has been set as &H300 through the microswitch. [58]

Personal Computer

The computer is a Tandy IBM compatible PC, with compatible VDU, that has 640 Kbyte RAM and a 42 Mbyte hard disk. The computer has a 286 processor and a speed of 16 MHz. It uses Turbo C++ 5.0 to convert the signal from the A/D converter into cutting force data. Their is an Epson Fx-80 dot matrix printer connected to the computer to print the cutting force data.

Computer Software

A program was developed to convert the information from the A/D converter into actual cutting force data. The program was written in Turbo C ++ version 5.0 programming language. It calculates the average forces in the x, y and z axes and also the resultant cutting force that was produced. The cutting force data is automatically stored onto the hard disk of the computer, where it can be retrieved for printing.

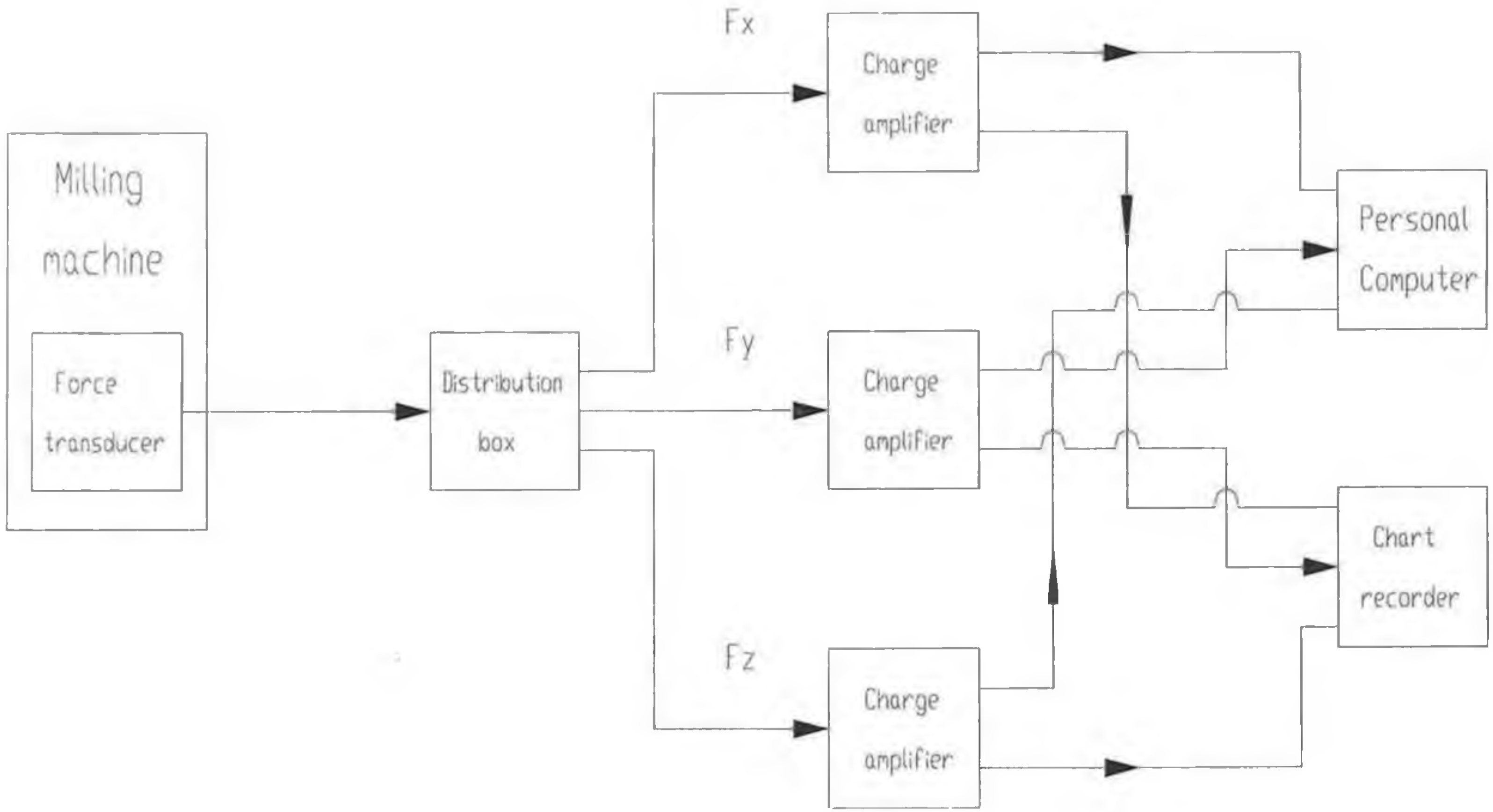

Figure 5.3.3b, Block diagram of force measurement equipment set-up

5.4 Experimental Procedure

5.4.1 Tool Life Tests

The workpiece material was cut into blocks of approximately 300mm long, 50mm wide and 200mm deep, with the 300mm and 50mm lengths aligned with the x and y axes respectively. This was done so that there would be no variation of the diffusion of heat from the cutting zone as a result of variations in workpiece block size. This also meant that the time to machine a layer of material was constant for constant feed rate.

Prior to machining, the hardness of each block was measured in five different locations using a Hardness Testing machine. This was done to monitor the hardness of the workpiece blocks, to ensure that no large variations in hardness values occurred. This practice is in accordance with ISO tool life testing procedure, which recommends a maximum acceptable variation in hardness of 5%.

Before carrying out tool life tests, each block was skimmed to remove any scale or surface contamination and also to produce a flat surface on the top of the block.

Before the start of each tool life test the clearance on each tooth of the cutter was measured. During the tool life test the teeth are measured at regular time intervals. The cutting tool was removed from the machine and placed under the toolmaker's microscope. The wear on the tooth was then measured from the datum line to the point of maximum wear. The clearance value is then subtracted from the measured value to give the actual wear on the tooth.

The tests were carried out under half immersion (12.5mm cut) and under dry cutting conditions. For the HSS cutting tools, the up-milling mode was used, while for cemented carbides down-milling was used. No coolant was used because the same shape of curve is produced when machining dry but in a shorter time period than if coolant was used. Another reason is that the choice of coolant can affect the results obtained depending on the tool manufacturer or the tool material and so cutting under dry conditions eliminates any unknown factors. [18]

The majority of the tests were conducted using the one-variable at a time method. For example, the feed rate and depth of cut were fixed at nominal values while the cutting speed was varied from its minimum to maximum acceptable limit.

5.4.2 Surface Finish Tests

Surface finish tests were carried out on a selection of the cutting tool using an experimental technique known as 'design of experiment'. A 180mm long and 50mm wide block of workpiece material was used for the tests. A new cutter was used after every second surface finish tests because tool wear increases the surface finish produced. Using a new tool after every second test meant, that the surface finish that was produced was due to the cutting conditions used.

The tests were carried out by machining a slot (25 mm wide) across the 50 mm length of the block of workpiece material. This meant that six different tests could be carried out on the block before measurement was required.

The surface roughness measurement was carried out by using the Mitutoyo Surftest 402 described earlier in this chapter. Generally, a workpiece surface to be measured is not uniform in roughness and varies, depending on the portion to be measured. In this respect, it is necessary to select a portion or portions to measure so that population mean of the surface can be obtained. For this reason it was decided to take three measurements of surface roughness from various locations on the machined surface and to average the three readings as the value of surface roughness for the test.

5.4.3 Cutting Force Measurement

The cutters used in the tests were Clarkson high speed steel (HSS) end mills with an 8% cobalt content. The end mills were 25mm in diameter with 5 teeth and a Weldon shank. A new cutter was used for each individual cutting force test because tool wear increases the cutting forces produced. Using a new tool for each test meant, that only the cutting forces produced due to the cutting conditions were recorded.

The milling machine (Bridgeport VMC 760-20 with a Heidenhain TNC2500c controller) was setup with a 3 component Kistler dynamometer (piezoelectric transducer, type 9265A3) which had a 180*180*70mm block of the workpiece material attached to it. The dynamometer was connected to a set of charge amplifiers (Kistler type 5011) via a distribution box. The amplified signal was then sent to both a UV chart recorder (Micro Movements type M12-150A) and a personal computer (Tandy 286Dx-12MHz with a Dash-8 interface board). The UV chart recorder gave a visual representation of the three different cutting forces present, while at the same time the computer converts the amplified signal via a A/D converter and then a Turbo C++ program converts the digital signal into cutting forces and outputs the average cutting forces for each axis. The chart recorder printout gave a means of verifying that the results obtained from the computer were correct.

The computer program was run from between 4-6 times per test, depending on the feed rate of the machine. The average force for each axis was then calculated and the resultant force was calculated using the average values obtained.

The speed range, feed range and depths of cut to be used for the tests were determined following consultation of the Machining Data Handbook Volume 2 [1]. The ranges chosen for the tests were increased in order to observe the behaviour of the cutting forces, outside of the recommended machining range. Four cutting speeds, feeds and depths of cut were selected. The tests were carried out by varying one parameter while keeping the two other parameters constant.

CHAPTER 6

EXPERIMENTAL RESULTS AND ANALYSIS

ONE - VARIABLE AT A TIME

6.1 Introduction

Both cutting force tests and tool life tests were carried out by using the one - variable - at - a - time method. For the cutting force test, only HSS cutting tools from one manufacturer were used. For the tool life tests, both cemented carbide and HSS cutting tools were used. For each tool material both the uncoated and coated versions were used, with three different manufacturers being selected for HSS, while two were chosen for cemented carbide tools.

In conducting the experiments, two of the machining parameters out of the three (cutting speed, feed rate and depth of cut) are kept constant. The third parameter was varied from one end of its operating range to the other, in order to observe its affect on the machining response (cutting force, tool life).

6.2 Cutting force tests

The cutting force tests were carried out using uncoated Clarkson HSS cutting tools (as specified in section 5.2) to observe the effect of cutting speed, feed rate and depth of cut on the force produced. The purpose of these tests is to estimate the cutting forces and derive optimum cutting conditions to minimise the cutting forces produced.

The speed range, feed range and depths of cut to be used for the tests were determined following consultation of the Machining Data Handbook Volume 2 [1]. The ranges chosen for the tests were increased in order to observe the behaviour of the cutting forces, outside of the recommended machining range. Four cutting speeds, feed rates and depths of cut were selected.

The tests were carried out under dry cutting conditions, using full immersion (or slot milling) and in the up-milling mode of cut. A new cutting tool was used for each cutting force test. This is done to ensure that the changes in the cutting forces produced are only due to the variation in the cutting parameter and are not affected by the wear of the cutting tool.

Table 6.2a The cutting conditions

Cutting Speed (m/min)	Feed Rate (mm/min)	Depth of Cut (mm)
8, 12, 16, 20	46, 69, 92, 115	0.5, 1, 2, 4

a) **Analysis of cutting speed on cutting forces**

For the analysis of the effect of cutting speed on cutting force, the feed rate and the depth of cut were kept constant at 69 mm/min and 1mm respectively, while the speed was varied from 8 m/min to 20 m/min.

Table 6.2b Cutting force with varying cutting speed

Cutting speed (m/min)	Force on x axis (N)	Force on y axis (N)	Force on z axis (N)	Resultant Force (N)
8	498.04	192.58	68.76	538.38
12	368.23	124.28	55.84	392.63
16	301.72	112.62	51.26	326.11
20	243.53	90.35	32.59	261.79

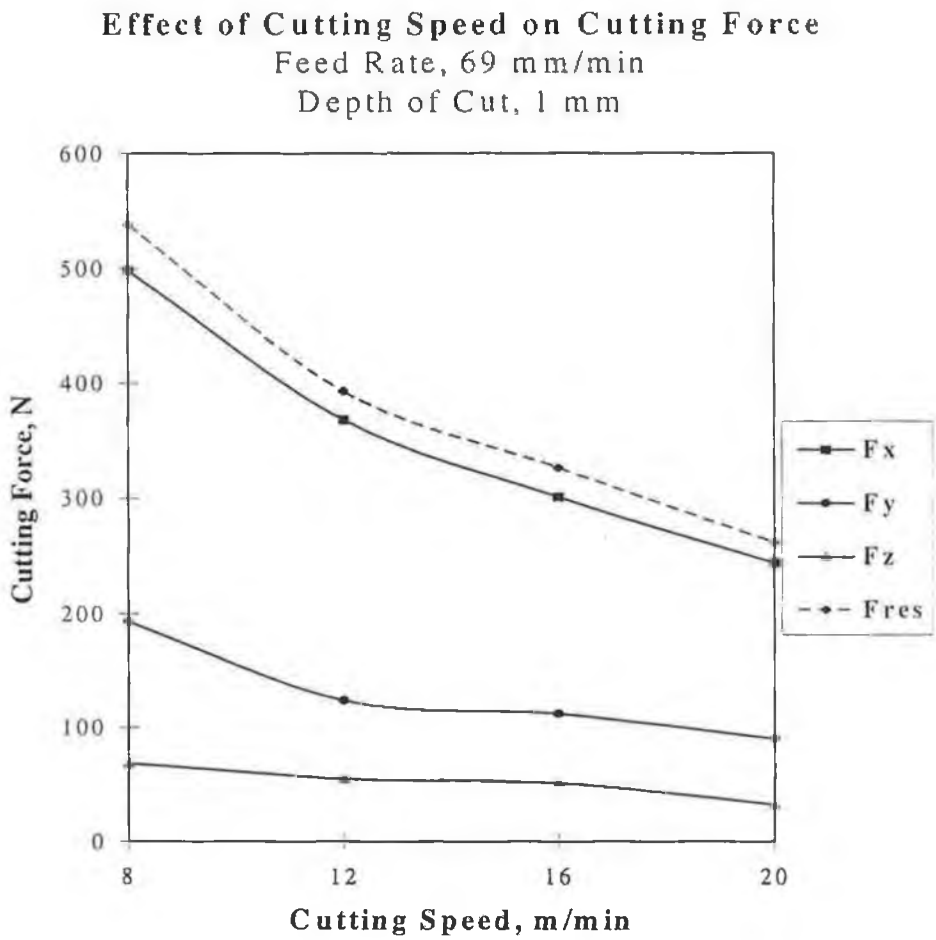

Figure 6.2a Graph of cutting force vs. cutting speed

From the graph it can be seen that the cutting forces decrease as the cutting speed increases, with the feed force (Fx) being the largest of the three force present. The feed force drops by over 20% with each increase in speed of 4 m/min. with the feed force at 20 m/min being less than 50% of the feed force at 8 m/min. Therefore it is desirable to machine at a high a cutting speed as possible. This is because as the speed increases each tooth spends less time in the cutting area, consequently the chip thickness decreases which results in a decrease in the chip load and therefore the cutting forces decrease. It can also be attributed to the fact that at low cutting speeds the co-efficient of friction between the teeth of the cutter and the workpiece increases and as a result the cutting forces increase. [1]

It is usually observed that as the cutting speed decreases, the shear angle also decreases. A small shear angle results in a long shear plane. For a fixed shear strength, an increase in shear plane area causes an increase in the shearing forces required to produce stress for deformation. [1]

b) Analysis of feed rate on cutting forces

For the analysis of the effect of feed rate on cutting forces, the cutting speed and the depth of cut were kept constant at 12 m/min and 1mm respectively, while the feed was varied from 46 mm/min to 115 mm/min.

Table 6.2c Cutting force with varying feed rate

Feed rate (mm/min)	Force on x axis (N)	Force on y axis (N)	Force on z axis (N)	Resultant Force (N)
46	270.84	119.00	47.25	299.58
69	368.23	124.28	55.84	392.63
92	462.97	156.33	68.19	493.39
115	535.47	184.50	76.39	571.49

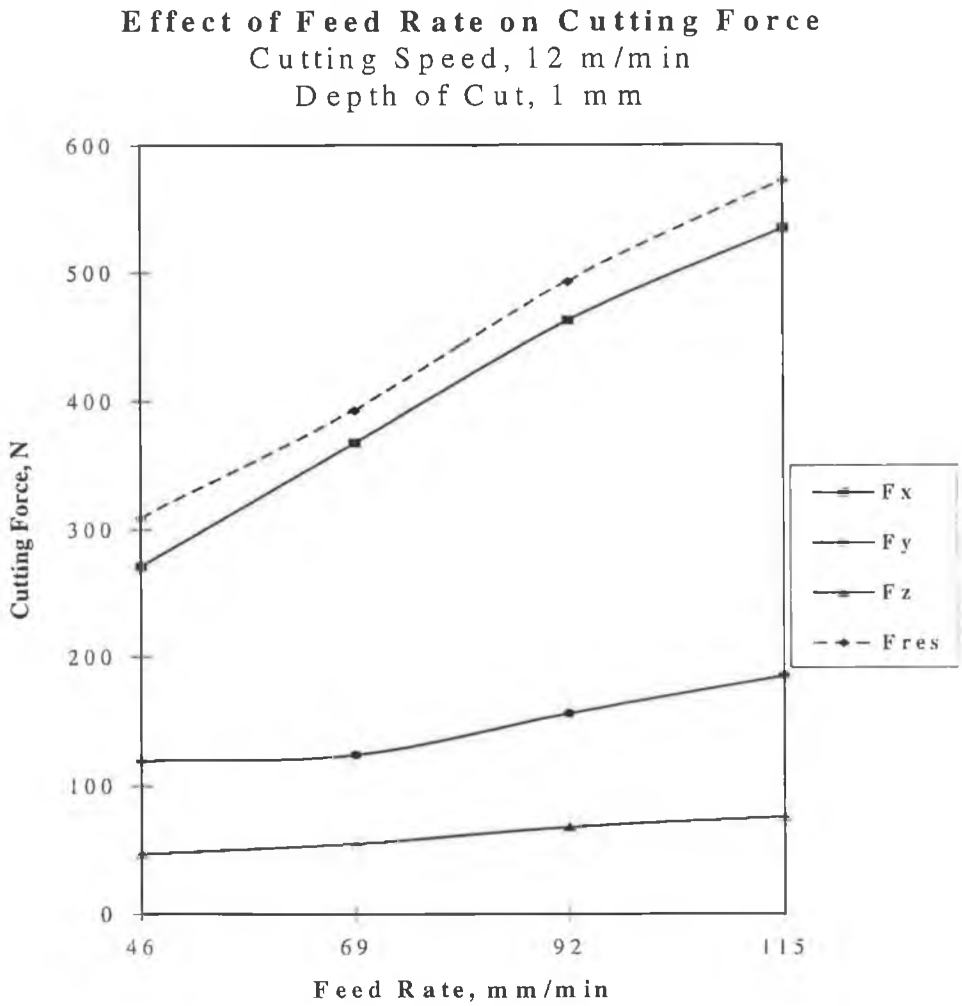

Figure 6.2b Graph of cutting force vs. feed rate

From the graph it can be seen that the feed force (Fx) is the largest of the three forces present. Again, as was the case for cutting speed, this force accounts for approximately 80% of the total force produced. The normal force (Fy) is the next largest force with the vertical force (Fz) being the smallest of the three forces.

From the graph it can also be seen that the cutting force increases linearly as the feed rate increases. The feed force increased by over 100% across the range, with the normal and vertical forces increasing by over 50% from 46 mm/min to 115 mm/min. This is due to the fact that as the feed increases the chip thickness increases and as a result the chip load increases, which means that the pressure and therefore cutting force on the tool increase. [1]

c) **Analysis of depth of cut on cutting forces**

For the analysis of the effect of depth of cut on cutting forces, the cutting speed and the feed rate were kept constant at 12 m/min and 69 mm/min respectively, while the depth of cut was varied from 0.5 mm to 4 mm.

Table 6.2d Cutting force with varying depth of cut

Depth of cut (mm)	Force on x axis (N)	Force on y axis (N)	Force on z axis (N)	Resultant Force (N)
0.5	193.11	71.06	37.81	209.21
1	368.23	124.28	55.84	392.63
2	737.22	308.26	187.10	820.69
4	999.51	607.87	343.52	1219.23

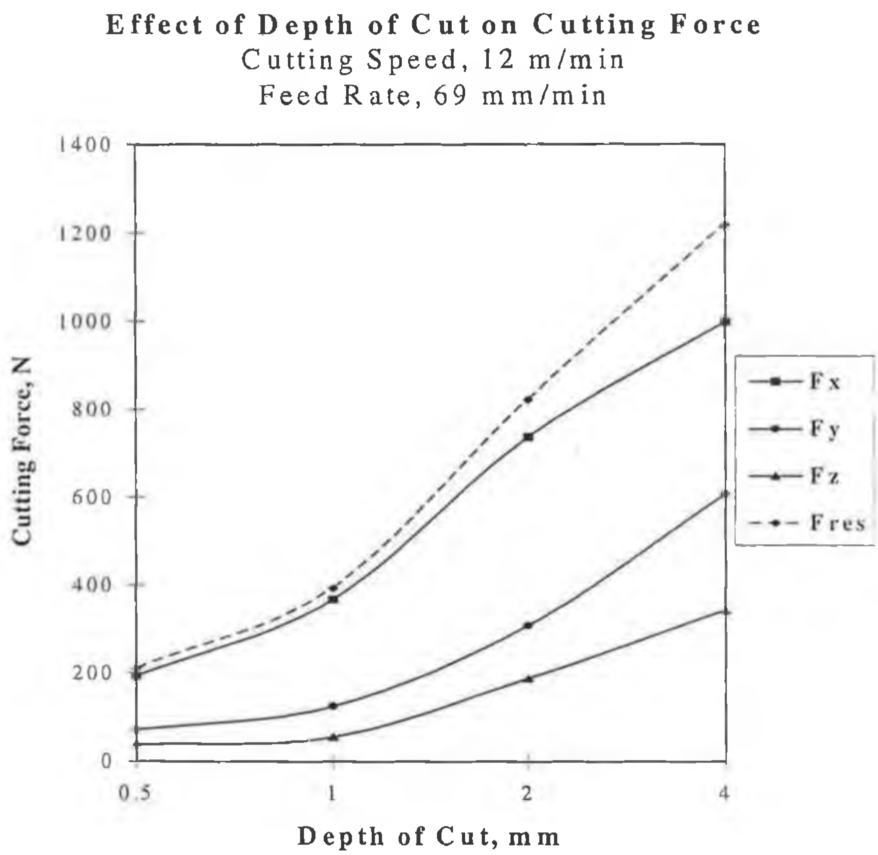

Figure 6.2c Graph of cutting forces vs. depth of cut

From the graph of cutting force vs. depth of cut, it can be seen that the feed force (Fx) is the largest of the three forces present. The feed force accounts for approximately 60% of the total force acting on the tool. The normal force (Fy) is the next largest force, with the vertical force (Fz) being the smallest of the three.

It can also be seen that the cutting forces increase as the depth of cut increases. The cutting forces increase by over 500% between 0.5mm and 4mm depths of cut. This increase in force with an increase in depth of cut is due to the increase in the size of the chip that occurs with an increase in the depth of cut. The large cuts mean an increase in cutting area and therefore an increase in the cutting forces. [1]

Conclusions

From the measurements of cutting forces taken during the full immersion, dry cutting tests of tool steel, the following conclusions can be drawn;

- The feed force (Fx) is the largest of the three cutting forces present, followed by the normal force (Fy) and finally the vertical force (Fz).

- As the cutting speed increases the cutting forces decrease.

- As the feed rate increases the cutting forces increase.

- As the depth of cut increases the cutting forces increase.

To minimise the forces produced during machining, it is recommended that the following cutting ranges be used;

Cutting Speed	~	12 - 18 m/min
Feed rate	~	55 - 100 mm/min
Depth of cut	~	1.0 - 2.5 mm

6.3 Tool Life Tests

The tool life tests were carried out using both HSS and cemented carbide cutting tools. Tools from different manufacturers were used for the HSS and cemented carbide tests. Both the uncoated and coated versions of the cutting tools were used. The purpose of the tests was to observe the effect of cutting speed, feed rate and depth of cut on the tool life of the cutting tool and to determine optimum cutting conditions to increase the tool life.. Other goals of this study include; the investigation of the different cutting tool materials that were used for machining tool steel (Din 1.2311). to see which of the materials is most suited for the operation. To examine the performance of different manufacturers of the same cutting tool and also the performance of uncoated cutting tools versus their coated counterparts.

The speed range, feed range and depths of cut to be used for the tests were determined following consultation of the both the Machining Data Handbook Volume 2 [1] and the various tool manufacturer handbooks [46-50]. Three cutting speeds, feeds and depths of cut were selected. For ease of comparison, all of the HSS cutting tools were run under the same cutting conditions. However, because of the difference in grades of the cemented carbides and the difference in performance between the uncoated and coated cutting tools, the cemented carbides have to run at different cutting conditions and ranges.

The tests were carried out under dry cutting conditions, using half immersion (or side milling), in the up-milling mode of cut for HSS and down-milling mode for cemented carbide. The cutting tool was deemed to have failed when the average flank wear on the teeth exceeded 0.3mm or when the flank wear on any individual tooth on the cutter exceeded 0.5mm. [18]

Table 6.3a. Cutting Conditions used for Tool Life Tests

Cutting Conditions	High Speed Steel		Sandvik		Iscar	
	Uncoated	**Coated**	**Uncoated**	**Coated**	**Uncoated**	**Coated**
Cutting speed, m/min	10, 15, 20	10, 15, 20	55, 65 75	98, 105 112	75, 85 95	125, 140 155
Feed Rate mm/min	127, 191, 255	127, 191, 255	310, 330 370	500, 550 600	380, 430 480	500. 530 570
Depth of Cut, mm	1, 2, 4	1, 2, 4	1, 2, 4	1, 2, 4	1, 2, 4	1. 2. 4

Factor affecting Tool Life

a) Effect of Cutting Speed on Tool Life

This directly effects the tool wear rate, surface finish, cutting forces and the type of chip formed. At low speeds the material behaves in a brittle manner, with discontinuous chips and low tool wear rates, however it also results in a poor surface finish. High speeds result in continuous chips and improved surface finish but on the downside causes an increase in cutting temperature which leads to high tool wear rate and therefore the tool life is low. The major effect of speed is on tool wear rates, therefore efforts must be made to balance these factors to attain the most desired conditions. [44]

b) Effect of Feed Rate on Tool Life

This is similar to cutting speed in that it influences cutting forces, tool wear rates and surface finish, but to a lesser extent. The larger the feed rate, the greater is the cutting force and temperature in the cutting zone. The increase in cutting force also increases the likelihood of chipping of the cutting edge through mechanical shock. An increase in feed rate also results in an increase in tool wear rates and produces a poor surface finish. The surface finish produced is a direct function of the feed rate. [44]

c) Effect of depth of cut on tool life.

This has a significant effect on the cutting forces produced. In that a small increase in the depth of cut results in a significant increase in the cutting forces but only has a small effect on the resulting surface finish. [44]

6.3.1 Uncoated end mill manufacturer comparison

a) Effect of Cutting Speed

The tests were carried out by keeping both the feed rate and depth of cut constant at 90 mm/min and 1 mm respectively, while varying the cutting speed from 10 - 20 m/min.

Table 6.3.1a. Tool Life with varying Cutting Speed

Cutting Speed	Tool Life (minutes)	
(m/min)	Clarkson	Strassmann
10	96	124
15	88	112
20	78	96

As can be seen from both the table and the graph, tool life decreases with increasing cutting speed. This can be attributed to the fact that the cutting temperature increases with increasing speed. The rise in temperature is generated by two sources of heat. These sources of heat are from the energies created in the shear plane during the formation of the chip and from the friction between the chip and the rake face. This excess heat causes diffusion wear, which occurs by the process of chemical dissolution of the tool material in the chip, particularly at the hottest point of contact, which is a short distance back from the cutting edge. Another effect of high temperature in the cutting zone is that it can produce thermal shock cracks. These cracks are caused by thermal cycling as a result of intermittent cutting, which is a feature of milling operations. Under these conditions the effects of abrasion wear are negligible. [11]

Figure 6.3.1a shows the performance of the two sets of cutting tools with varying cutting speed. It can be seen from the bar chart that the Strassmann tools out perform the Clarkson by a considerable amount at every cutting speed used. The Strassmann lasted from between 23-29% longer than the Clarkson across the range.

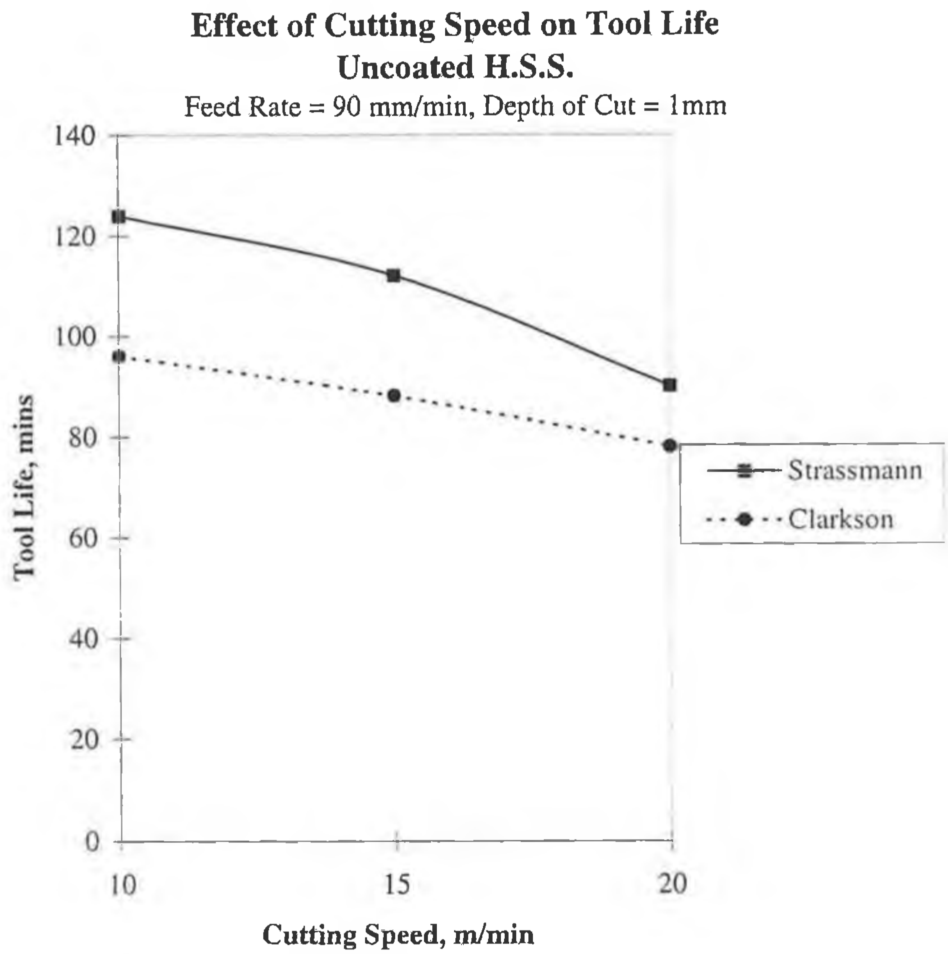

Figure 6.3.1a, Tool manufacturer comparison (varying cutting speed)

b) Effect of Feed Rate

The tests were carried out by keeping both the cutting speed and depth of cut constant at 15 m/min and 1 mm respectively, while varying the feed rate from 60 - 120 mm/min. The following table and graph are a representation of the tool life's obtained at varying feed rates.

Table 6.3.1b. Tool Life with varying Feed Rate

Feed Rate	Tool Life (minutes)	
(mm/min)	Clarkson	Strassmann
60	105	120
90	88	112
120	58	106

As can be seen from both the table and the graph, tool life decreases with increasing feed rate. This can be attributed to the fact that as the feed increases the greater is the cutting force produced per unit area of chip-tool contact on the rake face and work-tool contact on the flank face. The increase in cutting force can also be attributed to the fact that the chip thickness and therefore chip load increases with feed rate. This increase in chip load causes both an increase in the cutting pressure and temperature. The increase in the pressure results in increased abrasive wear and the rise in temperature causes an increase in the diffusion wear on the tool. Of the two types of wear discussed in this section, diffusion wear is the more prominent.[11]

Figure 6.3.1b shows the performance of the two sets of cutting tools with varying feed rates. Again it can be seen that the Strassmann tools out perform the Clarkson by a considerable amount. The Strassmann tools lasted over 15% longer than the Clarkson at the low feed rates and over 40% longer at the high feed rates.

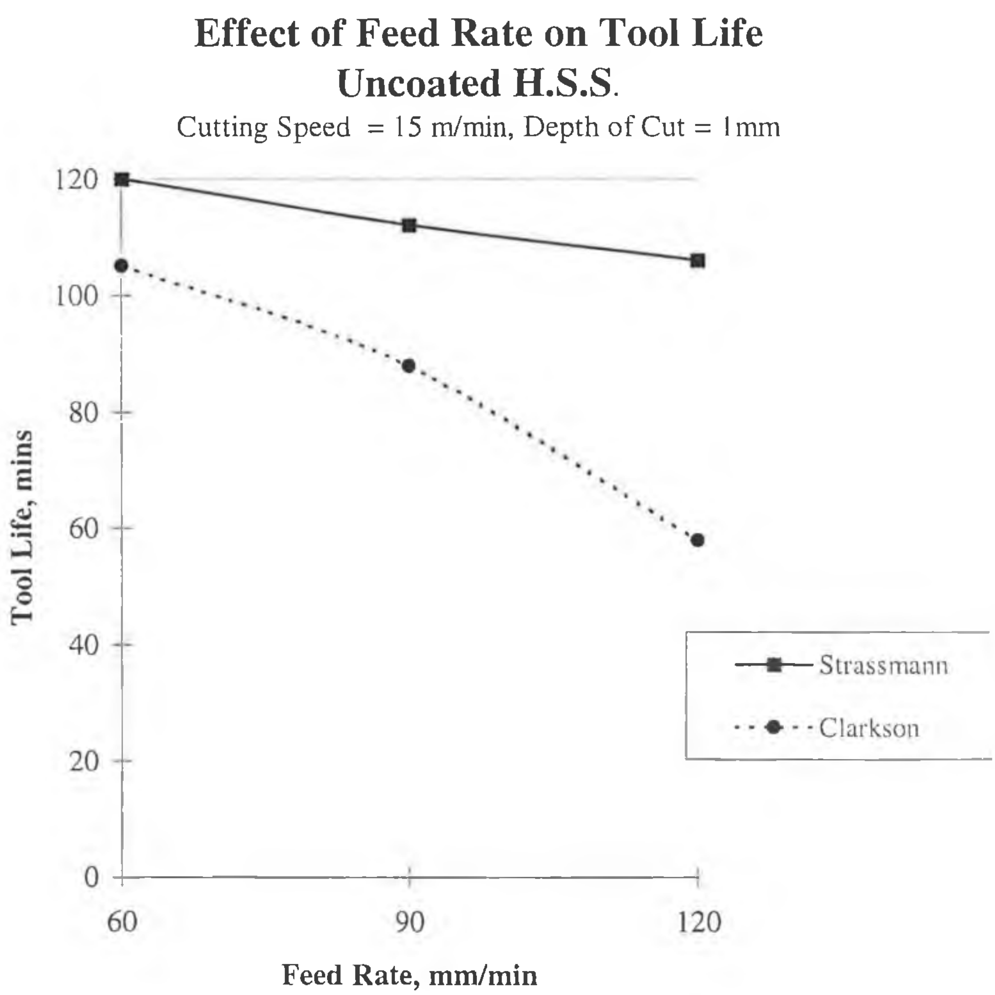

Figure 6.3.1b, Tool manufacturer comparison (varying feed rate)

c) Effect of Depth of Cut

The tests were carried out by keeping both the cutting speed and feed rate constant at 15 m/min and 90 mm/min respectively, while varying the depth of cut from 1 - 4 mm. The following table and graph are a representation of the tool life's obtained at varying depths of cut.

Table 6.3.1c Tool Life with varying Depth of Cut

Depth of Cut	Tool Life (minutes)	
(mm)	Clarkson	Strassmann
1	88	112
2	80	94
4	58	80

As can be seen from the graph, an increase in the depth of cut results in a decrease in the tool life. This is due to the fact that as the depth of cut increases the temperature in the cutting zone increases. [44] The rise in temperature with increasing depth of cut results in increased diffusion wear. The increase in the depth of cut also results in an increase in chip load and therefore cutting pressure, which increases the abrasive wear on the tool. The overall result is an increase in total wear due to increases in both diffusion and abrasive wear with increasing depth of cut. [11]

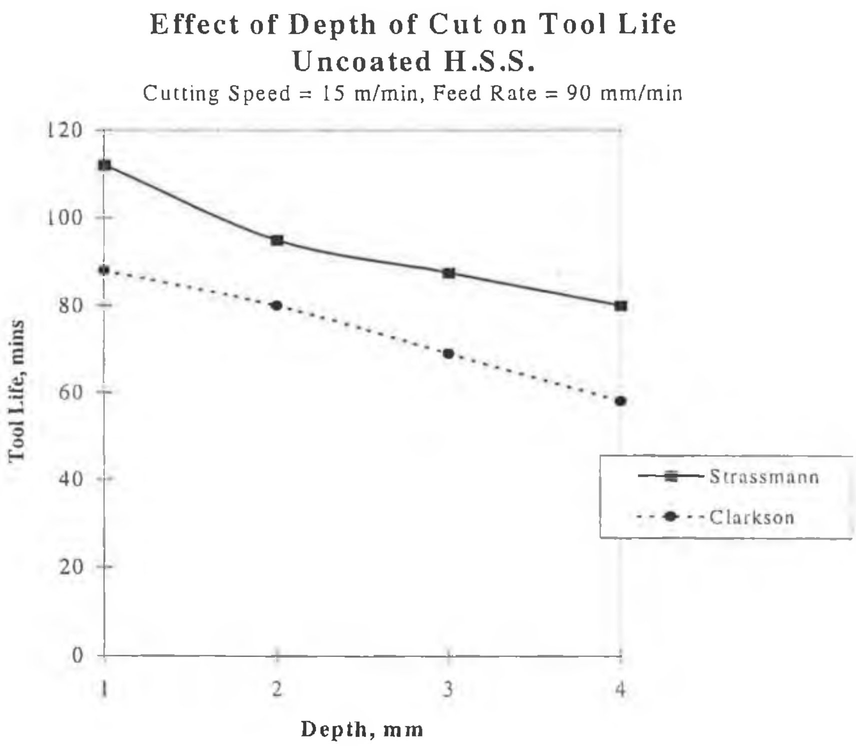

Figure 6.3.1c, Tool manufacturer comparison (varying depth of cut)

Figure 6.3.1c shows the performance of the two sets of cutting tools with varying depths of cut. Once again it can be seen that the Strassmann tools performed better than the Clarkson by a considerable amount. They out performed the Clarkson by at least 20% across the range and by a maximum of 40% at 4mm depth of cut.

Conclusions

From the graphs of cutting speed, feed rate and depth of cut versus tool life, it can be seen that Strassmann cutters perform by at least 15% and up to 40% better than Clarkson. On average Strassmann have 27% longer tool life than Clarkson tools.

One of the reasons why Strassmann performs better than Clarkson is that the secondary clearances on the rake faces are smaller on the Strassmann cutters. There is also less variation in these clearances on the Strassmann compared to the Clarkson tools. The net effect of this is that teeth on the Strassmann wear at a uniform rate and therefore all of the teeth fail at roughly the same time. Whereas the teeth on the Clarkson wear at different rates and causes some teeth to wear quickly while other teeth wear very little.

The prices of the two different cutting tools are as follows;

- Strassmann ~ £44.30 per tool (excl. Vat),
- Clarkson ~ £38.56 per tool (excl. Vat),

The Strassmann tools cost 15% more than the Clarkson tools. With the Strassmann out performing the Clarkson by an average of 27% it is recommended that Strassmann be chosen ahead of Clarkson.

6.3.2 Tool Coating Comparison (Clarkson)

a) Effect of Cutting Speed

The tests were carried out by keeping both the feed rate and depth of cut constant at 90 mm/min and 1 mm respectively, while varying the cutting speed from 10 - 20 m/min.

Table 6.3.2a Tool Life with varying Cutting Speed

Cutting Speed	**Tool Life (minutes)**	
(m/min)	**Uncoated**	**Coated**
10	96	155
15	88	148
20	78	140

As can be seen from both the table and the graph, tool life decreases with increasing cutting speed. This can be attributed to the fact that the cutting temperature increases with increasing speed. The rise in temperature is generated by two sources of heat. These sources of heat are from the energies created in the shear plane during the formation of the chip and from the friction between the chip and the rake face. This excess heat causes diffusion wear, which occurs by the process of chemical dissolution of the tool material in the chip, particularly at the hottest point of contact, which is a short distance back from the cutting edge. Another effect of high temperature in the cutting zone is that it can produce thermal shock cracks. These cracks are caused by thermal cycling as a result of intermittent cutting, which is a feature of milling operations. Under these conditions the effects of abrasion wear are negligible. [11]

It can be clearly seen from the graph, that coated cutting tools out-perform the uncoated tools by at least 60% across the cutting speed range. The coated tools lasted 60% longer at 10 m/min and lasted 80% longer at 20 m/min. This can be attributed to the fact that TiN coatings produce less cutting forces and as a result less cutting temperature is generated. They also do not chemically interact or alloy with the workpiece material and are more thermally stable. The combined effect of the previous two properties results in increased solution wear resistance. This coupled with lower cutting zone temperature results in less overall tool wear. [13]

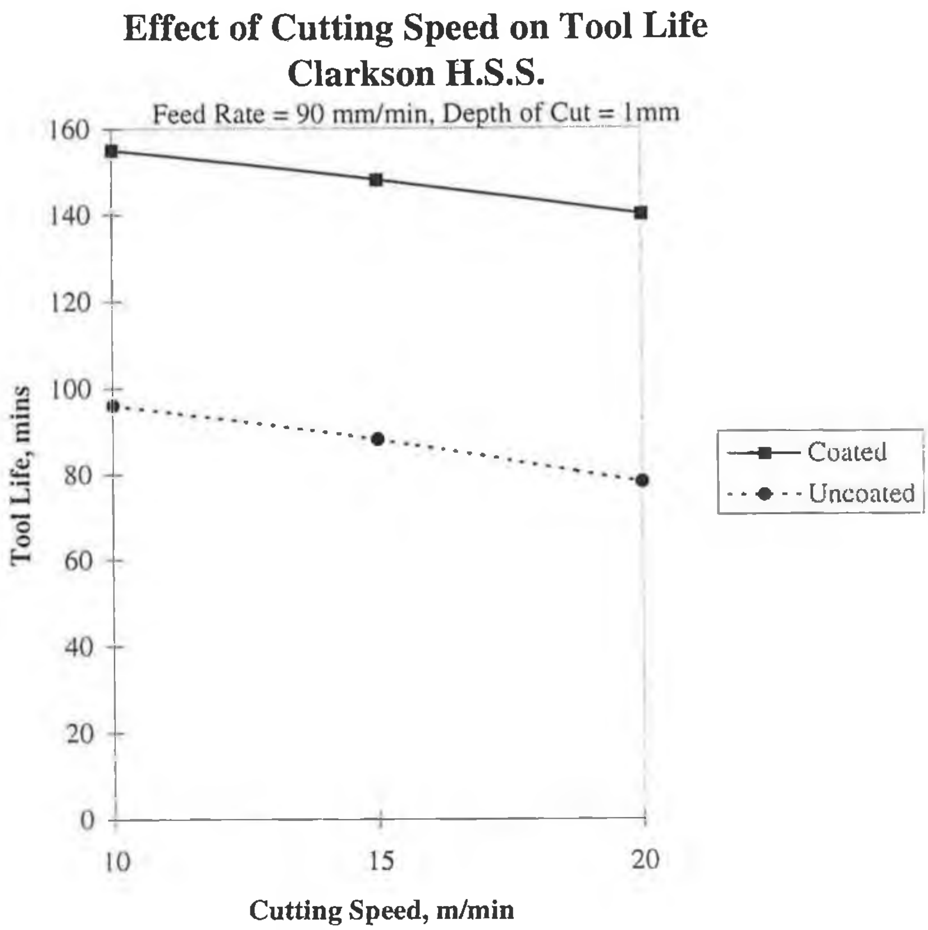

Figure 6.3.2a, Tool manufacturer comparison (varying cutting speed)

b) Effect of Feed Rate

The tests were carried out by keeping both the cutting speed and depth of cut constant at 15 m/min and 1 mm respectively, while varying the feed rate from 60 - 120 mm/min. The following table and graph are a representation of the tool life's obtained at varying feed rates.

Table 6.3.2b Tool Life with varying Feed Rate

Feed Rate	Tool Life (minutes)	
(mm/min)	Uncoated	Coated
60	105	182
90	88	148
120	58	112

As can be seen from both the table and the graph, tool life decreases with increasing feed rate. This can be attributed to the fact that as the feed increases the greater is the cutting force produced per unit area of chip-tool contact on the rake face and work-tool contact on the flank face. The increase in cutting force can also be attributed to the fact that the chip thickness and therefore chip load increases with feed rate. This increase in chip load causes both an increase in the cutting pressure and temperature. The increase in the pressure results in increased abrasive wear and the rise in temperature causes an increase in the diffusion wear on the tool. Of the two types of wear discussed in this section, diffusion wear is the more prominent. [11]

The coated tools out-perform the uncoated tools by at least 50 % across the range.

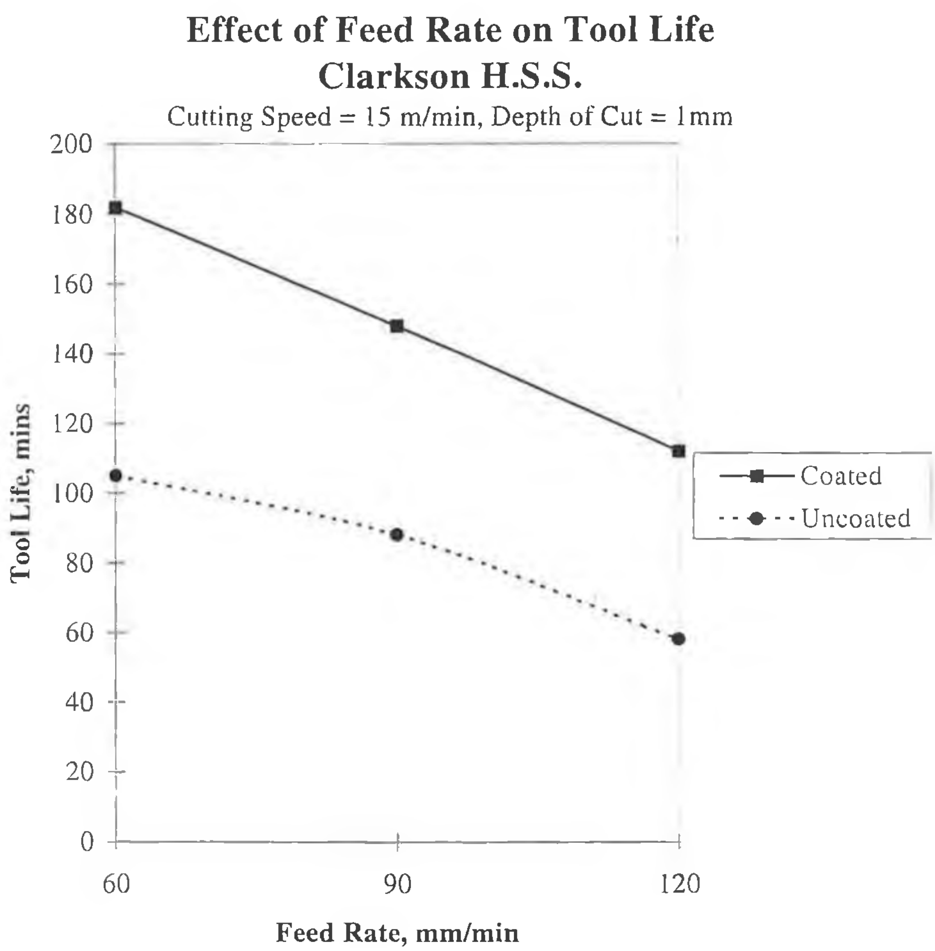

Figure 6.3.2b, Tool coating comparison (varying feed rate)

c) Effect of Depth of Cut.

The tests were carried out by keeping both the cutting speed and feed rate constant at 15 m/min and 90 mm/min respectively, while varying the depth of cut from 1 - 4 mm. The following table and graph are a representation of the tool life's obtained at varying depths of cut.

Table 6.3.2c Tool Life with varying Depth of Cut

Depth of Cut	**Tool Life (minutes)**	
(mm)	**Uncoated**	**Coated**
1	88	148
2	80	200
4	58	248

As can be seen from the graph the depth of cut has two very different effects on the tool life of uncoated and coated tools. For the uncoated tool an increase in the depth of cut results in a decrease in the tool life. This is due to the fact that as the depth of cut increases the temperature in the cutting zone increases. The rise in temperature with increasing depth of cut is greater for uncoated tools than for coated tools and results in increased diffusion wear. The increase in the depth of cut also results in an increase in chip load and therefore cutting pressure, which increases the abrasive wear on the tool. The overall result is an increase in total wear due to increases in both diffusion and abrasive wear with increasing depth of cut. [11]

On the other hand, for coated tools an increase in the depth of cut results in a increase in tool life. This is due to the fact, that although the overall temperature in the cutting zone increases with increasing depth of cut, the size of the chip produced also increases and the proportion of the overall temperature transmitted to the chip and workpiece increases, while the increase in the cutting tool temperature is very small. [44] This increase in temperature of the chip/workpiece has the effect of reducing the hardness of the workpiece material making it less abrasive on the cutting tool, therefore reducing the amount of abrasive wear present on the cutting tool. The small rise in the tool temperature increases the diffusion wear but not significantly. The overall effect of the cutting zone temperature increase is that the abrasion wear decreases, more than the diffusion wear increases, and therefore there is a net reduction in overall tool wear with increasing depth of cut.

Again coated tools out-perform uncoated tools by at least 60% across the entire depth of cut range, rising from 68% at 1mm depth of cut to over 300% longer tool life at 4mm depth of cut.

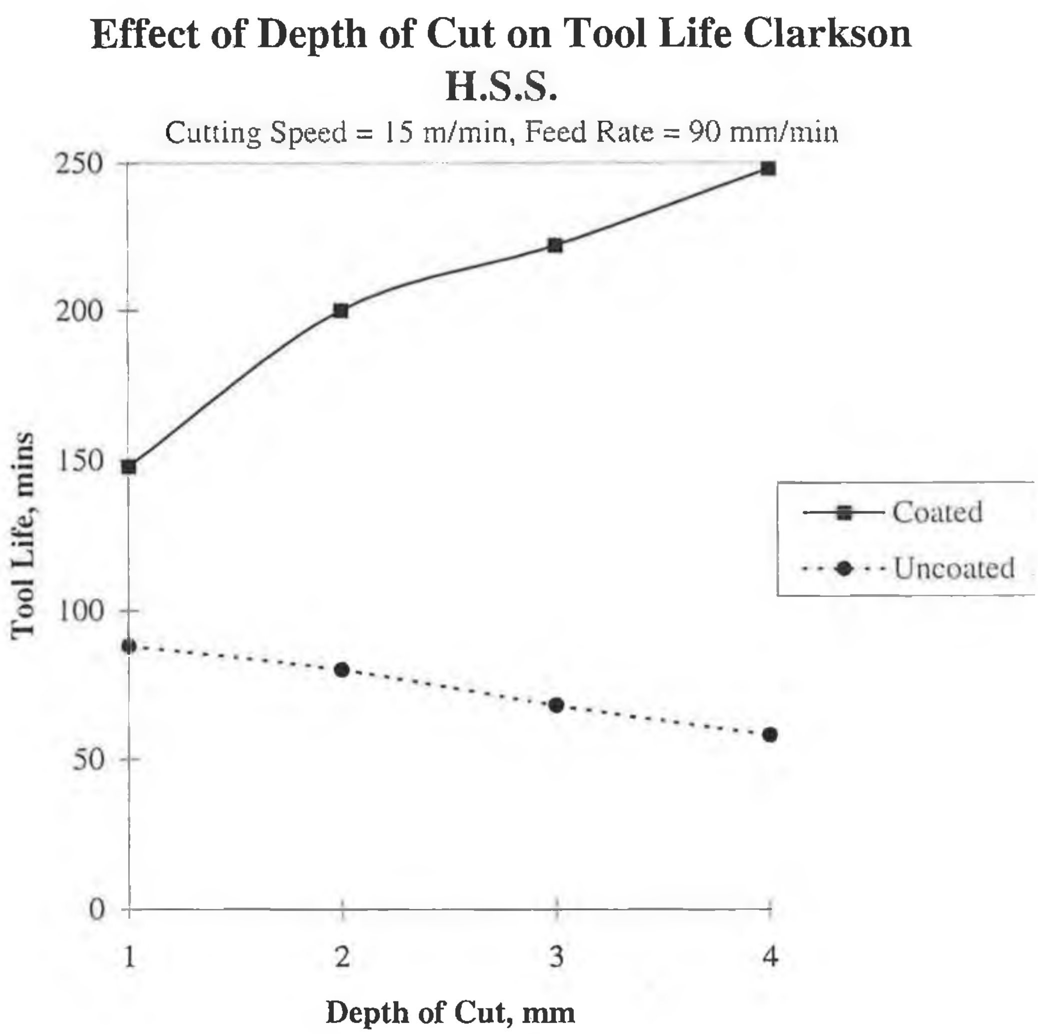

Figure 6.3.2c, Tool manufacturer comparison (varying depth of cut)

Conclusions

The performance of the coated tools exceeds that of the uncoated tools by at least 50% for all cutting speeds, feed rates and depths of cut. On average the coated tools last 104% longer than the uncoated tools. The performance increases with increasing cutting speed, rising from 60% at 10 m/min to 80% longer tool life at 20 m/min. Whereas with increasing feed the performance falls from 73% at 60 mm/min to 50% longer tool life at 120 mm/min. With depth of cut the tool life increases from 68% at 1mm to 300% at 4mm. Therefore in order to get the most tool life benefits out of the coated tools it is advisable to machine at a high depth of cut, coupled with medium cutting speeds and feed rates.

The main reasons why coated tools perform better than their uncoated counterparts is that they are more chemically inert, thermally stable and possess better physical properties than uncoated tools at the temperatures that are present in milling operations. This makes them more resistant to diffusion wear and abrasion wear which are the predominant wear mechanisms in milling.

One of the reasons why coated tools are abrasion resistant is because they possess higher hardness than uncoated at both room and elevated temperatures. Another reason is that the surface of the coating itself, has a lower coefficient of friction than the surface of the substrate (uncoated tool). This benefits the tool in two ways, firstly less friction is produced and this results in lower abrasion between the cutting tool and workpiece, while at the same time this reduction in friction means that less heat is generated and therefore less temperature dependent wear (diffusion wear) is generated.

The chemical inertness and thermal stability of coated tools, means that they are less reactive, which means that their is less movement of the atoms in the coated tools and therefore less diffusion wear due to migration of atoms from the surface of the tool into the workpiece. [13]

The prices of the two different cutting tools are as follows;

- Uncoated ~ £38.56 per tool (excl. Vat),
- Coated ~ £61.98 per tool (excl. Vat),

The coated tools cost 60% more than the uncoated tools. With the coated tools out-performing the uncoated by an average of 104%. It is recommended that for Clarkson cutters, that coated tools be preferred ahead of uncoated tools.

6.3.3 Tool Coating Comparison (Strassmann)

a) Effect of Cutting Speed

The tests were carried out by keeping both the feed rate and depth of cut constant at 90 mm/min and 1 mm respectively, while varying the cutting speed from 10 - 20 m/min.

Table 6.3.3a Tool Life with varying Cutting Speed

Cutting Speed	Tool Life (minutes)	
(m/min)	Uncoated	Coated
10	124	190
15	112	166
20	96	145

As can be seen from both the table and the graph, tool life decreases with increasing cutting speed. This can be attributed to the fact that the cutting temperature increases with increasing speed. The rise in temperature is generated by two sources of heat. These sources of heat are from the energies created in the shear plane during the formation of the chip and from the friction between the chip and the rake face. This excess heat causes diffusion wear, which occurs by the process of chemical dissolution of the tool material in the chip, particularly at the hottest point of contact, which is a short distance back from the cutting edge. Another effect of high temperature in the cutting zone is that it can produce thermal shock cracks. These cracks are caused by thermal cycling as a result of intermittent cutting, which is a feature of milling operations. Under these conditions the effects of abrasion wear are negligible. [11]

It can be seen from the graph, that coated cutting tools out-perform the uncoated tools by 50% on average across the cutting speed range. The coated tools lasted 53% longer at 10 m/min and lasted 51% longer at 20 m/min. This is due to the fact that less cutting forces are produced when machining with coated tools, which results in lower cutting temperature. They are also more thermally and chemically stable than uncoated tools and therefore they do not interact or alloy with the workpiece material. The combined effect of the previous two properties results in increased solution wear resistance. [13]

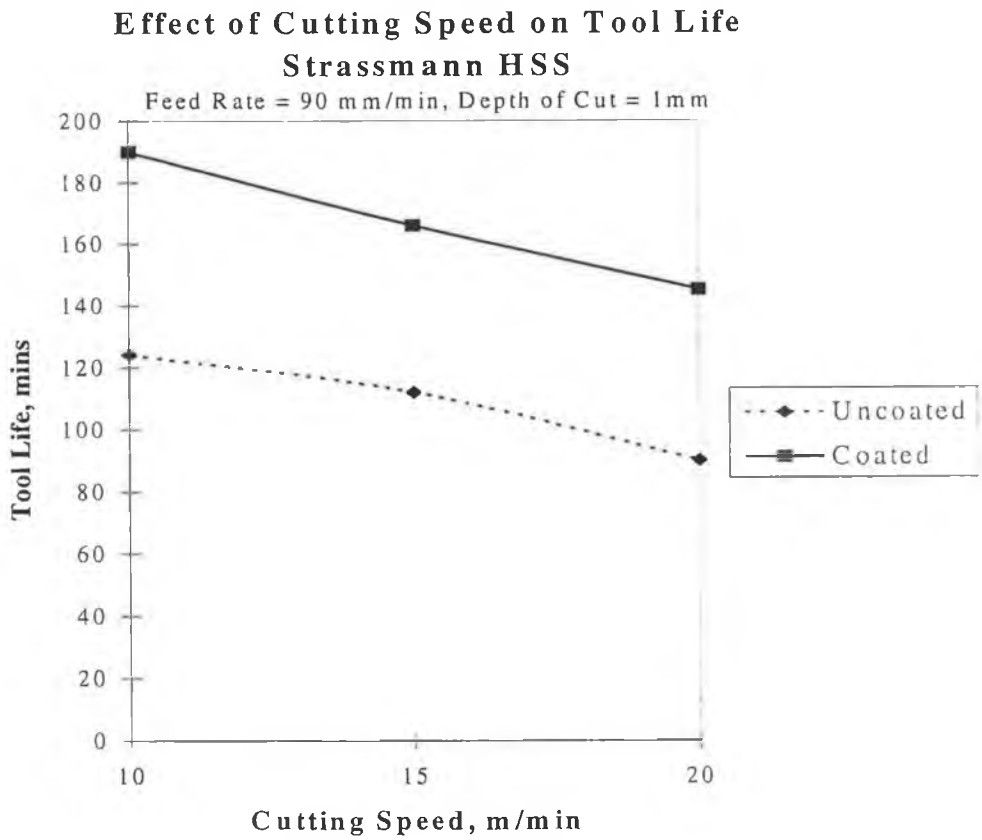

Figure 6.3.3a, Tool manufacturer comparison (varying cutting speed)

b) Effect of Feed Rate

The tests were carried out by keeping both the cutting speed and depth of cut constant at 15 m/min and 1 mm respectively, while varying the feed rate from 60 - 120 mm/min. The following table and graph are a representation of the tool life's obtained at varying feed rates.

Table 6.3.3b Tool Life with varying Feed Rate

Feed Rate	**Tool Life (minutes)**	
(mm/min)	**Uncoated**	**Coated**
60	120	204
90	112	166
120	106	158

in the cutting zone. This increased resistance is due to the chemical inertness and higher hardness level of TiN at elevated temperatures. The coated tools perform better at lower feeds, lasting 84% longer at 60 m/min and 50% longer at 120 m/min. Therefore in order to get the most benefit out of using coated tools it is advisable to operate at a low a feed rate as possible. [13]

c) Effect of depth of cut on tool life.

The tests were carried out by keeping both the cutting speed and feed rate constant at 15 m/min and 90 mm/min respectively, while varying the depth of cut from 1 - 4 mm. The following table and graph are a representation of the tool life's obtained at varying depths of cut.

Table 6.3.3c Tool Life with varying Depth of Cut

Depth of Cut	**Tool Life (minutes)**	
(mm)	**Uncoated**	**Coated**
1	112	166
2	95	248
4	80	328

The effect of depth of cut is very different on the tool life's of uncoated and coated tools. For the uncoated tool an increase in the depth of cut results in a decrease in the tool life. This is due to the fact that the temperature increases more for uncoated tools than for coated tools and results in increased diffusion wear. The increase in the depth of cut also results in an increase in chip load and therefore cutting pressure, which increases the abrasive wear on the tool. The overall result for uncoated tools is an increase in total wear due to increases in both diffusion and abrasive wear with increasing depth of cut. [11]

On the other hand, for coated tools an increase in the depth of cut results in a increase in tool life. This is because the size of the chip produced increases with increased depth of cut and therefore the proportion of the overall temperature transmitted to the chip increases. The net result is that the increase in the cutting tool temperature is very small. This small increase in tool temperature has the effect of increasing the diffusion wear but not significantly. The increase in overall cutting temperature is mainly transmitted to the chip and workpiece, which results in a softening of the surface workpiece material. The resulting reduction in hardness of the workpiece material causes a reduction in the abrasiveness of the workpiece material. This has the effect of reducing the amount of abrasive wear on the cutting tool. The overall effect of the increase in cutting temperature is that the abrasion wear decreases, more than the diffusion wear increases, and therefore there is a net reduction in overall tool wear with increasing depth of cut. [13]

Again coated tools out-perform uncoated tools by at least 50% across the entire depth of cut range, rising from 50% at 1mm depth of cut to over 330% longer tool life at 4mm depth of cut.

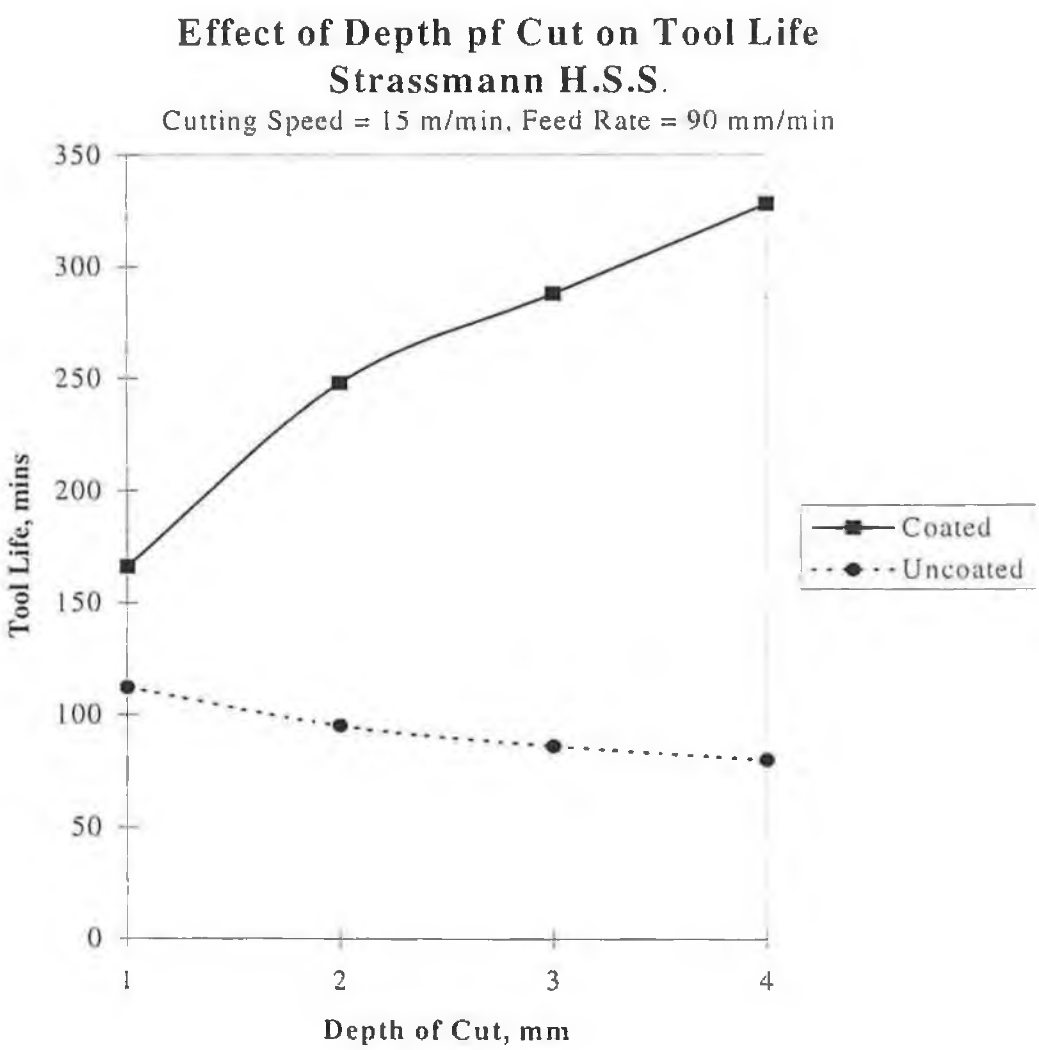

Figure 6.3.3c, Tool manufacturer comparison (varying depth of cut)

Conclusions

The performance of the coated tools exceeds that of the uncoated tools by at least 50% for all cutting speeds, feed rates and depths of cut. On average the coated tools last 95% longer than the uncoated tools. The performance remains constant with increasing cutting speed, lasting 53% longer at 10 m/min and 51% longer at 20 m/min.. Whereas with increasing feed the performance falls from 73% at 60 mm/min to 50% longer tool life at 120 mm/min. With depth of cut the tool life increases from 50% at 1mm to 310% at 4mm. Therefore most tool life benefits are obtained by operating coated tools at a high depth of cut, coupled with medium cutting speeds and feed rates.

The reasons why coated tools perform better than their uncoated counterparts is that they are more chemically inert and thermally stable at the temperatures that are present in milling operations. This makes them more resistant to diffusion wear which is the predominant wear mechanism in milling. They possess higher hardness at elevated temperatures and as a result have higher abrasion wear resistance than uncoated tools. The surface of the coating has a lower co-efficient of friction than that of the substrate material (uncoated tool), this has the effect of reducing the amount of friction between the tool and workpiece surfaces which results in less abrasive wear on the cutting tool. Friction between the tool and workpiece produces heat which increases the temperature in the cutting zone and increases the temperature dependent wear (diffusion wear) on the tool. Therefore the reduction in friction between the coating and workpiece, means that less heat is produced and consequently the amount of temperature dependent wear is reduced. [13]

The coated tools cost 60% more than the uncoated tools. With the coated tools out-performing the uncoated by an average of 95% across the entire range. It is recommended that for Strassmann cutters, that coated tools be preferred ahead of uncoated tools.

6.3.4 Coated end mill comparison

a) Effect of Cutting Speed

The tests were carried out by keeping both the feed rate and depth of cut constant at 90 mm/min and 1 mm respectively, while varying the cutting speed from 10 - 20 m/min.

Table 6.3.4a Tool Life with varying Cutting Speed

Cutting Speed	Tool Life, (minutes)		
(m/min)	Kestag	Clarkson	Strassman
10	145	155	190
15	131	148	166
20	112	140	145

As can be seen from both the table and the graph, tool life decreases with increasing cutting speed. This can be attributed to the fact that cutting temperature increases with increasing speed. The rise in temperature is generated by two sources of heat. These sources of heat are from the energies created in the shear plane during the formation of the chip and from the friction between the chip and the rake face. This excess heat causes diffusion wear, which occurs by the process of chemical dissolution of the tool material in the chip, particularly at the hottest point of contact, which is a short distance back from the cutting edge. Another effect of high temperature in the cutting zone is that it can produce thermal shock cracks. These cracks are caused by thermal cycling as a result of intermittent cutting, which is a feature of milling operations. Under these conditions the effects of abrasion wear are negligible. [11]

It can be clearly seen from the graph, that Strassmann have the longest tool life of the three tools, with Clarkson next and finally Kestag with the shortest tool life.. The Strassmann out-performs the Clarkson by 23% at 10 m/min, however this drops to 3% at 20 m/min.. It out-performs the Kestag by the same percentage across the entire range, lasting 30% longer at 10 m/min and also at 20 m/min. The Clarkson performs 7% better than Kestag at 10 m/min, with the performance rising to 25% longer tool life at 20 m/min.

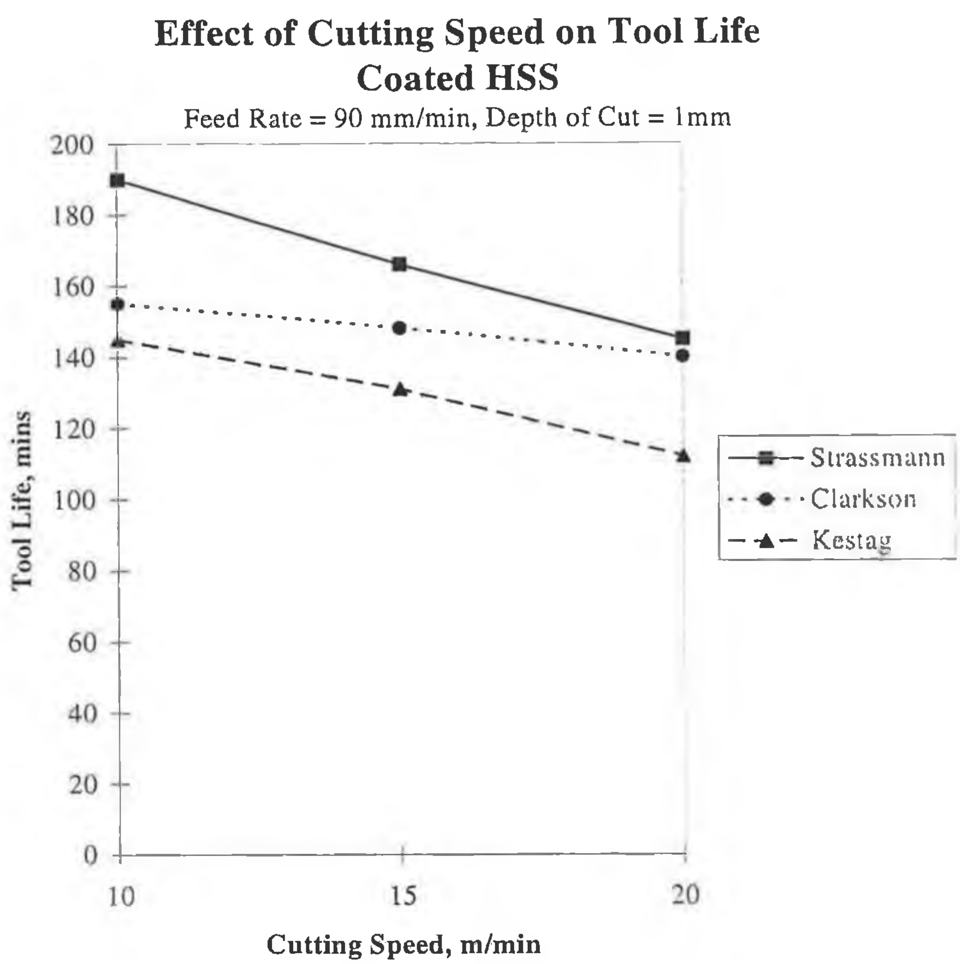

Figure 6.3.4a, Effect of Cutting Speed on Tool Life

b) Effect of Feed Rate on Tool Life

The tests were carried out by keeping both the cutting speed and depth of cut constant at 15 m/min and 1 mm respectively, while varying the feed rate from 60 - 120 mm/min. The following table and graph are a representation of the tool life's obtained at varying feed rates.

Table 6.3.4b Tool Life with varying Feed Rate

Feed Rate	Tool Life, (minutes)		
(mm/min)	Kestag	Clarkson	Strassman
60	155	182	204
90	131	148	166
120	100	112	158

As can be seen from both the table and the graph, tool life decreases with increasing feed rate. This can be attributed to the fact that as the feed increases the greater is the cutting force produced per unit area of chip-tool contact on the rake face and work-tool contact on the flank face. The increase in cutting force can also be attributed to the fact that the chip thickness and therefore chip load increases with feed rate. This increase in chip load causes both an increase in the cutting pressure and temperature. The increase in the pressure results in increased abrasive wear and the rise in temperature causes an increase in the diffusion wear on the tool. Of the two types of wear discussed in this section, diffusion wear is the more prominent.[11]

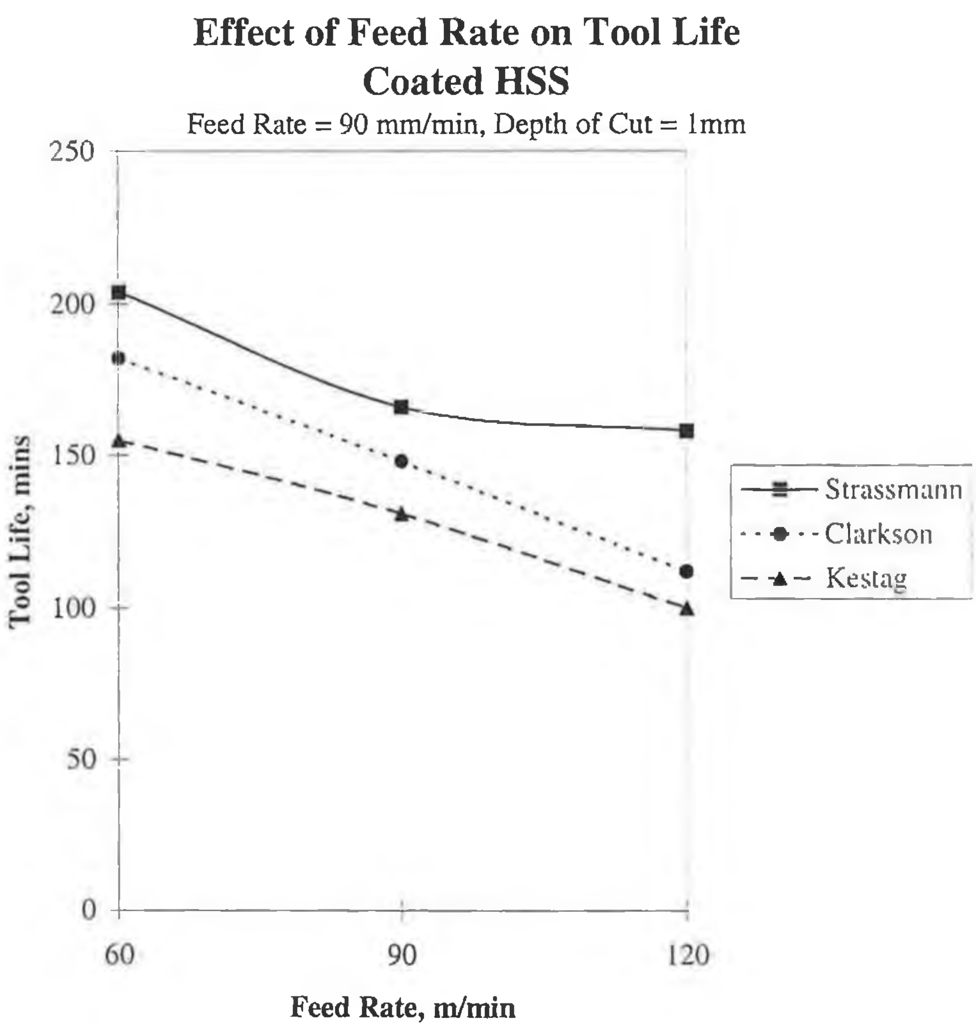

Figure 6.3.4b Effect of Feed Rate on Tool Life

From the graph of Tool Life vs. Feed Rate, it can be seen that once again Strassmann has the longest tool life of the three cutters, with Clarkson next and finally Kestag with the shortest tool life. The Strassmann perform 12% better than Clarkson and 30% better than Kestag at 60 mm/min. This rises to 40% longer tool life than Clarkson and 58% more than Kestag at 120 mm/min. The Clarkson possess 17% longer tool life than Kestag at 60 mm/min and 12% at 120 mm/min.

c) Effect of Depth of Cut

The tests were carried out by keeping both the cutting speed and feed rate constant at 15 m/min and 90 mm/min respectively, while varying the depth of cut from 1 - 4 mm. The following table and graph are a representation of the tool life's obtained at varying depths of cut.

Table 6.3.4c Tool Life with varying Depth of Cut

Depth of Cut	**Tool Life, (minutes)**		
(mm)	**Kestag**	**Clarkson**	**Strassman**
1	131	148	166
2	173	200	248
4	200	248	328

It can be seen that an increase in the depth of cut results in an increase in tool life. This is due to the fact that the size of the chip produced increases with increasing depth of cut and therefore the proportion of the overall temperature transmitted to the chip/workpiece increases. The net result is that the increase in the cutting tool temperature is very small. This small increase in the tool temperature increases the amount of diffusion wear on the tool, but not significantly. The large increase in the chip/workpiece temperature has the effect of reducing the hardness of the workpiece material, making it less abrasive and reducing the wear on the cutting tool. The overall effect of the cutting temperature increase is that the amount of abrasion wear decreases, more than the diffusion wear increases, and consequently there is a net reduction in overall tool wear with increasing depth of cut. [13]

From the graph it can be seen that Strassmann has the best performance of the three. The Clarkson has the second best tool life with the Kestag possessing the shortest tool life of the three. The Strassmann has 12% longer tool life than Clarkson at 1mm and this rises from 25% at 2mm, to 32% longer tool life at 4mm depth of cut. The Strassmann performs 27% longer than the Kestag at 1mm and 43% at 2mm and possesses over 60% longer tool life at 4mm depth of cut. The Clarkson lasted 13% longer than Kestag at 1mm and by 24% at 4mm depth of cut.

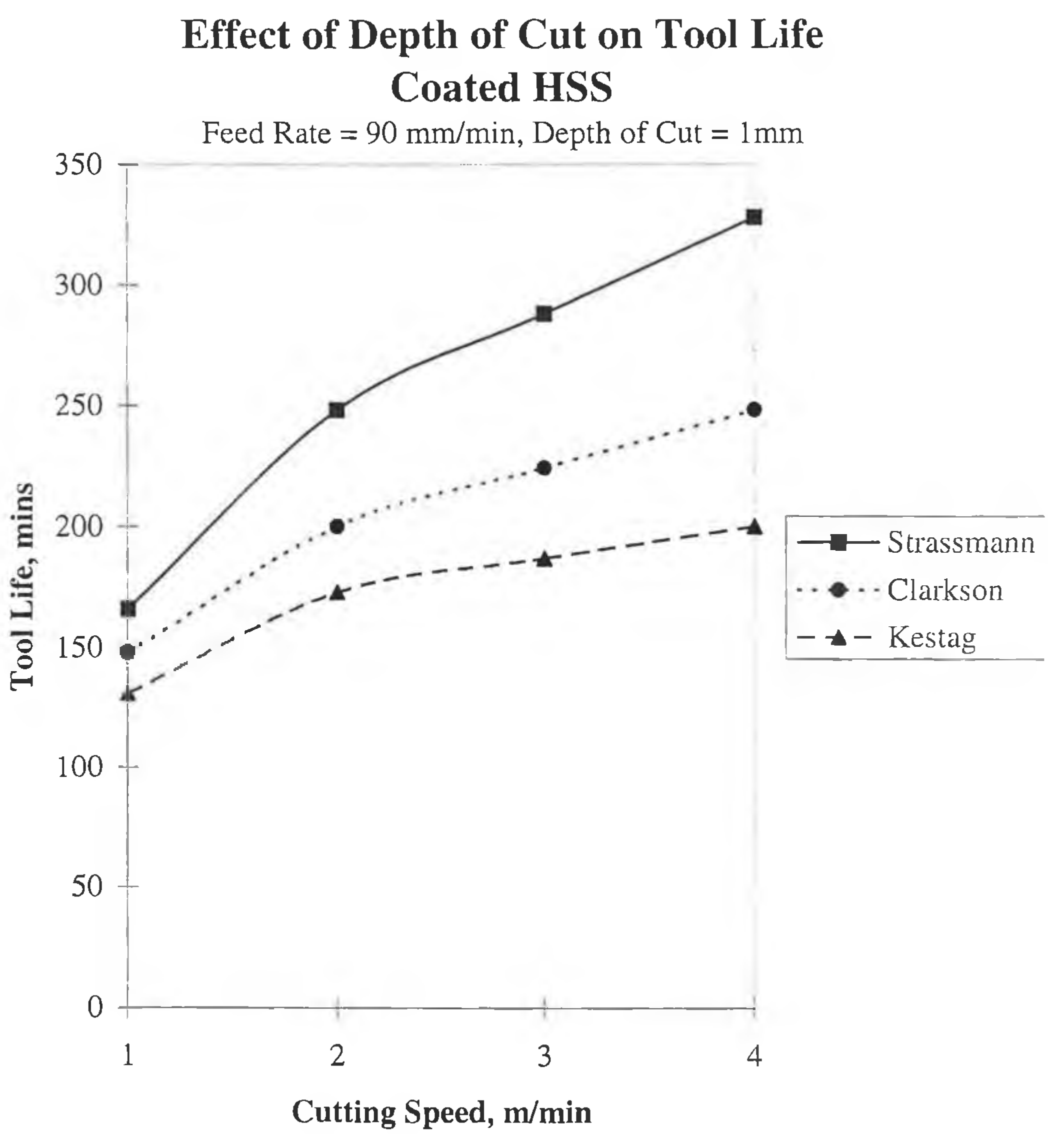

Figure 6.3.4c Effect of Depth of Cut on Tool Life

Conclusions

From both the graphs of cutting speed, feed rate and depth of cut versus tool life, it can be seen that Strassmann cutters perform by at least 3% and up to 41% better than Clarkson. On average Strassmann have 19% longer tool life than Clarkson tools. The Strassmann lasts at least 27% and up to 64% longer than Kestag tools. On average Strassmann performed 37% longer than Kestag.

One of the reasons why Strassmann performs better than both Clarkson and Kestag is that the secondary clearances on the rake faces are smaller on Strassmann cutters. There is also less variation in these clearances than on the tools produced by the other tool manufacturers. The net effect of this is that teeth on the Strassmann wear at a uniform rate and therefore all of the teeth fail at roughly the same time. Whereas the teeth on Clarkson and Kestag wear at different rates and causes some teeth to wear quickly while other teeth wear very little. This causes the tool to wear a lot quicker than it would if the teeth had uniform clearances and therefore wore at the same rate.

The Clarkson performs better than Kestag, because although it has a variance in the clearances on its rake face, there are less discrepancies than on the Kestag. This results in a more uniform wear rate on the Clarkson compared to Kestag.

The Strassmann tools cost 15% more than the Clarkson tools but 23% less than Kestag cutters. With the Strassmann out-performing the Clarkson by an average of 19% and the Kestag by 37% it is recommended that Strassmann coated tools be chosen ahead of Clarkson and Kestag.

6.3.5 Conclusions on High Speed Steel

From the tool life tests on H.S.S. end mills the following conclusions on their behaviour and performances can be made.

Uncoated H.S.S. End Mills

⇒ An increase in the cutting speed results in a decrease in tool life.

⇒ An increase in the feed rate results in a decrease in tool life.

⇒ An increase in the depth of cut results in a decrease in tool life.

⇒ The Strassmann cutting tools perform on average 27% better than their Clarkson counterparts. It is therefore advised that Strassmann be chosen ahead of Clarkson.

⇒ The performance of the Strassmann over the Clarkson increases with both increasing feed rate and depth of cut, but decreases for increasing cutting speed.

Coated H.S.S. End Mills

⇒ An increase in the cutting speed results in a decrease in tool life.

⇒ An increase in the feed rate results in a decrease in tool life.

⇒ An increase in the depth of cut results in an increase in tool life.

⇒ The coated tools perform by on average 100% better than their uncoated counterparts.

⇒ The Strassmann cutting tools perform on average 19% better than Clarkson and 37% better than Kestag. It is therefore advised that Strassmann be chosen ahead of both Clarkson and Kestag.

⇒ The performance of Strassmann over Clarkson and Kestag increases with both increasing feed rate and depth of cut, but decreases for increasing cutting speed.

⇒ In order to get the most out of the coated tools it is recommended that for roughing operations, a depth of cut between 2mm and 4mm should be used. This should be coupled with a medium cutting speed (14-16 m/min) and a high feed rate (100-120 mm/min).

Tool Geometry

From the tests it can be concluded that tool geometry and in particular the clearance on the rake face, is the most significant factor affecting tool wear rates and consequently the tool life that is obtainable. It is the uniformity of these clearances that is the underlining reason for the enhanced performance of the Strassmann cutting tools over both Clarkson and Kestag.

Figure 6.3.5a is a representation of a new cutting tool, which has a small clearance on the rake face. Figure 6.3.5b is a representation of a worn tool and shows wear on the flank.

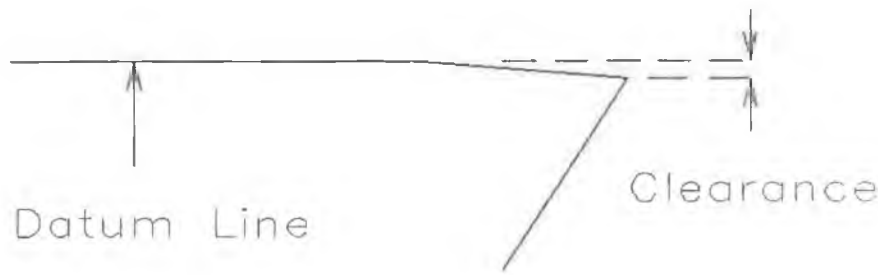

Figure 6.3.5a, A new cutting tool

The clearance present on the rake face of the cutting teeth is not constant, it varies from tooth to tooth and from one end mill to another. This affects the wear of the tool, in that, teeth on the same tool wear at different rates.

This occurs because the chipload (wear rate) varies on cutters with different clearance values The teeth with the least clearance confront more chipload than the teeth with higher clearance. However this does not balance out tool life; rather, a domino effect ensues. As one tooth fails prematurely, the following tooth carries an excessive chipload, repeating the wear cycle. The end result is inevitably shorter tool life.

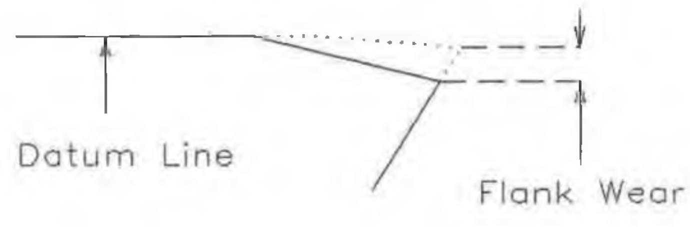

Figure 6.3.5b, A worn cutting tool

As was already mentioned earlier, most cutters tend to have teeth with different rake clearance values which results in different wear rates on the same cutting tool. However, during the investigation one particular tool in the batch was found, to have no rake clearance on any of its teeth. This particular tool had a significantly longer tool life than expected. Although this tool was a standard tool, it had the geometry of a qualified cutting tool and although the findings are inconclusive it has nonetheless raised some interesting points on the benefits of using qualified tools. In light of these findings it is suggested that further research work could be conducted into the performance of qualified tools compared to standard tools.

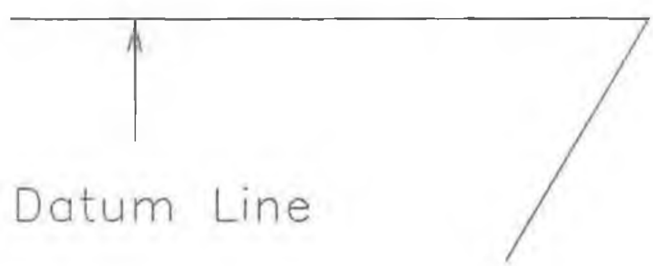

Figure 6.3.5c, A tooth with no rake clearance

6.3.6 Uncoated Cemented Carbide (Sandvik)

In order to investigate the relationships between cutting conditions (cutting speed, feed rate and depth of cut) and tool life for cemented carbides, a series of cutting tests were conducted. For the experiments each variable was tested at three levels, with the two other variables being kept constant.

The inserts that were used for the tests where 9 mm long, 2.4 mm thick, had a nose radius 0.8mm and were grade P30 carbide. The toolholder required 3 inserts per tool and each insert had two cutting edges.

The cutting conditions for the first cutting tests were chosen following consultation with the tool manufacturers catalogue. However these conditions proved to be very unsuitable and a lot of cutting tests had to be undertaken before a suitable combination was found. This is because tool manufacturer catalogues tend to be general and the cutting data is only suitable for the widely used workpiece materials such as mild steel and grey cast iron. This lack of data cutting on some of the more specialized workpiece materials is in essence one of the main reasons for carrying out machinability studies such as this investigation.

a) Effect of Cutting Speed on Tool Life

The tests were carried out by keeping both the feed rate and depth of cut constant at 340 mm/min and 1 mm respectively, while varying the cutting speed from 55 - 75 m/min.

Table 6.3.6a, Tool Life with varying Cutting Speed

Cutting Speed (m/min)	Tool Life (minutes)
55	34
65	28
75	20.5

As can be seen from the both the table and the graph, tool life decreases with increasing cutting speed. This can be attributed to the fact that as the cutting speed increases, the friction between the rake face on cutting tool and the workpiece increases and as a result the cutting temperature increases. The temperature also rises due to the heat that is generated from the energies created in the shear plane during the formation of the chip. This excess heat causes diffusion wear, which occurs by the process of chemical dissolution of the tool material in the chip, particularly at the hottest point of contact, which is a short distance back from the cutting edge. Another effect of high temperature in the cutting zone, which is particularly detrimental to carbides, is that it can produce thermal shock cracks. These cracks are caused by thermal cycling as a result of intermittent cutting, which is a feature of milling operations. Under these conditions the effects of abrasion wear are negligible. [11]

The tool life decreases by 40% across the range, with the cutting speed increasing by 36% from 55 m/min to 75 m/min. This roughly equates to a 1 % decrease in tool life for every percent increase in cutting speed.

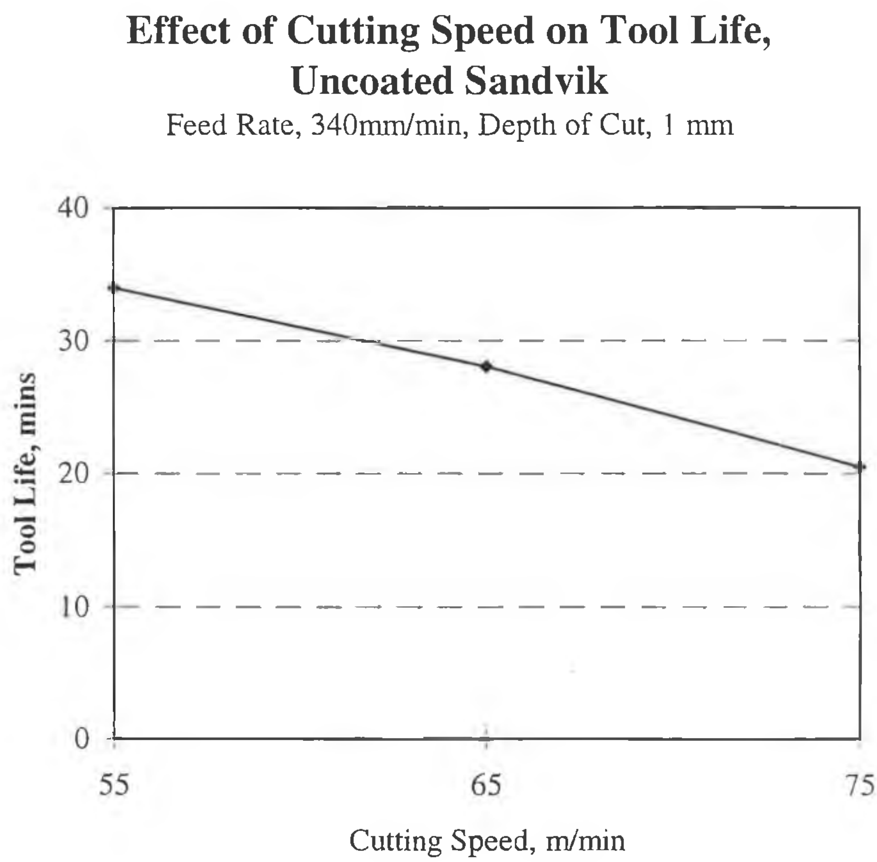

Figure 6.3.6a, Effect of Cutting Speed on Tool Life

b) Effect of Feed Rate on Tool Life

The tests were carried out by keeping both the cutting speed and depth of cut constant at 65 mm/min and 1 mm respectively, while varying the cutting speed from 310 - 370 m/min.

Table 6.3.6b. Tool Life with varying Feed Rate

Feed Rate (mm/min)	Tool Life (minutes)
310	36
340	28
370	22

As can be seen from both the table and the graph, tool life decreases with increasing feed rate. This can be attributed to the fact that as the feed increases the greater is the cutting force produced per unit area of chip-tool contact on the rake face and work-tool contact on the flank face. The increase in cutting force can also be attributed to the fact that the chip thickness and therefore chip load increases with feed rate. This increase in chip load causes both an increase in the cutting pressure and temperature. The increase in the pressure results in increased abrasive wear and the rise in temperature causes an increase in the diffusion wear on the tool. Of the two types of wear discussed in this section, diffusion wear is the more prominent.[11]

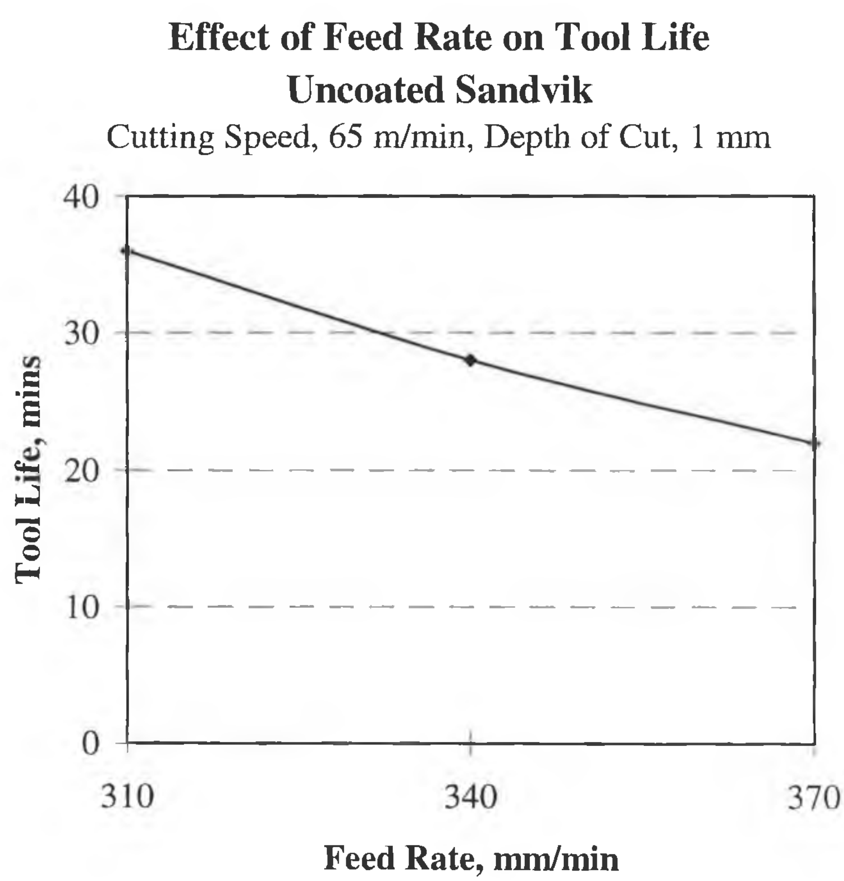

Figure 6.3.6b, Effect of Feed Rate on Tool Life

The tool life decreases by 39% across the range, with the feed rate increasing by 19% from 310 mm/min to 370 mm/min. This roughly equates to a 2 % decrease in tool life for every percent increase in feed rate.

c) Effect of Depth of Cut on Tool Life

The tests were carried out by keeping both the cutting speed and feed rate constant at 65 m/min and 340 mm/min respectively, while varying the depth of cut 1 - 4 mm.

Table 6.3.6c. Tool Life with varying Depth of Cut

Depth of Cut (mm)	Tool Life (minutes)
1	28
2	22
4	16

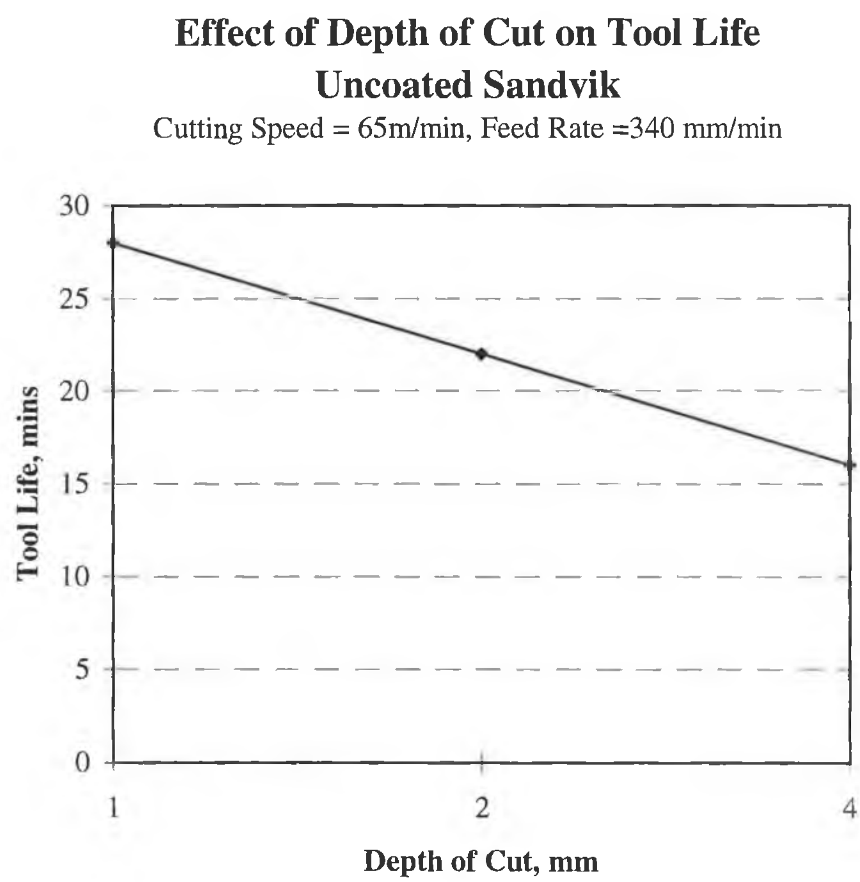

Figure 6.3.6c, Effect of Depth of Cut on Tool Life

As can be seen from both the table and the graph, tool life decreases with increasing depth of cut. This can be attributed to the fact that as the depth of cut increases the greater are the both the cutting force produced between the chip and tool and the cutting temperature. The increase in cutting force can be attributed to the fact that the chip thickness and therefore chip load increases with increasing depth of cut. This increase in chip load causes both an increase in the cutting pressure and temperature. The increase in the pressure results in increased abrasive wear and the rise in temperature causes an increase in the diffusion wear on the tool. Of the two types of wear discussed in this section, diffusion wear is the more prominent. The increase in temperature with an increase in the depth of cut is not as significant as that for both cutting speed and feed rate. This is because with an increase of depth of cut the length of cutting edge in contact with the workpiece increases resulting in greater dissipation of heat produced during cutting. [11]

The tool life decreases by 43% across the range, with the depth of cut increasing by 300 % from 1 mm to 4 mm. This roughly equates to a 1 % decrease in tool life for every 7 percent increase in depth of cut.

Conclusions

- An increase in the cutting speed causes an increase in the diffusion wear and consequently causes a decrease in the tool life.

- An increase in the feed rate results in an increase in both diffusion and abrasive wear, therefore resulting in a reduction in the tool life.

- An increase in the depth of cut results in an increase in the diffusion wear and a small increase in the abrasion wear, causing a reduction in the tool life.

The feed rate is the most significant factor of the three cutting conditions, followed by the cutting speed and depth of cut. The depth of cut has a very minor affect on the tool life, with only a 43 % decrease in the tool life over a 300 % increase in the depth of cut.

6.3.7 Uncoated Cemented Carbide (Iscar)

a) Effect of Cutting Speed on Tool Life

The tests were carried out by keeping both the feed rate and depth of cut constant at 430 mm/min and 1 mm respectively, while varying the cutting speed from 75 - 95 m/min.

Table 6.3.7a, Tool Life with varying Cutting Speed

Cutting Speed (m/min)	Tool Life (minutes)
75	21
85	17
95	13

As can be seen from the both the table and the graph, tool life decreases with increasing cutting speed. This can be attributed to the fact that the cutting temperature increases with increasing speed. The rise in temperature is generated by two sources of heat. These sources of heat are from the energies created in the shear plane during the formation of the chip and from the friction between the chip and the rake face. This excess heat causes diffusion wear, which occurs by the process of chemical dissolution of the tool material in the chip, particularly at the hottest point of contact, which is a short distance back from the cutting edge. Another effect of high temperature in the cutting zone is that it can produce thermal shock cracks. These cracks are caused by thermal cycling as a result of intermittent cutting, which is a feature of milling operations. Under these conditions the effects of abrasion wear are negligible. [11]

The tool life decreases by 43% across the range, with the cutting speed increasing by 26% from 75 m/min to 95 m/min. This roughly equates to a 1.5 % decrease in tool life for every percent increase in cutting speed.

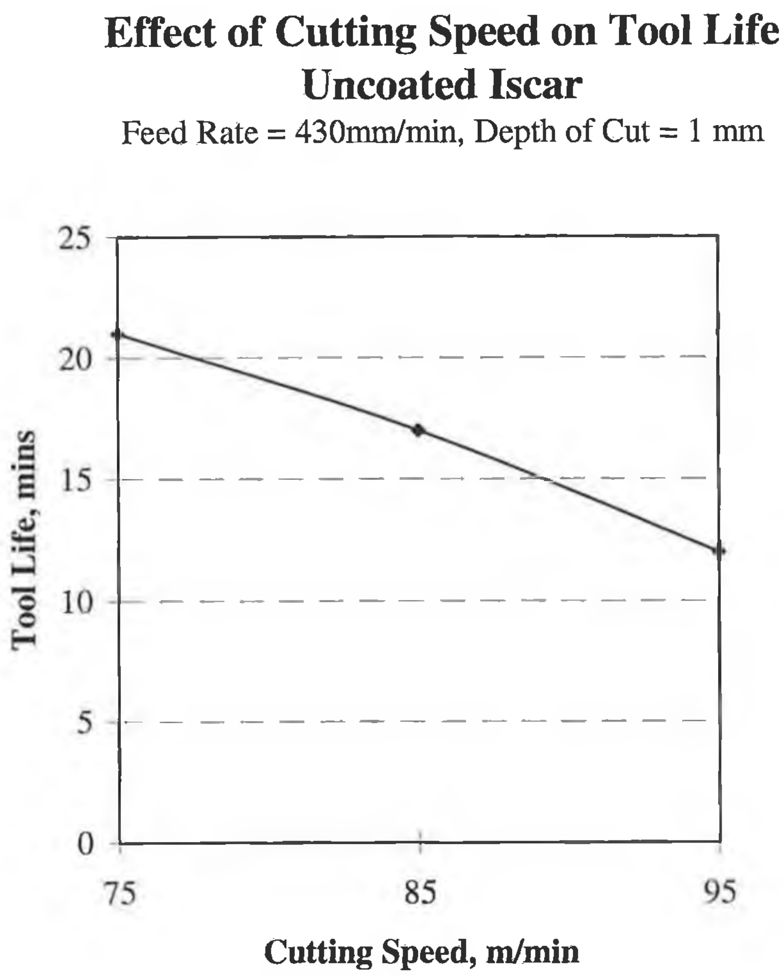

Figure 6.3.7a, Effect of Cutting Speed on Tool Life

b) Effect of Feed Rate on Tool Life

The tests were carried out by keeping both the cutting speed and depth of cut constant at 85 mm/min and 1 mm respectively, while varying the cutting speed from 380 - 480 mm/min.

Table 6.3.7b, Tool Life with varying Feed Rate

Feed Rate (mm/min)	Tool Life (minutes)
380	20
430	17
480	12

As can be seen from both the table and the graph, tool life decreases with increasing feed rate. This is due to the increase in the cutting forces produced per unit area of chip-tool contact on the rake face and work-tool contact on the flank face. This increase in cutting force can also be attributed to the fact that the chip thickness and therefore chip load increases with feed rate. The increased chip load causes both an increase in the cutting pressure and temperature and results in increased abrasive wear and diffusion wear on the tool. Of the two types of wear discussed in this section, diffusion wear is the more prominent, however abrasive wear has now become a quite significant factor. [11]

The tool life decreases by 25% across the range, with the feed rate increasing by 26% from 380 mm/min to 480 mm/min. This roughly equates to a 1 % decrease in tool life for every percent increase in feed rate.

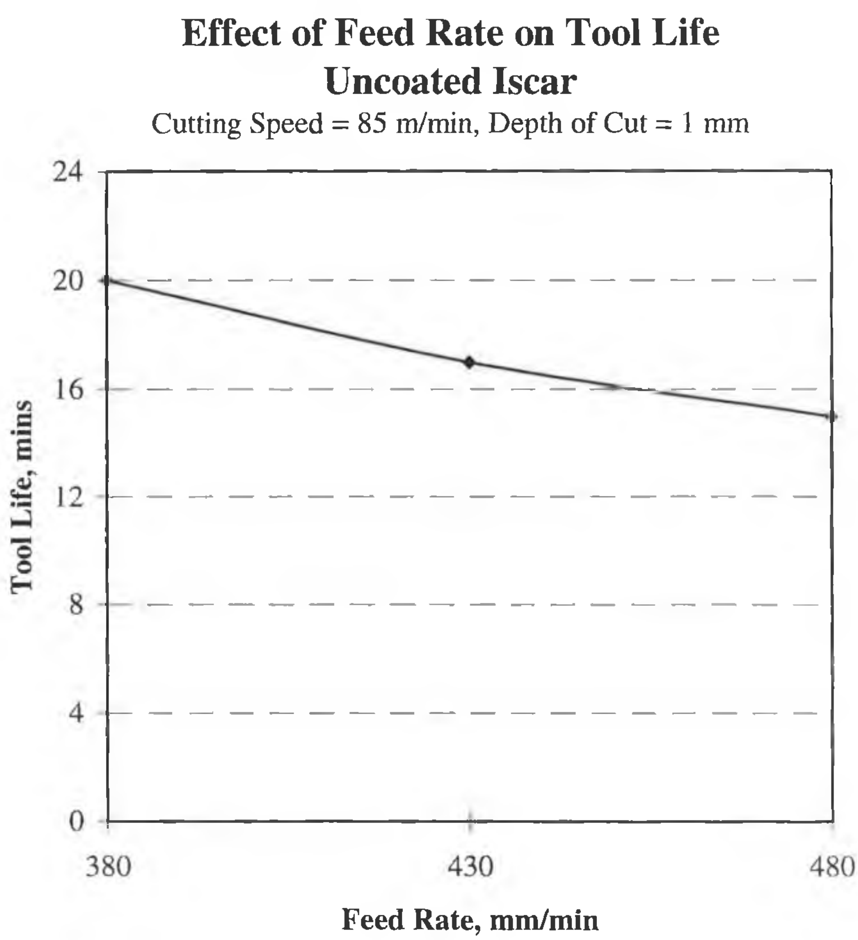

Figure 6.3.7b, Effect of Feed Rate on Tool Life

c) Effect of Depth of Cut on Tool Life

The tests were carried out by keeping both the cutting speed and feed rate constant at 85 m/min and 430 mm/min respectively, while varying the depth of cut 1 - 4 mm.

Table 6.3.7c, Tool Life with varying Cutting Speed

Depth of Cut (m/min)	Tool Life (minutes)
1	17
2	13.5
4	10.5

As can be seen from both the table and the graph, tool life decreases with increasing depth of cut. This can be attributed to the fact that as the depth of cut increases the greater are the cutting force produced between the chip and tool and the cutting temperature. The increase in cutting force is due to the fact that the chip thickness and therefore chip load increases with increasing depth of cut. This increase in chip load causes both an increase in the cutting pressure and temperature. The increase in the pressure results in increased abrasive wear and the rise in temperature causes an increase in the diffusion wear on the tool. Although the effect of diffusion wear is the more prominent, the affect of abrasive wear is more noticeable, due to the increase in the cutting force on the tool. The increase in temperature with an increase in the depth of cut is not as significant as that for both cutting speed and feed rate. This is because with an increase of depth of cut, the length of cutting edge in contact with the workpiece increases resulting in greater dissipation of heat produced during cutting. [11]

The tool life decreases by 38 % across the range, with the depth of cut increasing by 300 % from 1 mm to 4 mm. This roughly equates to a 1 % decrease in tool life for every 8 percent increase in depth of cut.

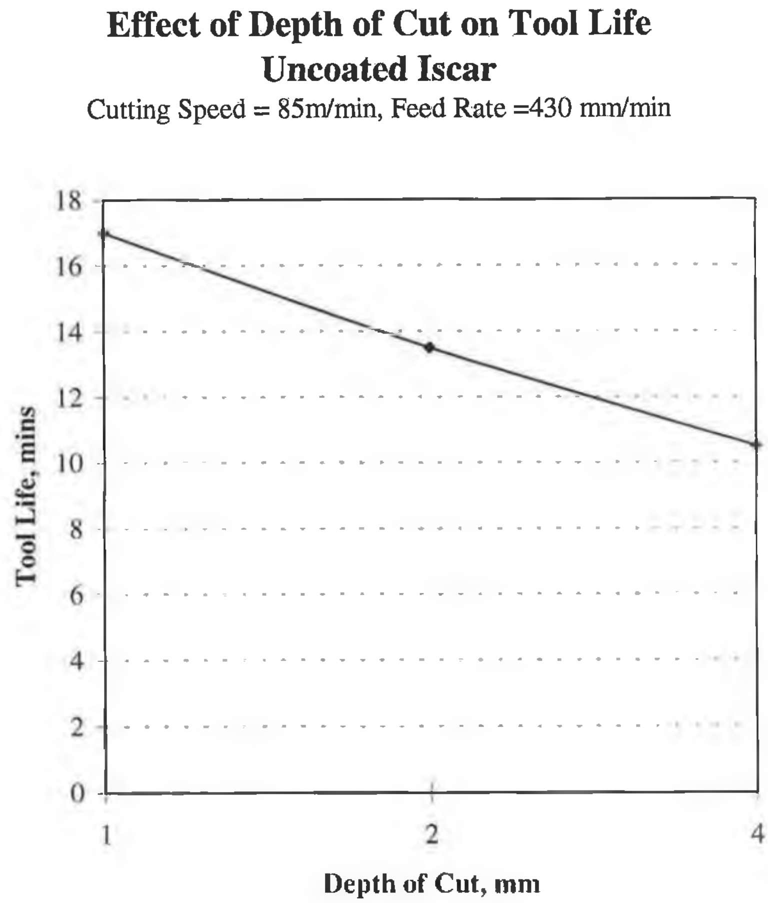

Figure 6.3.7c, Effect of Depth of Cut on Tool Life

Conclusions

- An increase in the cutting speed causes an increase in the diffusion wear and consequently causes a decrease in the tool life.
- An increase in the feed rate results in an increase in both diffusion and abrasive wear, therefore resulting in a reduction in the tool life.
- An increase in the depth of cut results in an increase in the diffusion wear and a small increase in the abrasion wear, causing a reduction in the tool life.

The cutting speed is the most significant factor of the three cutting conditions, followed by the feed rate and depth of cut. The reason for the difference between the Sandvik and Iscar cutting tools, is that the cutting speed is higher for the Iscar and therefore has a greater effect on the tool life.

6.3.8 Coated Cemented Carbide (Sandvik)

a) Effect of Cutting Speed on Tool Life

This directly effects the tool wear rate, surface finish, cutting forces and the type of chip formed. For cemented carbides there is a very narrow temperature range in which the material gives optimum performance. At low temperatures, pressure welding of the chips results in edge buildup, whereas at high cutting temperatures, scaling and crater wear are predominant factors. However, for coated cemented carbides this problem is reduced due to the chemical inertness and good thermal shock resistance of the TiCN coating. This means that the coated tools can be operated at higher cutting speeds and feed rates than uncoated inserts. Another reason for the increased operating range of the coated cutting tools is that the coated tools have better substrate materials than the uncoated. The uncoated inserts have a P25 substrate material while the coated inserts have a P40 substrate. [11]

The tests were carried out by keeping both the feed rate and depth of cut constant at 550 mm/min and 1 mm respectively, while varying the cutting speed from 98 - 112 m/min.

Table 6.3.8a. Tool Life with varying Cutting Speed

Cutting Speed (m/min)	Tool Life (minutes)
98	67
105	55
112	45

As can be seen from the both the table and the graph, tool life decreases with increasing cutting speed. This can be attributed to the fact that the cutting temperature increases with increasing speed. The rise in temperature is generated by two sources of heat. These sources of heat are from the energies created in the shear plane during the formation of the chip and from the friction between the chip and the rake face. This excess heat causes diffusion wear, which occurs by the process of chemical dissolution of the tool material in the chip, particularly at the hottest point of contact, which is a short distance back from the cutting edge. Another effect of high temperature in the cutting zone is that it can produce thermal shock cracks. These cracks are caused by thermal cycling as a result of intermittent cutting, which is a feature of milling operations. Under these conditions the effects of abrasion wear are negligible.

The tool life decreases by 33% across the range, with the cutting speed increasing by 14% from 98 m/min to 112 m/min. This roughly equates to a 2 % decrease in tool life for every percent increase in cutting speed.

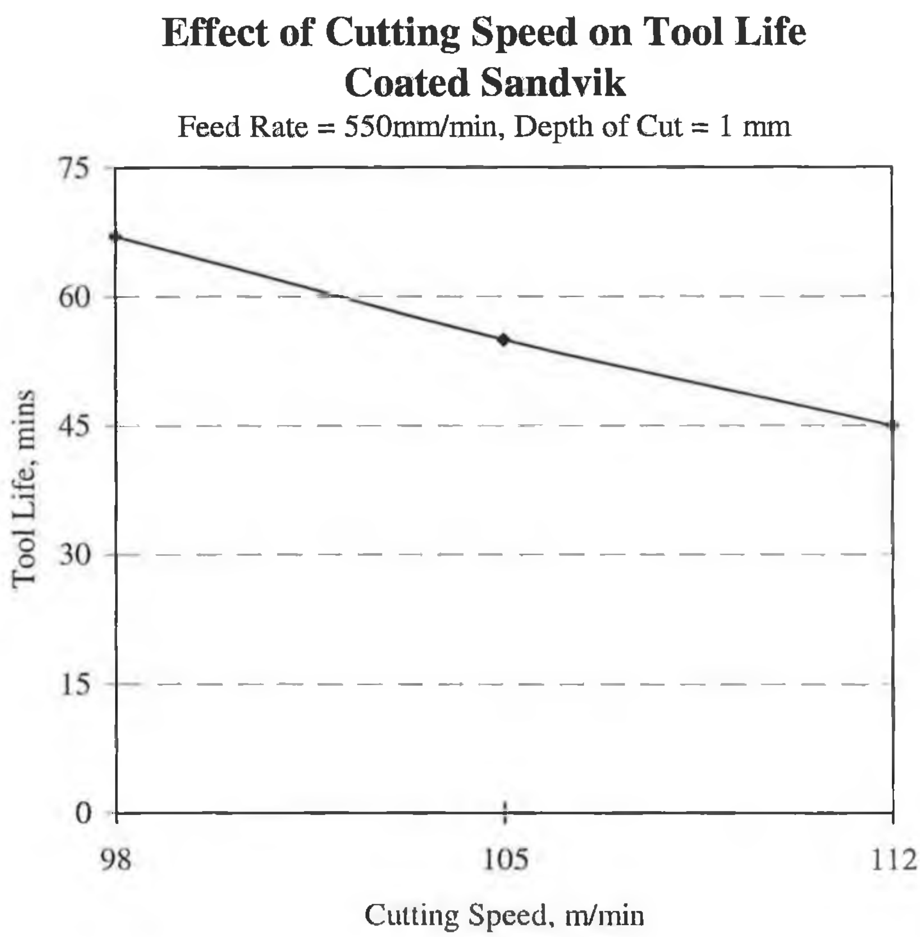

Figure 6.3.8a, Effect of Cutting Speed on Tool Life

b) Effect of Feed Rate on Tool Life

The tests were carried out by keeping both the cutting speed and depth of cut constant at 105 m/min and 1 mm respectively, while varying the feed rate from 500 - 600 mm/min.

Table 6.3.8b. Tool Life with varying Feed Rate

Feed Rate (mm/min)	Tool Life (minutes)
500	62
550	55
600	50

As can be seen from both the table and the graph, tool life decreases with increasing feed rate. This is due to the increase in the cutting forces produced per unit area of chip-tool contact on the rake face and work-tool contact on the flank face. This increase in cutting force can also be attributed to the fact that the chip thickness and therefore chip load increases with feed rate. The increased chip load causes both an increase in the cutting pressure and temperature and results in increased abrasive wear and diffusion wear on the tool. However, this increase in wear is not as large as the increase in wear for uncoated Sandvik inserts. The tool life for uncoated inserts decreases by 2% for every 1% increase in feed rate, while the tool life of coated tools only decreases by 1% for every 1% increase in feed rate. This means that the coated tool wears at half the rate of the uncoated tools and can be attributed to the improved chemical inertness, and thermal wear and abrasive wear resistance of the TiCN coating. [46]

The tool life decreases by 20% across the range, with the feed rate increasing by 20% from 500 mm/min to 600 mm/min. This roughly equates to a 1 % decrease in tool life for every percent increase in feed rate.

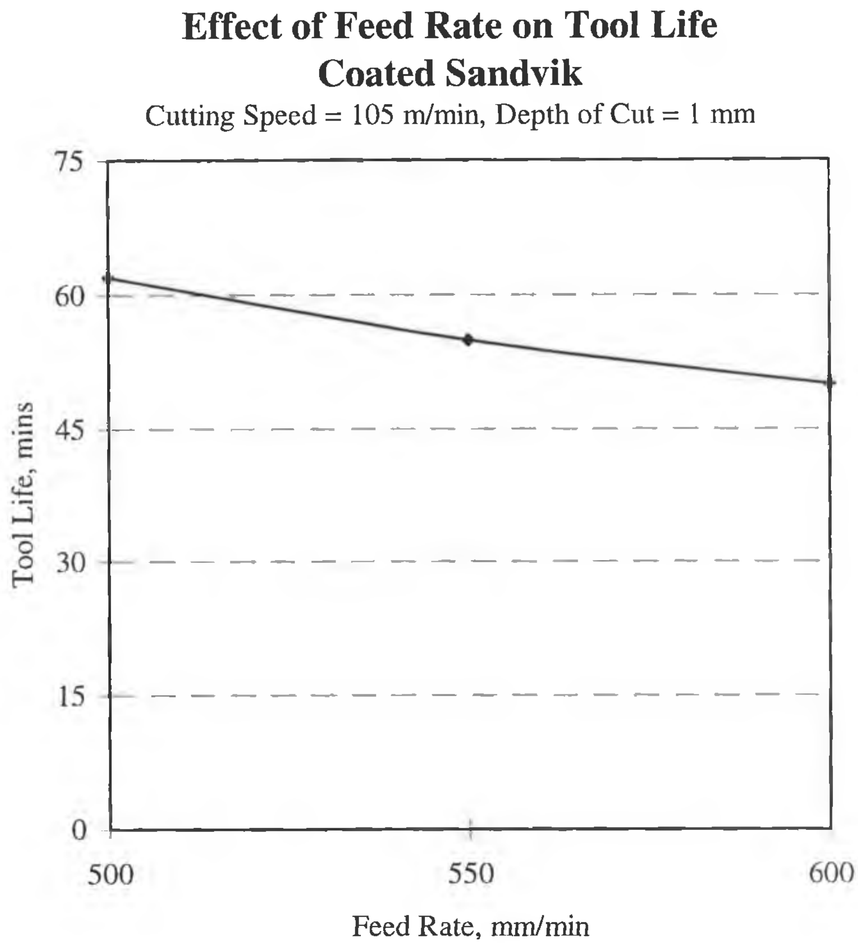

Figure 6.3.8b, Effect of Feed Rate on Tool Life

c) Effect of Depth of Cut on Tool Life

For coated cemented carbide tools, the depth of cut is the most significant of the three cutting variables. It has a considerable effect on the too life, a moderate effect on the cutting forces and only a minor effect on the surface finish produced.

The tests were carried out by keeping both the cutting speed and feed rate constant at 85 m/min and 430 mm/min respectively, while varying the depth of cut 1 - 4 mm.

Table 6.3.8c, Tool Life with varying Depth of Cut

Depth of Cut (mm)	Tool Life (minutes)
1	55
2	64
4	70

It can be seen from the graph that for coated tools an increase in the depth of cut results in a increase in tool life. This is due to the fact, that although the overall temperature in the cutting zone (cutting zone temperature) increases with increasing depth of cut, the length of cutting edge in contact with the workpiece increases. This results in greater dissipation of heat to the chip and workpiece during cutting, while the increase in the cutting tool temperature (tool temperature) is very small. This increase in temperature of the chip/workpiece has the effect of reducing the hardness (softening) of the workpiece material making it less abrasive on the cutting tool, while the TiCN coating maintains its hardness at elevated temperatures. [46] The overall effect of the two aforementioned occurrences is the reduction of the abrasive wear present on the cutting tool. The small rise in the tool temperature increases the diffusion wear but not significantly because the TiCN coating is more chemically inert and thermally stable than the uncoated insert and is therefore less susceptible to diffusion wear. The overall effect of the cutting zone temperature increase is that the abrasion wear decreases, more than the diffusion wear increases, and therefore there is a net reduction in overall tool wear with increasing depth of cut.

The tool life increases by 27% across the range, with the depth of cut increasing by 300% from 1 mm to 4 mm. This roughly equates to a 1 % increase in tool life for every 10 percent increase in depth of cut.

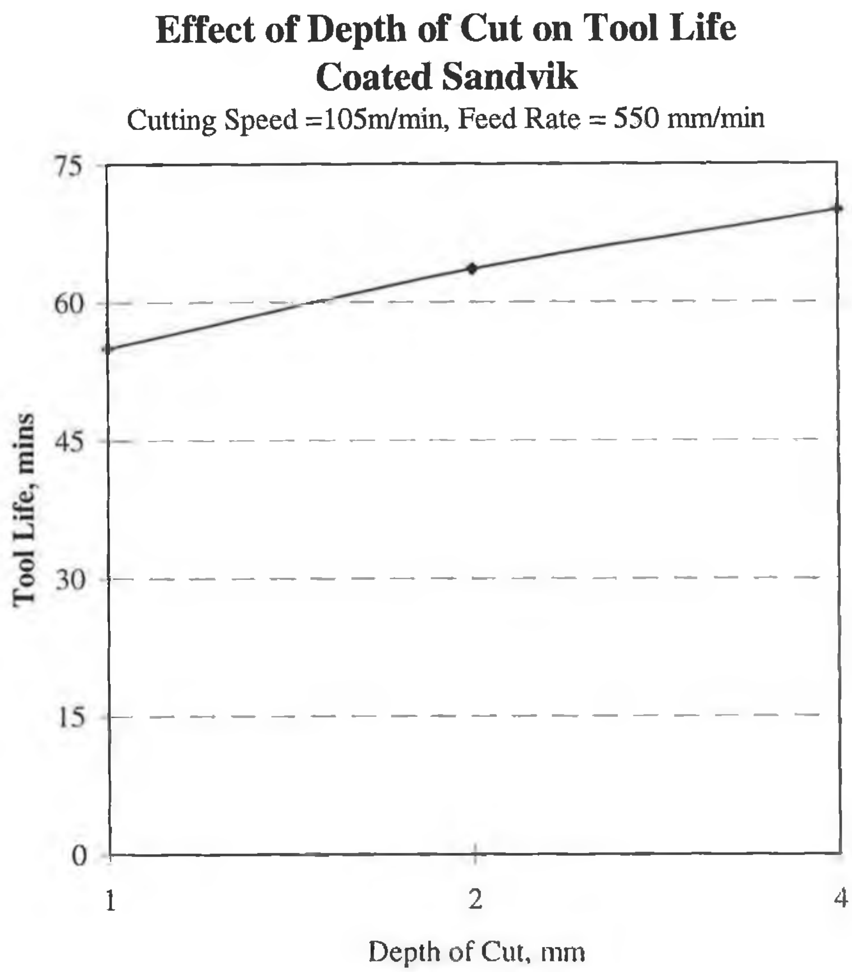

Figure 6.3.8c, Effect of Depth of Cut on Tool Life

<u>Conclusions</u>

- An increase in the cutting speed causes an increase in the diffusion wear and consequently causes a decrease in the tool life.
- An increase in the feed rate results in an increase in both diffusion and abrasive wear, therefore resulting in a reduction in the tool life.
- An increase in the depth of cut results in a decrease in the abrasive wear and a small increase in the diffusion wear, causing a increase in the tool life.

6.3.9 Coated Cemented Carbide (Iscar)

a) Effect of Cutting Speed on Tool Life

The tests were carried out by keeping both the feed rate and depth of cut constant at 540 mm/min and 1 mm respectively, while varying the cutting speed from 125 - 155 m/min.

Table 6.3.9a. Tool Life with varying Cutting Speed

Cutting Speed (m/min)	Tool Life (minute)
125	54
140	48
155	40

As can be seen from the both the table and the graph, tool life decreases with increasing cutting speed. This can be attributed to the fact that the cutting temperature increases with increasing speed. The rise in temperature is generated by two sources of heat. These sources of heat are from the energies created in the shear plane during the formation of the chip and from the friction between the chip and the rake face. This excess heat causes diffusion wear, which occurs by the process of chemical dissolution of the tool material in the chip, particularly at the hottest point of contact, which is a short distance back from the cutting edge. Another effect of high temperature in the cutting zone is that it can produce thermal shock cracks. These cracks are caused by thermal cycling as a result of intermittent cutting, which is a feature of milling operations. Under these conditions the effects of abrasion wear are negligible. [11]

The tool life decreases by 26% across the range, with the cutting speed increasing by 24% from 98 m/min to 112 m/min. This roughly equates to a 1 % decrease in tool life for every percent increase in cutting speed.

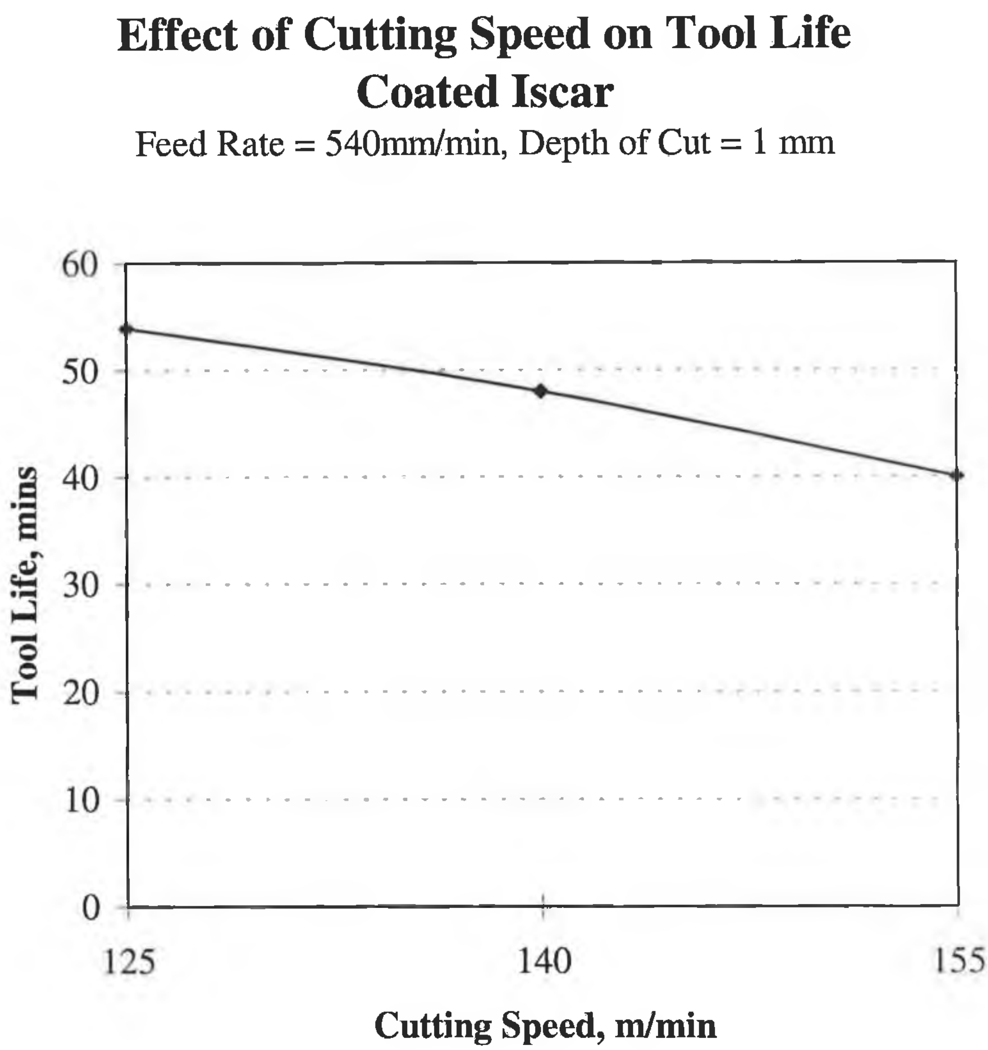

Figure 6.3.9a, Effect of Cutting Speed on Tool Life

b) Effect of Feed Rate on Tool Life

This is similar to cutting speed in that it influences cutting forces, tool wear rates and surface finish, but to a lesser extent. The larger the feed rate, the greater is the cutting force and temperature in the cutting zone. The increase in cutting force also increases the likelihood of chipping of the cutting edge through mechanical shock. An increase in feed rate also results in an increase in tool wear rates and produces a poor surface finish.

The tests were carried out by keeping both the cutting speed and depth of cut constant at 140 m/min and 1 mm respectively, while varying the feed rate from 500 - 570 mm/min.

Table 6.3.9b. Tool Life with varying Feed Rate

Feed Rate (mm/min)	Tool Life (minutes)
500	52
540	48
570	41

As can be seen from both the table and the graph, tool life decreases with increasing feed rate. This is due to the increase in the cutting forces produced per unit area of chip-tool contact on the rake face and work-tool contact on the flank face. This increase in cutting force can also be attributed to the fact that the chip thickness and therefore chip load increases with feed rate. The increased chip load causes both an increase in the cutting pressure and temperature and results in increased abrasive wear and diffusion wear on the tool. [11] However, this increase in wear is not as large as the increase in wear for uncoated Sandvik inserts. The tool life for uncoated inserts decreases by 2% for every 1% increase in feed rate, while the tool life of coated tools only decreases by 1% for every 1% increase in feed rate. This means that the coated tool wears at half the rate of the uncoated tools and can be attributed to the improved chemical inertness, and thermal wear and abrasive wear resistance of the TiCN coating.

The tool life decreases by 21% across the range, with the feed rate increasing by 14% from 500 mm/min to 570 mm/min. This roughly equates to a 1.5 % decrease in tool life for every percent increase in feed rate.

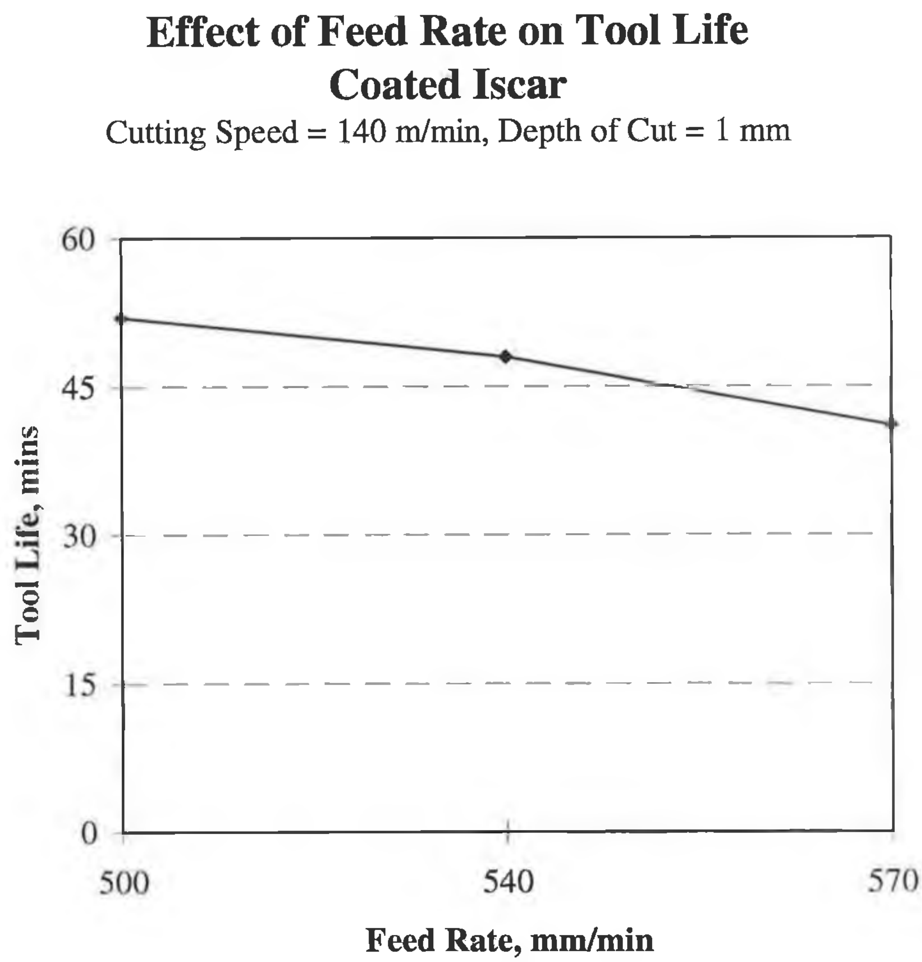

Figure 6.3.9b, Effect of Feed Rate on Tool Life

c) Effect of Depth of Cut on Tool Life

The tests were carried out by keeping both the cutting speed and feed rate constant at 140 m/min and 540 mm/min respectively, while varying the depth of cut 1 - 4 mm.

Table 6.3.9c, Tool Life with varying Cutting Speed

Depth of Cut (mm)	Tool Life (minutes)
1	48
2	54
4	58.5

It can be seen from the graph that for coated tools an increase in the depth of cut results in a increase in tool life. This is due to the fact, that although the overall temperature in the cutting zone (cutting zone temperature) increases with increasing depth of cut, the length of cutting edge in contact with the workpiece increases. This results in greater dissipation of heat to the chip and workpiece during cutting, while the increase in the cutting tool temperature (tool temperature) is very small. [44] This increase in temperature of the chip/workpiece has the effect of reducing the hardness (softening) of the workpiece material making it less abrasive on the cutting tool [37], while the TiCN coating maintains its hardness at elevated temperatures. The overall effect of the two aforementioned occurrences is the reduction of the abrasive wear present on the cutting tool. The small rise in the tool temperature increases the diffusion wear but not significantly because the TiCN coating is more chemically inert and thermally stable than the uncoated insert and is therefore less susceptible to diffusion wear. The overall effect of the cutting zone temperature increase is that the abrasion wear decreases, more than the diffusion wear increases, and therefore there is a net reduction in overall tool wear with increasing depth of cut.

The tool life increases by 22% across the range, with the depth of cut increasing by 300% from 1 mm to 4 mm. This roughly equates to a 1 % increase in tool life for every 10 percent increase in depth of cut.

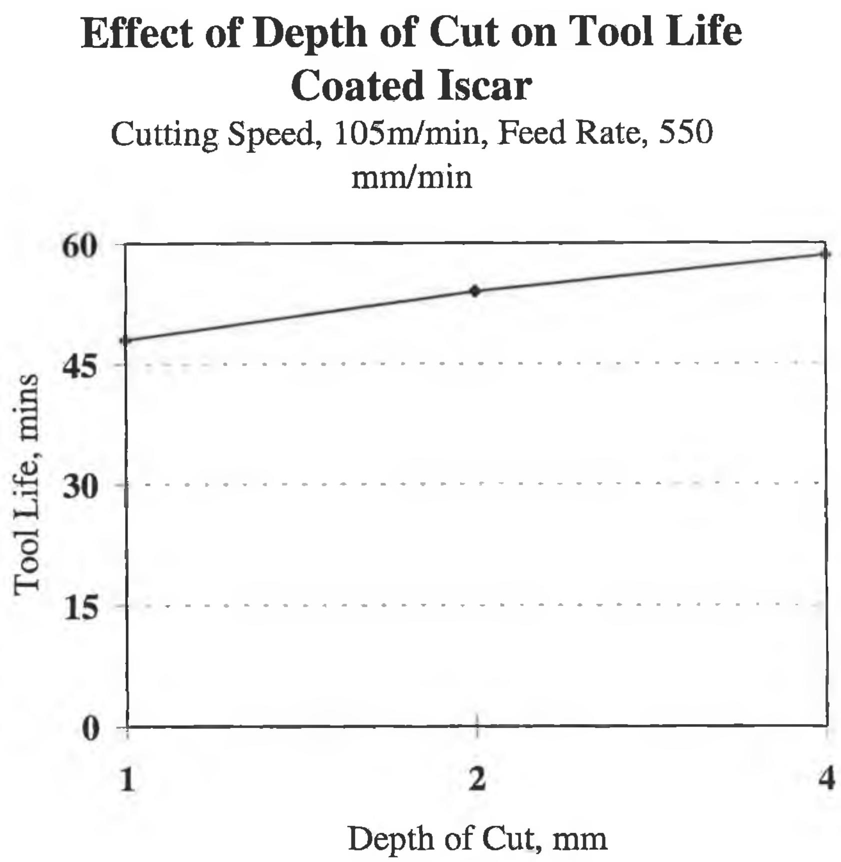

Figure 6.3.9c, Effect of Depth of Cut on Tool Life

<u>Conclusions</u>

- An increase in the cutting speed causes an increase in the diffusion wear and consequently causes a decrease in the tool life.

- An increase in the feed rate results in an increase in both diffusion and abrasive wear, therefore resulting in a reduction in the tool life.

- An increase in the depth of cut results in a decrease in the abrasive wear and a small increase in the diffusion wear, causing a increase in the tool life.

6.3.10 Conclusions on Cemented Carbide

Although the different cemented carbide cutting tools where run at various cutting speeds and feed rates, it is still possible to compare their performances relative to one another by comparing their metal removal rates. The equation for metal removal rate is as follows; [1]

$$Q = f * d * a \qquad (6.1)$$

where, f feed rate (mm/min)

d axial depth of cut (mm)

a radial depth of cut (mm)

From the graph of tool life vs. metal removal rate (for varying feed rate) it can be seen that for uncoated inserts the Sandvik tools perform the better of the two manufacturers. Although the Iscar inserts operate at much higher metal removal rates, the Sandvik inserts last nearly twice as long and therefore they are able to machine a lot more metal during their working life.

It can be seen that the coated inserts are far superior to uncoated inserts, with the coated inserts lasting roughly 100% longer than the uncoated and with the coated tools running at 60% higher metal removal rates than the uncoated. It can also be seen that the coated Sandvik inserts perform better than their Iscar counterparts, with the Sandvik lasting approximately 20% longer than the Iscar at the same metal removal rates.

There are a variety of reasons why the coated inserts perform better than their uncoated counterparts. The TiCN coating has a lower co-efficient of friction than the uncoated carbide and as a result produces less friction between the tool and workpiece surfaces. This reduction in friction means that less heat is generated in the cutting zone but also means that the cutting forces produced are lower than that for uncoated tools. The reduction in heat means that less diffusion wear occurs and the reduction in the cutting forces means that less abrasive wear occurs. The coating has a higher hardness than the uncoated and it maintains its hardness level at elevated temperatures, whereas the hardness of the carbide decreases quite considerably at the temperatures present during machining operations. This increased hot-hardness means that the coated tool is more abrasion resistant than the uncoated tool. Another reason for the improved performance of coated tools is that the coating is more chemically stable and is therefore less likely to react with the workpiece than the uncoated carbide, thus further reducing the diffusion wear on the cutting tool. Therefore the reason why coated inserts perform better than uncoated inserts is that they possess higher resistance to both diffusion wear and abrasive wear, and also that they create conditions which further reduce the abrasive and diffusion wear on the tool. [17]

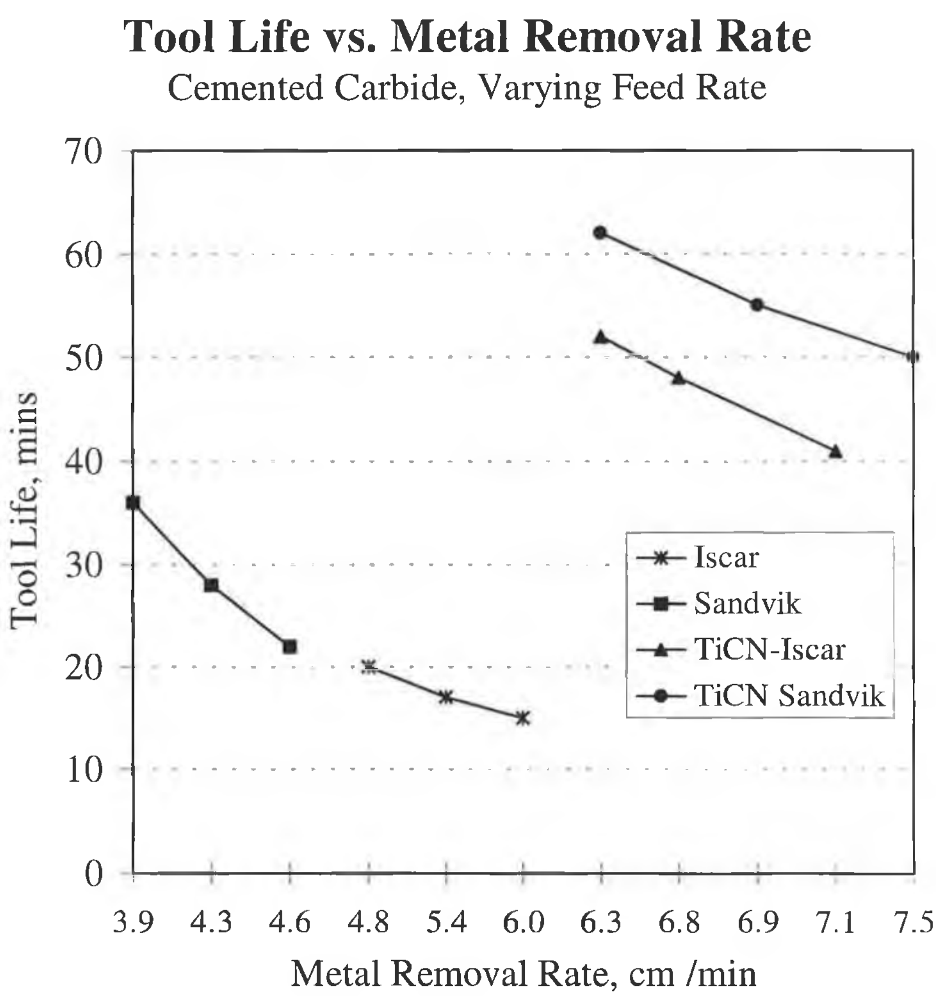

Figure 6.3.10a, Metal Removal Rate vs. Tool Life

As can be seen from figure 6.3.10b, depth of cut has two very different effects on the tool life's of uncoated and coated cemented carbide. For the uncoated tool an increase in the depth of cut results in a decrease in the tool life. This is due to the fact that as the depth of cut increases the temperature in the cutting zone increases. The rise in temperature with increasing depth of cut is greater for uncoated tools than for coated tools and results in increased diffusion wear. [13] The increase in the depth of cut also results in an increase in chip load and therefore cutting pressure, which increases the abrasive wear on the tool. [11] The overall result is an increase in total wear due to increases in both diffusion and abrasive wear with increasing depth of cut.

On the otherhand, for coated tools an increase in the depth of cut results in an increase in the tool life. This increase in tool life is due to a number of factors. Although the overall temperature in the cutting zone (cutting zone temperature) of coated tool increases with increasing depth of cut, the length of cutting edge in contact with the workpiece also increases, resulting in greater dissipation of heat to the chip and workpiece during cutting. This means that the increase in the cutting tool temperature (tool temperature) is very small. [44] This increase in temperature of the chip/workpiece has the effect of reducing the hardness (softening) of the workpiece material [37] making it less abrasive on the cutting tool, while the TiCN coating maintains its hardness at elevated temperatures.[46] The small rise in the tool temperature increases the diffusion wear but not significantly because the TiCN coating is more chemically inert and thermally stable than the uncoated insert and is therefore less susceptible to diffusion wear. The overall effect of the cutting zone temperature increase is that the abrasion wear decreases, more than the diffusion wear increases, and therefore there is a net reduction in overall tool wear with increasing depth of cut.

From the figure 6.3.10b it can be clearly seen that the coated tools are far superior to the uncoated tools, with the coated inserts lasting roughly 100% longer than the uncoated at low metal removal rates and by over 500% longer at high metal removal rates. It can also be seen that once again the coated Sandvik inserts perform better than their Iscar counterparts, with the Sandvik lasting approximately 20% longer than the Iscar at the same metal removal rates.

Papazafiriou and Elbestawi [47] stated that the for constant cutting conditions and grade of carbide, the greater the number of teeth the higher is the temperature produced in the cutting zone. Therefore the Iscar inserts produce a higher cutting temperature than the Sandvik. The higher temperature present with Iscar causes an increase in the diffusion wear on the cutting tool and results in a shorter tool life.

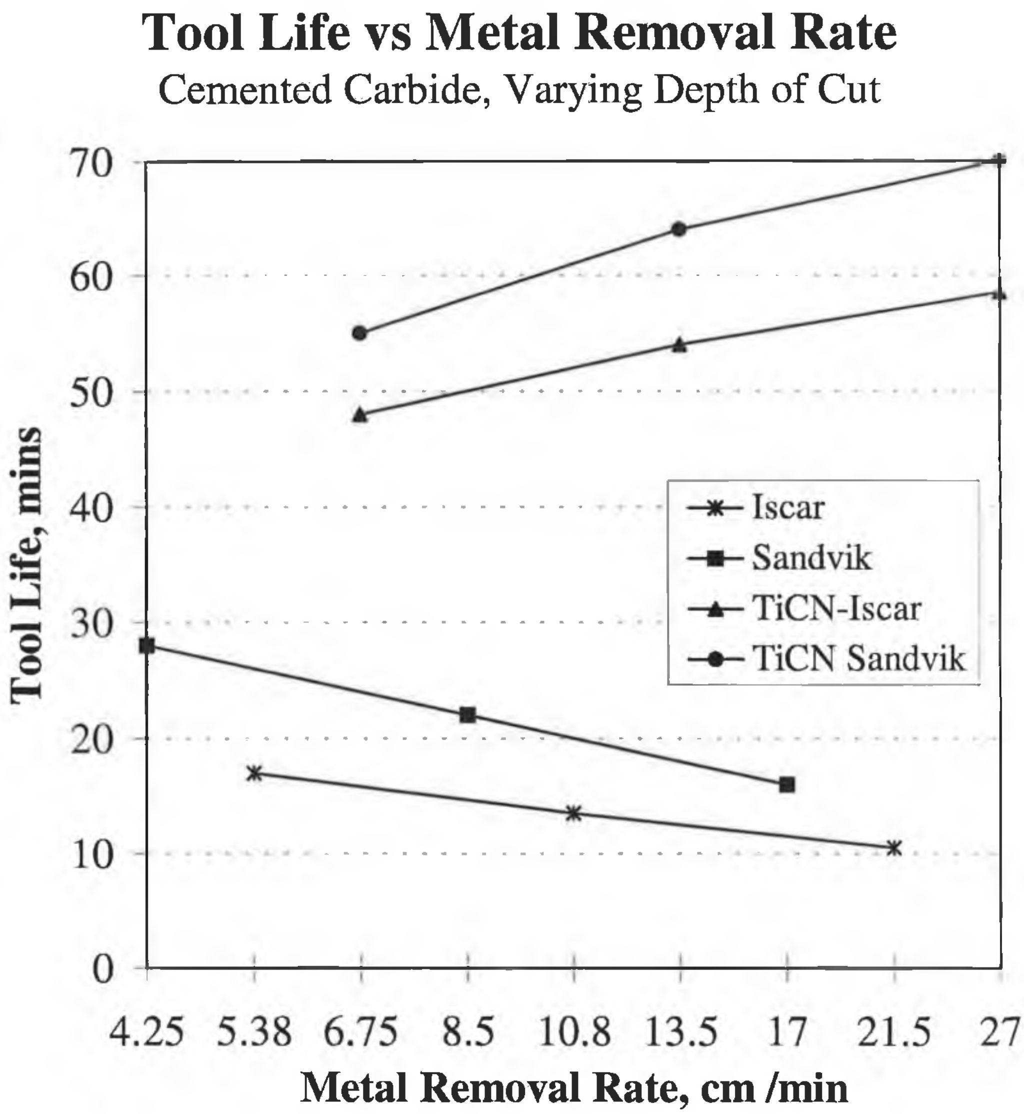

Figure 6.3.10b, Metal Removal Rate vs. Tool Life

Uncoated Cemented Carbide

⇒ An increase in the cutting speed results in a decrease in tool life.

⇒ An increase in the feed rate results in a decrease in tool life.

⇒ An increase in the depth of cut results in a decrease in tool life.

⇒ The Sandvik cutting tools perform better than their Iscar counterparts. It is therefore advised that Sandvik be chosen ahead of Iscar.

Coated Cemented Carbide End Mills

⇒ An increase in the cutting speed results in a decrease in tool life.

⇒ An increase in the feed rate results in a decrease in tool life.

⇒ An increase in the depth of cut results in an increase in tool life.

⇒ The coated tools perform by roughly 100% better than their uncoated counterparts at low metal removal rates and by over 500% better at high metal removal rates.

⇒ The Sandvik cutting tools perform on average 20% better than Iscar. It is therefore advised that Sandvik be chosen ahead of Iscar.

⇒ In order to get the most out of the coated tools it is recommended that for roughing operations, a depth of cut between 2mm and 4mm should be used. This should be coupled with a medium cutting speed (95-105 m/min) and a high feed rate (550-600 mm/min).

CHAPTER SEVEN

EXPERIMENTAL RESULTS AND ANALYSIS, DESIGN OF EXPERIMENT

7.1 Introduction

A machinability model can be defined as a functional relationship between the input of independent variables, such as speed, feed and depth of cut, and the output known as the response (tool life, surface finish or cutting forces) of a machining process. In order to develop this model it is necessary to design and carry out experimental work to provide the response data that is needed. In developing a database, this machining response data is used as the primary data and a mathematical model of these responses are developed as a function of the cutting variables using a model building module.

7.2 Response Surface Methodology

Response surface methodology (RSM) is a combination of mathematical and statistical techniques used in the empirical study of relationships and optimization where several independent input variables influence a dependent output variable or response. In applying the RSM, the response is viewed as a surface to which a mathematical model is fitted. Usually low order polynomials are used to represent the response surface. The eventual objective of RSM is the optimization of the independent variables in relation to the output variable or response.

RSM was initially developed by Box [61] for the study of optimization problems in the chemical processing industry. It has also been used in tool life and surface roughness testing in machining, in ultrasonic grinding and for the prediction of frictional damping in machined joints. It also assists in the understanding of the basic mechanism of the system under investigation.

It is assumed that the independent variables are continuous and controllable by the experimenter with negligible error. The response or the dependent variable is assumed to be a random variable. If all of these variables are assumed to be measurable, the response surface can be expressed as;

$$y = f(x_1, x_2, x_3 \ldots\ldots\ldots\ldots\ldots x_k) \qquad (7.1)$$

In a milling operation it maybe necessary to find a suitable combination of cutting speed (X_1), feed rate (X_2) and depth of cut (X_3) that optimize the tool life (y). Then the observed response y as a function of the cutting speed, feed rate and depth of cut can be expressed as;

$$y = f(x_1, x_2, x_3) + \varepsilon \qquad (7.2)$$

where y is the level of measured (experimental) response, f is the response function, x_1,x_2, and x_3 are levels of independent variables and ε is the experimental error.

A knowledge of the response function gives a complete summary of the results and enables the response for the values of factors that were not tested experimentally to be predicted mathematically. The true or expected (predicted) response is denoted by $\acute{y}$ which would be obtained in the absence of experimental error and is given by:

$$\acute{y} = y - \varepsilon = f(x_1, x_2, x_3 \ldots\ldots\ldots\ldots\ldots x_k) \qquad (7.3)$$

The surface generated by $\acute{y}$ is called the response surface. The two dimensional response surface might be represented graphically by drawing the x1 and x2 axis in the plane of paper and visualizing $\acute{y}$ as perpendicular to the plane of paper, as illustrated in figure 7.2a.

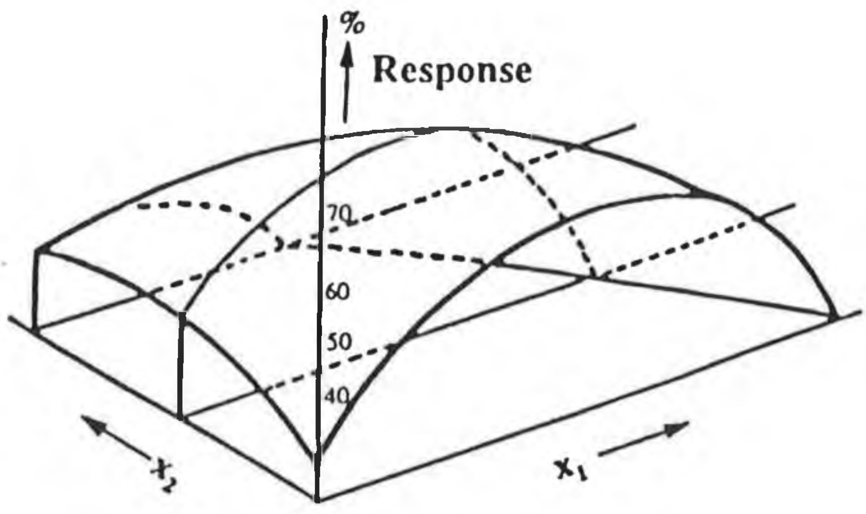

Figure 7.2a, A response surface [45]

Usually a low order polynomial (first order and second-order) in some regions of the independent variables is employed. [62]

The first-order model,

$$\mathbf{y} = \beta_0 + \Sigma\beta_i \mathbf{x}_i + \varepsilon \qquad \textbf{(7.4)}$$

The β parameters are usually solved by the method of least squares. The matrix approach of solving equation 7.4 has been adopted in our analysis. We define **y** to be an (n * 1) vector of observations on y, **x** to be an (n * p) matrix of independent variables, β yo be a (p * 1) vector of parameters to be estimated and ε to be an (n * 1) vector of errors. Equation 7.4 can be written in the matrix form as;

$$\mathbf{y} = \beta\mathbf{x} + \varepsilon \qquad \textbf{(7.5)}$$

The least squares estimate of β is the value b which, when substituted in equation 7.4, minimizes ε‘. The normal equation can be expressed as;

$$(\mathbf{x}^T\mathbf{x})\mathbf{b} = \mathbf{x}^T\mathbf{y} \qquad \textbf{(7.6)}$$

where β is replaced by **b** matrix. If $(\mathbf{x}^T\mathbf{x})$ is non-singular, the solution of the normal equation can be written as;

$$\mathbf{b} = (\mathbf{x}^T\mathbf{x})^{-1}\ \mathbf{x}^T\mathbf{y} \qquad \textbf{(7.7)}$$

where, $\mathbf{x}^T$ is the transpose of the matrix **x**,
$(\mathbf{x}^T\mathbf{x})^{-1}$ is the inverse of the matrix $(\mathbf{x}^T\mathbf{x})$.

The response surface analysis is done in terms of the fitted surface. Designs for fitting response surfaces are known as the response surface design. The main purpose of RSM is to ascertain the optimum operating regions for the system involving the independent variables. [45]

Experimental Design

A well designed experimental model can substantially reduce the number of experiments required. Many experiments involve a study of the effect of two or more factors. A response surface can be most efficiently fitted if proper attention is given to the choice of experimental design. The most widely used class of design for fitting the first-order model is orthogonal first-order design. This orthogonal first-order design minimizes the variance of the co-efficient (b's) of the equation. A first-order design is orthogonal if the off-diagonal elements of the ($\mathbf{x}^T\mathbf{x}$) matrix are all zero. where $\mathbf{x}$ is the calculated matrix or design matrix and $\mathbf{x}^T$ is the transpose of $\mathbf{x}$. This implies that the cross-products of the columns of $\mathbf{x}$ sum to zero. This class of first-order orthogonal design includes the 2^k factorial and factorial designs. The response surface is assumed to be plotted in K (number of factor) dimensional space in which the units are chosen so that the levels of the factors are -1 and +1, that is, the origin "0" for the variables is taken at the mid-point of the design, and the co-ordinates of the experimental points consists of -1's and +1's. As an example, suppose a 2^3 factorial design is used to fit the first-order model: [62]

$$\acute{y} = \beta_0 x_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \varepsilon \qquad (7.8)$$

The $\mathbf{x}$ matrix for fitting this model is as:

$$\mathbf{x} = \begin{array}{cccc} x_0 & x_1 & x_2 & x_3 \\ \left| \begin{array}{c} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{array} \right. & \begin{array}{c} -1 \\ 1 \\ -1 \\ 1 \\ -1 \\ 1 \\ 1 \\ -1 \end{array} & \begin{array}{c} -1 \\ -1 \\ 1 \\ 1 \\ -1 \\ -1 \\ 1 \\ 1 \end{array} & \left. \begin{array}{c} 1 \\ 1 \\ 1 \\ 1 \\ -1 \\ -1 \\ -1 \\ -1 \end{array} \right| \end{array}$$

The first column of the **x** matrix of independent variables contains only 1's. This is the general convention for any regression model containing a constant term β_0; by assuming the β_0 terms to be of the form $\beta_0 x_0$ where x_0 is a dummy variable always taking the value 1. It should be noted that the 2^k factorial does not afford an estimate of the experimental error unless some runs are repeated. A common method of including replication in the 2^k design is to augment the design with several observations at the centre ($x_i = 0$, $i = 1,2,...,k$). The inclusion of centre points to the 2^k design does not influence the regression coefficients (β_i) for $i \geq 1$, but the estimate of β_0 becomes the grand average of all observations. Moreover, the centre points do not influence or change the orthogonal property of the design. [62]

The coded values (logarithmic transformations) of the independent variables x_i, $i = 1,2,...,k$ are obtained from the following equation;

$$x = \frac{\ln X_n - \ln X_{n0}}{\ln X_{n1} - \ln X_{n0}} \tag{7.9}$$

The first order central composite design involving three variables as shown in figure 7.2b, consists of twelve experimental runs comprising of two blocks. Eight experiments constitute the 2^3 factorial design, with an added centre point repeated four times (9,10,11,12). Block 1 consists of experiments (1,4,6,7,9,10) and block 2 consists of (2,3,5,8,11,12) which together provide a precise estimate of the β parameters of equation (7.8).

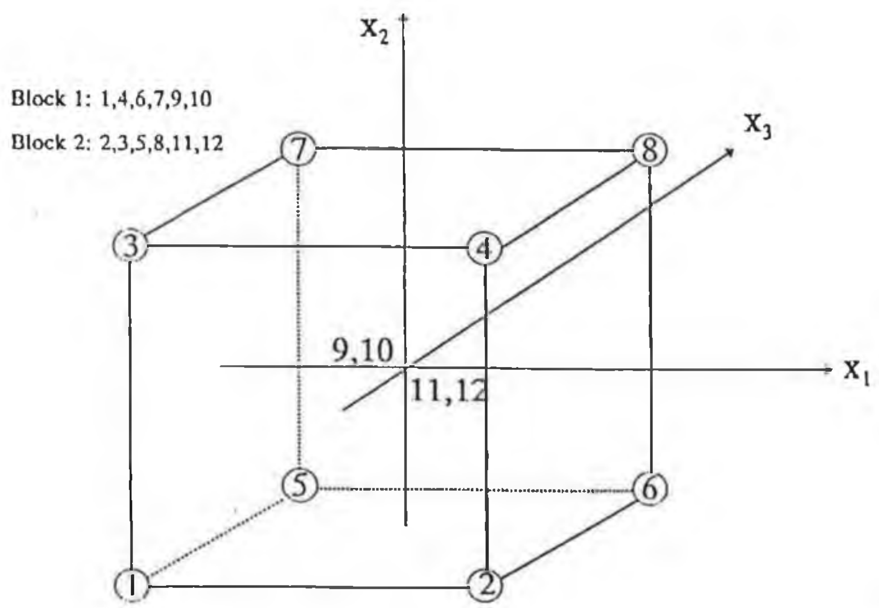

Figure 7.2b First-order orthogonal design for 2^3 factorial design.

Adequacy of models

The accuracy of the model is tested by a method known as the analysis of variance (ANOVA) technique. In this technique, the F ratio of the model is calculated and compared with the standard tabulated value of the F ratio for a specific level of confidence. If the calculated value of the F-ratio does not exceed the F-ratio obtained from the standard statistical tables, the model may be considered adequate to the confidence probability stated in the tables. [45]

Significance Testing of Independent Variables

The main objective of RSM is to achieve an optimum set of cutting conditions for the particular circumstances, i.e. the combination of cutting speed, feed rate and depth of cut that gives the best tool life. Therefore it is necessary to construct a model with significant terms only and to eliminate any variables which have a negligible effect on the outcome.

Precision of Prediction (Confidence Intervals)

A calculation can be made to determine the precision of the predicted model. This is done by calculating the confidence intervals and comparing them with the experimental values. The specific level of confidence interval for the predicted responses, $\ddot{y}$ are given by ($\ddot{y} \pm \Delta\ddot{y}$)

$$\Delta\ddot{y} = t_{df,\alpha/2} \sqrt{[V(y)]} \qquad (7.10)$$

where,

t_{df} the value of horizontal co-ordinate of the t distribution corresponding to the specified (df) degrees of freedom and level of confidence.

$V(y)$ the variance of the predicted responses y

α level of confidence interval

If the measured responses y are within the level of the predicted responses then that specified level of confidence is the precision of the model.

7.3 Worked Example

It has usually been found that metal cutting data is prone to a significant amount of error. This is mainly due to the non-homogeneity of the material being cut and its effect on the measurement of the machining data and also due to the measurement technique itself. For these tests a mathematical model has been developed for predicting the tool life of the cutting tool under different cutting conditions. In this model a 2^3 factorial design is employed to observe the effect of cutting speed, feed rate and depth of cut on the tool life when machining tool steel (DIN 1.2311, 290 BHN) using Strassmann High Speed Steel end mills.

The objective of the model is to produce an equation which represents the relationship between cutting conditions and the surface roughness produced following machining with a sharp cutting tool. The relationship between tool life and cutting speed, feed rate and depth of cut is as follows;

$$\mathbf{T = CV^{x}f^{y}d^{z}} \qquad \mathbf{(7.11)}$$

where;

T	tool life (min)
C	a constant
V	cutting speed (m/min)
f	feed rate (mm/min)
d	depth of cut (mm)
x, y, z	exponentially determined constants

Equation (7.11) can be rewritten as,

$$\mathbf{\ln T = \ln C + x \ln V + y \ln f + z \ln d} \qquad (7.12)$$

Equation (7.12) can be written as,

$$\mathbf{\acute{y} = y - \varepsilon = b_0x_0 + b_1x_1 + b_2x_2 + b_3x_3} \qquad (7.13)$$

Where $\hat{y}$ is the estimated response and y is the measured surface roughness on a logarithmic scale, ε is the experimental error, $x_0 = 1$ (a dummy variable), x_1. x_2 and x_3 are logarithmic transformations of the speed, feed rate and the depth of cut while the *b* values are the parameters to be estimated.

The b values, i.e. b_0, b_1, b_2,.......,etc., are to be estimated by the method of least squares, the basic formula is

$$\mathbf{b} = (\mathbf{X^T X})^{-1}\mathbf{X^T y} \qquad (7.14)$$

where the calculation matrix X is as follows;

$$\mathbf{X} = \begin{array}{cccc} x0 & x1 & x2 & x3 \\ \left|\begin{array}{cccc} 1 & -1 & -1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & 1 & -1 \\ 1 & -1 & -1 & 1 \\ 1 & 1 & -1 & 1 \\ 1 & -1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{array}\right| \end{array}$$

therefore,

$$(\mathbf{X^T X}) = \left|\begin{array}{cccc} 12 & 0 & 0 & 0 \\ 0 & 8 & 0 & 0 \\ 0 & 0 & 8 & 0 \\ 0 & 0 & 0 & 8 \end{array}\right|$$

and

$$(X^TX)^{-1} = \begin{vmatrix} 1/12 & 0 & 0 & 0 \\ 0 & 1/8 & 0 & 0 \\ 0 & 0 & 1/8 & 0 \\ 0 & 0 & 0 & 1/8 \end{vmatrix}$$

$$x_1 = \frac{\ln V - \ln V_{centre}}{\ln V_{centre} - \ln V_{high}} \tag{7.15}$$

$$x_2 = \frac{\ln f - \ln f_{centre}}{\ln f_{centre} - \ln f_{high}} \tag{7.16}$$

$$x_3 = \frac{\ln d - \ln d_{centre}}{\ln d_{centre} - \ln d_{high}} \tag{7.17}$$

Coding of cutting variables is as follows;

Independent	**Levels in coded form**		
Variables	-1 (low)	0 (centre)	1 (high)
V, m/min (x1)	12.8	16	20
f, mm/min (x2)	82	102	127
d, mm (x3)	1	2	4

Experimental Conditions

Trial Number	Block Number	Speed, V m/min	Feed, f mm/min	Depth, d mm	x1	x2	x3
1	1	12.8	82	1	-1	-1	-1
2	2	20	82	1	1	-1	-1
3	2	12.8	127	1	-1	1	-1
4	1	20	127	1	1	1	-1
5	2	12.8	82	4	-1	-1	1
6	1	20	82	4	1	-1	1
7	1	12.8	127	4	-1	1	1
8	2	20	127	4	1	1	1
9	1	16	102	2	0	0	0
10	1	16	102	2	0	0	0
11	2	16	102	2	0	0	0
12	2	16	102	2	0	0	0

Experimental Results

Trial 1;	Tool Life = 170	Trial 7;	Tool Life = 210
Trial 2;	Tool Life = 145	Trial 8;	Tool Life = 189
Trial 3;	Tool Life = 122	Trial 9;	Tool Life = 186
Trial 4;	Tool Life = 110	Trial 10;	Tool Life = 180
Trial 5;	Tool Life = 280	Trial 11;	Tool Life = 200
Trial 6;	Tool Life = 249	Trial 12;	Tool Life = 200

Mathematical Model Calculations

$x_1 \quad = \quad (\ln V - \ln 16)/\ln 20 - \ln 16$

$\therefore \quad x_1 \quad = \quad (\ln V - 2.7725)/2.9957 - 2.7725$

$\therefore \quad x_1 \quad = \quad (\ln V - 2.7725)/0.2231$

$\therefore \quad \mathbf{x_1 \quad = \quad 4.4814(\ln V) - 12.4251}$

$x_2 \quad = \quad (\ln f - \ln 102)/\ln 127 - \ln 102$

$\therefore \quad x_2 \quad = \quad (\ln f - 4.56175)/4.84419 - 4.56175$

$\therefore \quad x_2 \quad = \quad (\ln f - 4.4426)/0.21921$

$\therefore \quad \mathbf{x_2 \quad = \quad 4.56175(\ln f) - 21.09796}$

$x_3 \quad = \quad (\ln d - \ln 2)/\ln 4 - \ln 2$

$\therefore \quad x_3 \quad = \quad (\ln d - 0.69315)/1.38629 - 0.69315$

$\therefore \quad x_3 \quad = \quad (\ln d - 0.69315)/0.69315$

$\therefore \quad \mathbf{x_3 \quad = \quad 1.44269(\ln d) - 1}$

as stated earlier, $\mathbf{b = (X^TX)^{-1}X^Ty}$

Block 1 Calculations

where,

$$X = \begin{array}{cccc|c} X_0 & X_1 & X_2 & X_3 & \text{Trial number} \\ \left|1\right. & -1 & -1 & \left.-1\right| & 1 \\ \left|1\right. & 1 & 1 & \left.-1\right| & 4 \\ \left|1\right. & 1 & -1 & \left.1\right| & 6 \\ \left|1\right. & -1 & 1 & \left.1\right| & 7 \\ \left|1\right. & 0 & 0 & \left.0\right| & 9 \\ \left|1\right. & 0 & 0 & \left.0\right| & 10 \end{array}$$

$$y = \begin{vmatrix} \ln 170 \\ \ln 110 \\ \ln 249 \\ \ln 210 \\ \ln 186 \\ \ln 180 \end{vmatrix} \begin{matrix} 1 \\ 4 \\ 6 \\ 7 \\ 9 \\ 10 \end{matrix}$$

$$y = \begin{vmatrix} 5.1358 \\ 4.7005 \\ 5.5175 \\ 5.3471 \\ 5.2257 \\ 5.1929 \end{vmatrix} \begin{matrix} Y_1 \\ Y_4 \\ Y_6 \\ Y_7 \\ Y_9 \\ Y_{10} \end{matrix}$$

$$(\mathbf{X}^T\mathbf{X}) = \begin{vmatrix} 6 & 0 & 0 & 0 \\ 0 & 4 & 0 & 0 \\ 0 & 0 & 4 & 0 \\ 0 & 0 & 0 & 4 \end{vmatrix}$$

$$\therefore (\mathbf{X}^T\mathbf{X})^{-1} = \begin{vmatrix} 1/6 & 0 & 0 & 0 \\ 0 & 1/4 & 0 & 0 \\ 0 & 0 & 1/4 & 0 \\ 0 & 0 & 0 & 1/4 \end{vmatrix}$$

$$\mathbf{b_0} = 1/6(\mathbf{Y_1 + Y_4 + Y_6 + Y_7 + Y_9 + Y_{10}})$$

$$\mathbf{b_1} = 1/4(\mathbf{-Y_1 + Y_4 + Y_6 + Y_7})$$

$$\mathbf{b_2} = 1/4(\mathbf{-Y_1 + Y_4 - Y_6 + Y_7})$$

$$\mathbf{b_3} = 1/4(\mathbf{-Y_1 - Y_4 + Y_6 + Y_7})$$

substituting in the values for Y_1,......Y_{10},

$$b_0 = {}^1/_6(5.1358 + 4.7005 + 5.5175 + 5.3471 + 5.2257 + 5.1929)$$

$$\therefore \quad \mathbf{b_0 = 5.18659}$$

$$b_1 = {}^1/_4(-5.1358 + 4.7005 + 5.5175 - 5.3471)$$

$$\therefore \quad \mathbf{b_1 = -0.06624}$$

$$b_2 = {}^1/_4(-5.1358 + 4.7005 - 5.5175 + 5.3471)$$

$$\therefore \quad \mathbf{b_2 = -0.15142}$$

$$b_3 = {}^1/_4(-5.1358 - 4.7005 + 5.5175 + 5.3471)$$

$$\therefore \quad \mathbf{b_3 = 0.2571}$$

as was stated previously, equation (7.13)

$$\mathbf{\acute{y} = b_0x_0 + b_1x_1 + b_2x_2 + b_3x_3}$$

substituting the values for b_0, b_1, b_2, b_3

$$\acute{y}_1 = \mathbf{5.18659x_0 - 0.06624x_1 - 0.15142x_2 + 0.2571x_3}$$

<u>Block 2 Calculations</u>

where,

$$X = \begin{array}{ccccc} X_0 & X_1 & X_2 & X_3 & \text{Trial number} \\ |1 & 1 & -1 & -1| & 2 \\ |1 & -1 & 1 & -1| & 3 \\ |1 & -1 & -1 & 1| & 5 \\ |1 & 1 & 1 & 1| & 8 \\ |1 & 0 & 0 & 0| & 11 \\ |1 & 0 & 0 & 0| & 12 \end{array}$$

$$y = \begin{vmatrix} \ln 145 \\ \ln 122 \\ \ln 280 \\ \ln 189 \\ \ln 200 \\ \ln 200 \end{vmatrix} \begin{matrix} 2 \\ 3 \\ 5 \\ 8 \\ 11 \\ 12 \end{matrix}$$

$$y = \begin{vmatrix} 4.9767 \\ 4.8040 \\ 5.6348 \\ 5.2417 \\ 5.2983 \\ 5.2983 \end{vmatrix} \begin{matrix} Y_2 \\ Y_3 \\ Y_5 \\ Y_8 \\ Y_{11} \\ Y_{12} \end{matrix}$$

$$(\mathbf{X^TX}) = \begin{vmatrix} 6 & 0 & 0 & 0 \\ 0 & 4 & 0 & 0 \\ 0 & 0 & 4 & 0 \\ 0 & 0 & 0 & 4 \end{vmatrix}$$

$$\therefore (\mathbf{X^TX})^{-1} = \begin{vmatrix} {}^1/_6 & 0 & 0 & 0 \\ 0 & {}^1/_4 & 0 & 0 \\ 0 & 0 & {}^1/_4 & 0 \\ 0 & 0 & 0 & {}^1/_4 \end{vmatrix}$$

$$\mathbf{b_0} \quad = \quad {}^1/_6(Y_2+Y_3 + Y_5 + Y_8+ Y_{11} + Y_{12})$$

$$\mathbf{b_1} \quad = \quad {}^1/_4(-Y_2 +Y_3 + Y_5 + Y_8)$$

$$\mathbf{b_2} \quad = \quad {}^1/_4(-Y_2 +Y_3 - Y_5 + Y_8)$$

$$\mathbf{b_3} \quad = \quad {}^1/_4(-Y_2 -Y_3 + Y_5 + Y_8)$$

substituting in the values for $Y_2, \ldots\ldots Y_{12}$,

$\therefore \quad b_0 \quad = \quad {}^1/_6(4.9767 + 4.8040 + 5.6348 + 5.2417 + 5.2983 + 5.2983)$

$\therefore \quad \mathbf{b_0} \quad = \quad \mathbf{5.20899}$

$\therefore \quad b_1 \quad = \quad {}^1/_4(4.9767 - 4.8040 - 5.6348 + 5.2417)$

$\therefore \quad \mathbf{b_1} \quad = \quad \mathbf{-0.05508}$

$\therefore \quad b_2 \quad = \quad {}^1/_4(-4.9767 + 4.8040 - 5.6348 + 5.2417)$

$\therefore \quad \mathbf{b_2} \quad = \quad \mathbf{-0.14144}$

$\therefore \quad b_3 \quad = \quad {}^1/_4(-4.9767 - 4.8040 + 5.6348 + 5.2417)$

$\therefore \quad \mathbf{b_3} \quad = \quad \mathbf{0.27395}$

substituting the values of b_0, b_1, b_2, b_3 into equation 7.13

$$\mathbf{\acute{y}_2 = 5.20899x_0 - 0.05508x_1 - 0.14144x_2 + 0.27395x_3}$$

$\mathbf{\acute{y} = (\acute{y}_1 + \acute{y}_2)/2}$ (Average of the two sets results)

$$\therefore \acute{y} = (5.18659x_0 - 0.06624x_1 - 0.15142x_2 + 0.2571x_3) + (5.20899x_0 - 0.05508x_1 - 0.14144x_2 + 0.27395x_3)$$

$$\therefore \acute{y} = 5.19779x_0 - 0.06066x_1 - 0.14643x_2 + 0.26553x_3$$

substituting in the values for x_0, x_1, x_2, x_3

$$\therefore \acute{y} = 5.19779 - 0.06066(4.48142 \ln V - 12.4251) - 0.14643(4.56172 \ln f - 21.09796) + 0.26553(1.44269 \ln d - 1)$$

$$\therefore \acute{y} = 5.19779 - (0.271843 \ln V - 0.75371) - (0.65621 \ln f - 3.08937) + (0.38307 \ln d - .265525)$$

$\therefore \acute{y} \quad = \quad 8.77535 - 0.271843 \ln V - 0.65621 \ln f + 0.38307 \ln d$

As was stated earlier in equation 7.12,

$$\acute{y} = \ln T = \ln C + x \ln V + y \ln f + z \ln d$$

$$\therefore \quad C = e^{8.77535} \quad = 6472.71$$

$$x = -0.271843, \;\; y = -0.65621, \;\; z = 0.38307$$

$$\therefore \quad \mathbf{T} \quad = \quad \mathbf{6472.71\ (V^{-0.271843} * f^{-0.65621} * d^{0.38307})}$$

This equation is valid over the range;

$12.8 \leq V \leq 20$ m/min

$82 \leq f \leq 127$mm/min

$1 \leq d \leq 4$mm

Therefore a value for tool life can be estimated for a given cutting speed, feed rate and depth of cut.

7.4 Tool Life Tests

Following the completion of the 'One - variable - at a time experiments, the tools with the best performances from both the H.S.S. and cemented carbide categories were selected to tested in a 'Design of Experiment' model. The H.S.S. tool that was deemed to have the best performance was TiN-coated Strassmann cutting tools and the cemented carbide tool with the best performance was TiCN-coated Sandvik inserts.

7.4.1 High Speed Steel Tool

Experiment

The experiments were carried out on a Bridgeport Vertical Machining Centre (milling machine), in the up-milling mode using half immersion of the cutter and in the dry condition, i.e. without any coolant or lubricant. The Strassmann cutting tools were 25mm in diameter, had 5 cutting teeth and a weldon shank, a more detailed specification of the tool is given in chapter 5, section 1. A new cutting tool was used for each of the twelve tool life tests. The first block of six tests (i.e. 1, 2, 6, 7 and 10) were performed in a random manner. After analyzing these results, the second block of experiments (i.e. 2, 3, 5, 8, 11 and 12) were also conducted in a random manner. The combined set of experimental data is shown in table 7.4.1a together with the actual cutting condition and code indentification.

Experimental Results

Trial	Cutting Conditions			Coding			Tool Life
number	V,m/min	f,mm/min	d, mm	x_1	x_2	x_3	minutes
1	12.8	82	1	-1	-1	-1	**170**
2	20	82	1	1	-1	-1	**145**
3	12.8	127	1	-1	1	-1	**122**
4	20	127	1	1	1	-1	**110**
5	12.8	82	4	-1	-1	1	**280**
6	20	82	4	1	-1	1	**249**
7	12.8	127	4	-1	1	1	**210**
8	20	127	4	1	1	1	**189**
9	16	102	2	0	0	0	**186**
10	16	102	2	0	0	0	**180**
11	16	102	2	0	0	0	**200**
12	16	102	2	0	0	0	**200**

Analysis of Results

Using the technique shown in section 7.3, the results of the experiments can be transformed into an equation of tool life when milling using Strassmann TiN-coated end mills under the conditions described earlier in this section. This equation is as follows;

$$\therefore \quad T = 6472.71\,(V^{-0.271843} * f^{-0.65621} * d^{0.38307}) \quad (7.4.1)$$

and is valid over the range;

- $12.8 \leq V \leq 20$ m/min
- $82 \leq f \leq 127$mm/min
- $1 \leq d \leq 4$mm

From the equation it can be deduced that an increase in cutting speed or feed rate results in an decrease in the tool life, while an increase in the depth of cut results in an increase in the tool life.

The tool life predicting equation (7.4.1) can be plotted, as contours for each of the response surfaces at three selected levels of depth of cut. These selected levels were chosen as 1mm, 2mm and 4mm and are shown in figures 7.4.1a, b and c.

Adequacy of the postulated model

The analysis of variance (ANOVA) was used to check the adequacy of the developed model. As per this technique the calculated F_{rat} of the model was found to be 11.38 while the F_{rat} 5,2 for 95% confidence is 19.30 as obtained from statistical table. Hence the model is valid. The results of the ANOVA for the total block of 12 tests are shown in appendix B.

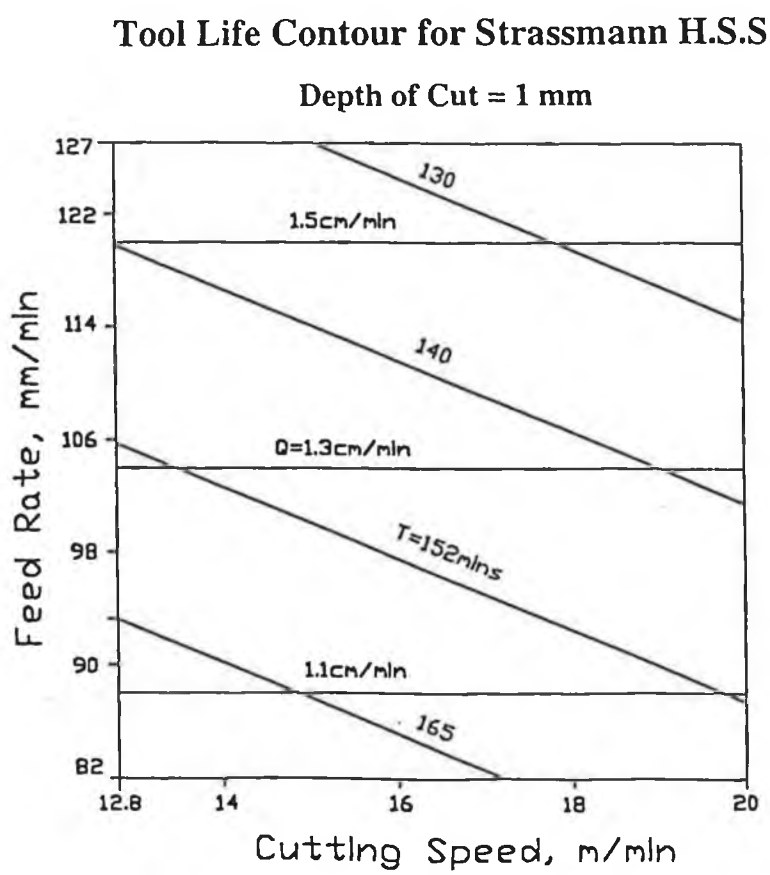

Figure 7.4.1a, Tool life contours (first-order model)

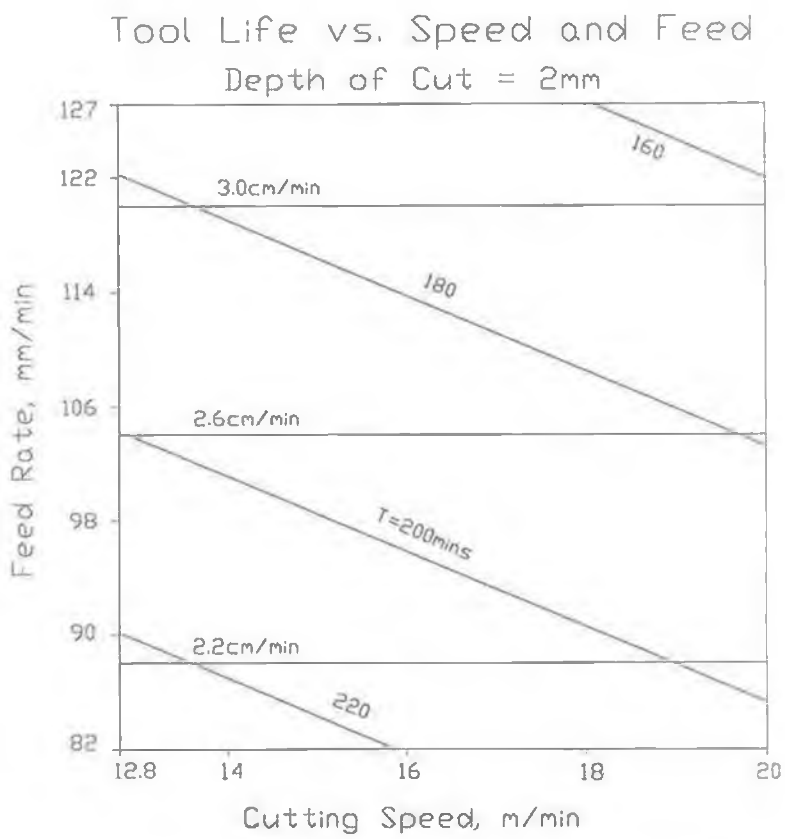

Figure 7.4.1b. Tool life contours (first-order model)

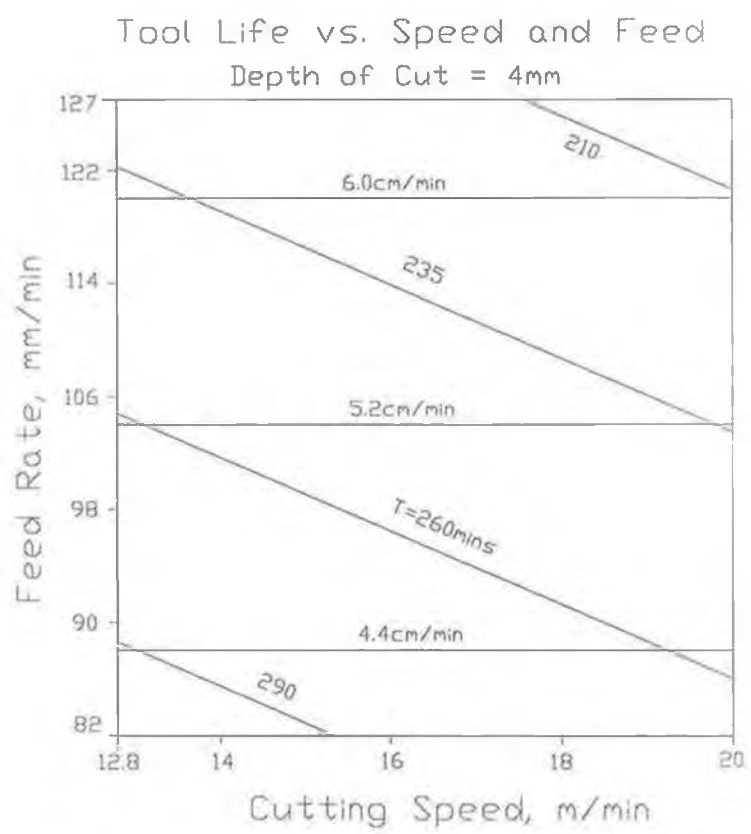

Figure 7.4.1c, Tool life contours (first-order model)

Conclusions

The predicting tool life equation can accurately estimate the tool life for any set of conditions within the boundaries of the cutting conditions specified, i.e. cutting speed (12.8 - 20m/min), feed rate (82 - 127 mm/min) and depth of cut (1 - 4 mm).

- An increase in the cutting speed causes a corresponding decrease in the tool life.
- An increase in the feed rate results in a decrease in the tool life.
- An increase in the depth of cut results in an increase in the tool life.
- The depth of cut is the most significant factor affecting tool life, with feed rate and cutting speed having a smaller effect.

From the graphs showing the contours of tool life for varying cutting speed and feed rate it can be concluded that the optimum conditions for improved tool life are found at a depth of cut of 4mm, with the reasons for this being explained in chapter 6, section 2.

Following this conclusion, the optimum conditions of cutting speed and feed rate can be found by finding the point on figure 7.4.1c, which combines maximum metal removal rate with extended tool life. It can be seen that there are three distinct possibilities on figure 7.4.1c, these points are on different tool life contours and metal removal rate lines and all three have advantages over one another.

Volume of metal removed = Machining time * Metal Removal Rate

At point a,

Total volume of metal removed = 290 mins * 4.4 cm^3/min

Volume 'a' = 1276 cm^3

At point b,

Total volume of metal removed = 260 * 5.2 cm^3/min

Volume 'b' = 1352 cm^3

At point c,

Total volume of metal removed = 235 * 6.0 cm^3/min

Volume 'c' = 1410 cm^3

As can be seen from the calculations, more metal is removed at point c. than at points 'a' or 'b'. Looking at the plot from the point of view of surface finish. it can be seen in figure 7.5.2c that there is only a small difference in the surface finishs produced between the three points, with point 'a' producing the better finish. Therefore after taking the three factors (tool life, metal removal rate and surface finish) into account, it is recommended that the conditions at point 'c' be selected as the optimum conditions for machining using coated Strassmann H.S.S. end mills.

Therefore the optimum set of cutting conditions for end milling tool steel P20 with a Brinell hardness of approx. 300, under dry cutting and half immersion machining, using 25mm diameter, Strassmann TiN-coated end mills are as follows:

- **Cutting Speed = 13 - 14 m/min**
- **Feed Rate = 90 - 120 mm/min**
- **Depth of Cut = 4 mm**

7.4.2 Cemented Carbide

Experiment

The experiments were carried out on a Bridgeport Vertical Machining Centre (milling machine), in the up-milling mode using half immersion of the cutter and in the dry condition, i.e. without any coolant or lubricant. The Sandvik cutting tools were 25mm in diameter, had 3 inserts and a weldon shank, a more detailed specification of the tool is given in chapter 5, section 1. A new cutting tool was used for each of the twelve tool life tests. The first block of six tests (i.e. 1, 2, 6, 7 and 10) were performed in a random manner. After analyzing these results, the second block of experiments (i.e. 2, 3, 5, 8, 11 and 12) were also conducted in a random manner. The combined set of experimental data is shown in table 7.4.2a together with the actual cutting condition and code indentification.

Experimental Results

Trial	**Cutting Conditions**			**Coding**			**Tool Life**
number	V, m/min	f, mm/min	d, mm	x_1	x_2	x_3	minutes
1	98	512	1	-1	-1	-1	**75.5**
2	112.5	512	1	1	-1	-1	**58.1**
3	98	590	1	-1	1	-1	**61.9**
4	112.5	590	1	1	1	-1	**52.3**
5	98	512	4	-1	-1	1	**82.88**
6	112.5	512	4	1	-1	1	**64.92**
7	98	590	4	-1	1	1	**66.8**
8	112.5	590	4	1	1	1	**57.6**
9	105	550	2	0	0	0	**64.4**
10	105	550	2	0	0	0	**63.7**
11	105	550	2	0	0	0	**62.9**
12	105	550	2	0	0	0	**65.1**

Analysis of Results

Using the technique shown in section 7.3, the results of the experiments can be transformed into an equation of tool life when milling using Sandvik TiCN-coated end mills under the conditions described earlier in this section. This equation is as follows;

$$\therefore \quad T \quad = \quad \mathbf{8.366155 \times 10^{7} (V^{-1.4923} * f^{-1.1382} * d^{0.0681})} \qquad (7.4.2)$$

and is valid over the range;

- $98 \leq V \leq 112.5$ m/min
- $512 \leq f \leq 590$ mm/min
- $1 \leq d \leq 4$mm

From the equation it can be deduced that an increase in cutting speed or feed rate results in an decrease in the tool life, while an increase in the depth of cut results in an increase in the tool life.

The tool life predicting equation (7.4.2) can be plotted, as contours for each of the response surfaces at three slected levels of depth of cut. These selected levels were chosen as 1mm, 2mm and 4mm and are shown in figures 7.4.2a, b and c.

Adequacy of the postulated model

The analysis of variance (ANOVA) was used to check the adequacy of the developed model. As per this technique the calculated F_{rat} of the model was found to be 7.60 while the F_{rat} 5,2 for 95% confidence is 19.30 as obtained from statistical table. Hence the model is valid. The results of the ANOVA for the total block of 12 tests are shown in appendix B.

Tool Life Contour for Sandvik Inserts

Depth of Cut = 1 mm

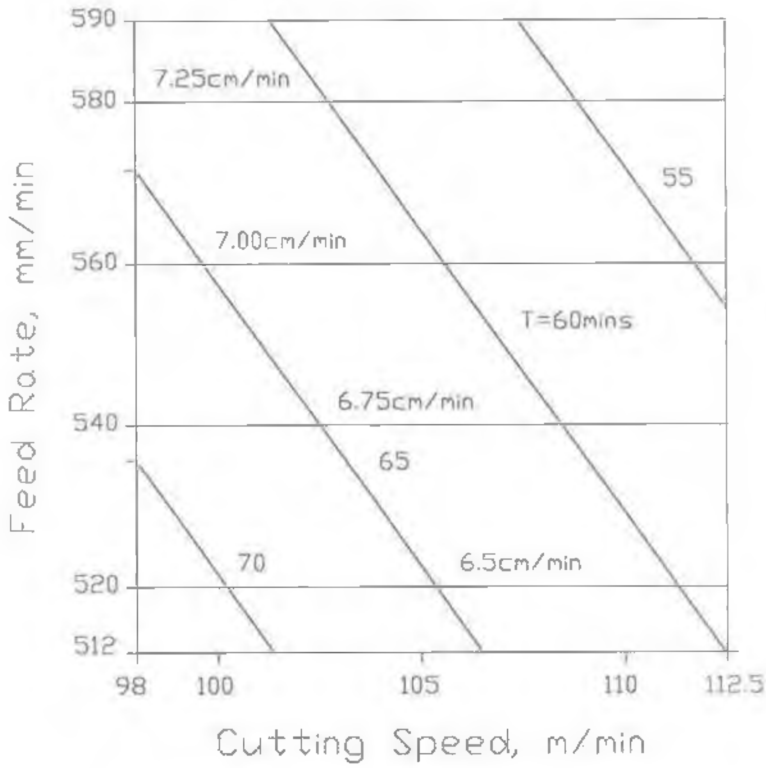

Figure 7.4.2a, Tool life contours (first-order model)

Tool Life Contour for Sandvik Inserts

Depth of Cut = 2 mm

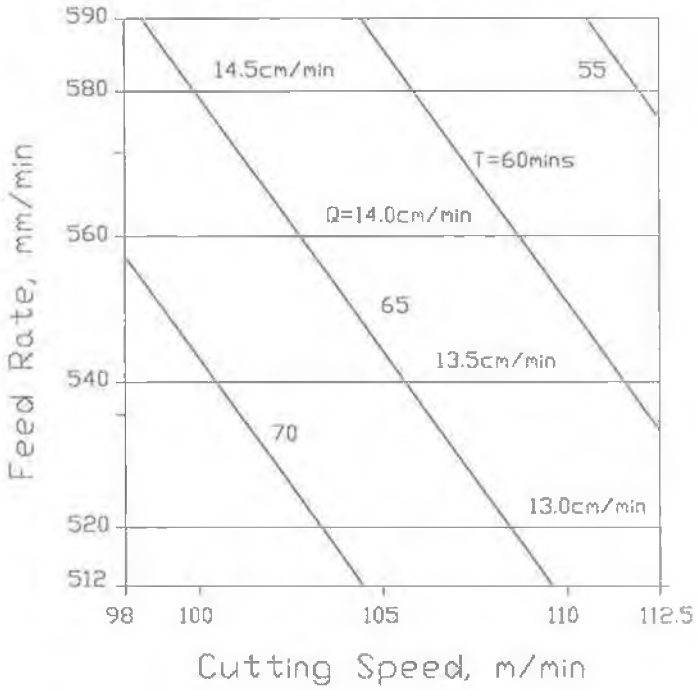

Figure 7.4.2b, Tool life contours (first-order model)

Tool Life Contour for Sandvik Inserts

Depth of Cut = 4 mm

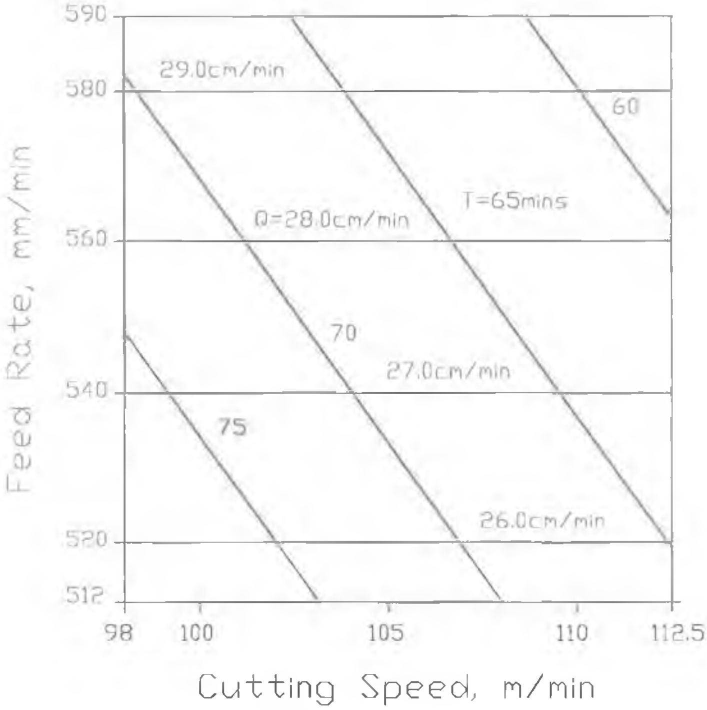

Figure 7.4.2c, Tool life contours (first-order model)

<u>Conclusions</u>

The predicting tool life equation can accurately estimate the tool life for any set of conditions within the boundaries of the cutting conditions specified, i.e. cutting speed (98 - 112.5 m/min), feed rate (512 - 590 mm/min) and depth of cut (1 - 4 mm).

- An increase in the cutting speed causes a corresponding decrease in the tool life.
- An increase in the feed rate results in a decrease in the tool life.
- An increase in the depth of cut results in an increase in the tool life.
- The depth of cut is the most significant factor affecting tool life, with feed rate and cutting speed having a smaller effect.

From the graphs showing the contours of tool life for varying cutting speed and feed rate it can be concluded that the optimum depth of cut for improved tool life is found at 4mm, as was already concluded from the one-variable at a time experiments. Following this conclusion, the optimum conditions of cutting speed and feed rate can be found by finding the point which combines maximum metal removal rate with extended tool life, i.e. the point which gives the most metal removed. From the graph it can be seen that there are two distinct possibilities (point a and point b) from which to chose. Point 'a' is located on the 75 minute contour at the intersection of the 27.0 cm^3/min metal removal rate, while point 'b' is situated on the 70 minute contour at the intersection of the 29.0 cm^3/min metal removal rate.

Volume of metal removed = Machining time * Metal Removal Rate

At point a,

Total volume of metal removed = 75 * 27.0 cm^3/min

Volume 'a' = 2025 cm^3

At point b,

Total volume of metal removed = 70 * 29.0 cm^3/min

Volume 'b' = 2030 cm^3

Although more metal is removed at point b, it is recommended that the conditions at point 'a' be selected because of the fact that the feed rate is lower and therefore the surface finish produced at point 'a' is superior to that at point 'b' as can be seen in figure 7.5.2c.

Therefore the optimum set of cutting conditions for end milling tool steel P20 with a Brinell hardness of approx. 300, under dry cutting and full immersion machining, using 25mm diameter, Sandvik TiCN-coated inserts are as follows;

- **Cutting Speed = 98 - 100 m/min**
- **Feed Rate = 540 - 580 mm/min**
- **Depth of Cut = 4 mm**

7.5 Surface Finish Tests

For the design of experiment model of both the H.S.S. and cemented carbide cutting tools, a model for surface finish was calculated. This model was conducted under the same cutting conditions as the tool life model and across the same ranges for each variable.

7.5.1 High Speed Steel Tool

Experiment

The experiments were carried out on a Bridgeport Vertical Machining Centre (milling machine), in the up-milling mode using full immersion of the cutter (slot milling) and in the dry condition, i.e. without any coolant or lubricant. The Strassmann cutting tools were 25mm in diameter, had 5 cutting teeth and a weldon shank. A new cutting tool was used for every second test. The experimental data is shown below in table 7.5.1a together with the actual cutting condition and code indentification.

Experimental Results

Trial	**Cutting Conditions**			**Coding**			**Surface**
number	V,m/min	f, mm/min	d, mm	x_1	x_2	x_3	**Finish, Ra**
1	12.8	82	1	-1	-1	-1	**4.75**
2	20	82	1	1	-1	-1	**3.10**
3	12.8	127	1	-1	1	-1	**6.01**
4	20	127	1	1	1	-1	**4.62**
5	12.8	82	4	-1	-1	1	**6.10**
6	20	82	4	1	-1	1	**4.12**
7	12.8	127	4	-1	1	1	**7.85**
8	20	127	4	1	1	1	**5.71**
9	16	102	2	0	0	0	**4.65**
10	16	102	2	0	0	0	**4.61**
11	16	102	2	0	0	0	**4.48**
12	16	102	2	0	0	0	**4.54**

Analysis of Results

Using the technique shown in section 7.3, the results of the experiments can be transformed into an equation for measuring the surface roughness while using Strassmann TiN-coated end mills under the conditions described earlier in this section. This equation is as follows;

$$\therefore \quad \mathbf{R_a} \quad = \quad \mathbf{1.55737\,(V^{-0.78454} * f^{0.70525} * d^{0.18277})} \qquad \mathbf{(7.4.1)}$$

and is valid over the range;

- $12.8 \leq V \leq 20$ m/min
- $82 \leq f \leq 127$mm/min
- $1 \leq d \leq 4$mm

From the equation it can be deduced that an increase in cutting speed results in a decrease in the surface finish, while an increase in the feed rate or the depth of cut results in an increase in the surface finish produced.

The surface finish equation (7.5.1) can be used to plot contours for each of the response surfaces at various levels of depth of cut. These selected levels were chosen as 1mm, 2mm and 4mm and are shown in figures 7.5.1a, b and c.

Adequacy of the postulated model

The analysis of variance (ANOVA) was used to check the adequacy of the developed model. As per this technique the calculated F_{rat} of the model was found to be 10.15 while the F_{rat} 5,2 for 95% confidence is 19.30 as obtained from statistical table. Hence the model is valid. The results of the ANOVA for the total block of 12 tests are shown in appendix B.

Surface Finish Contour for Strassmann H.S.S.

Depth of cut = 1 mm

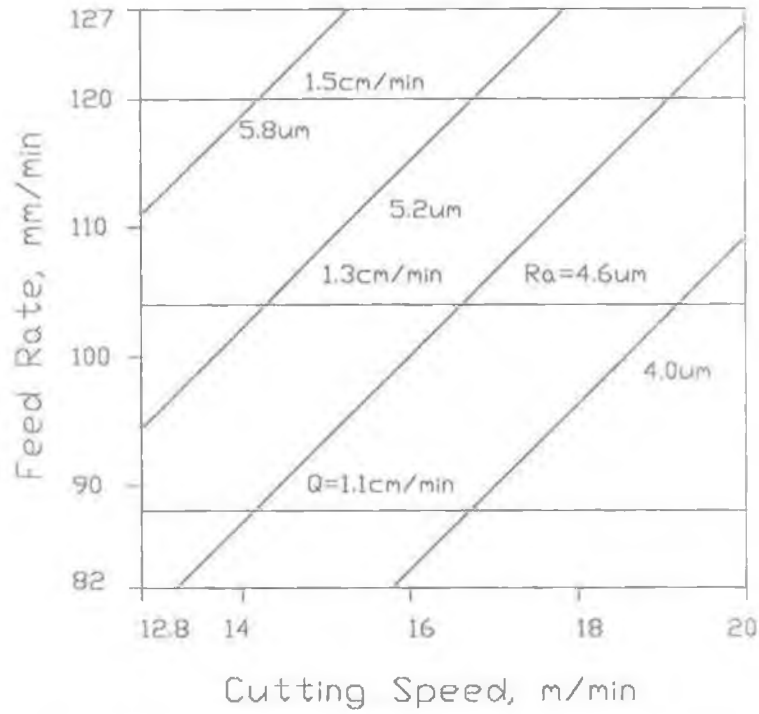

Figure 7.5.1a, Tool life contours (first-order model)

Surface Finish Contour for Strassmann H.S.S.

Depth of cut = 2 mm

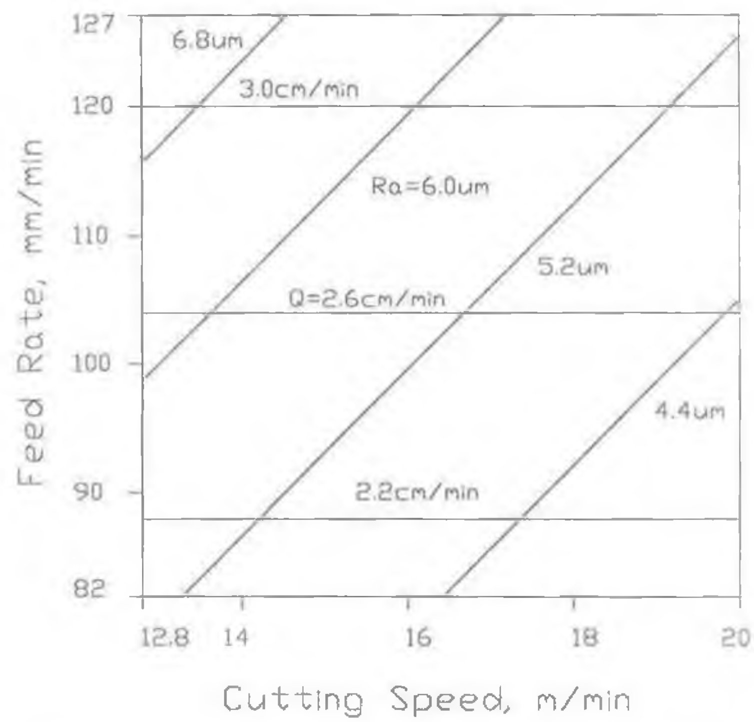

Figure 7.5.1b, Tool life contours (first-order model)

Surface Finish Contour for Strassmann H.S.S.

Depth of cut = 4 mm

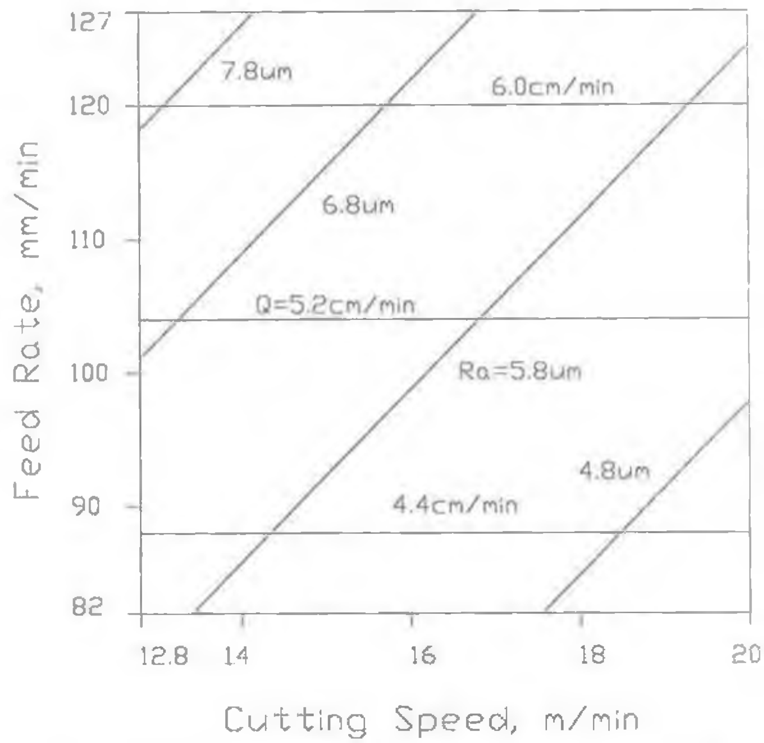

Figure 7.5.1c, Tool life contours (first-order model)

Conclusions

The surface finish equation can be used to accurately estimate the surface finish that will be produced for any set of conditions within the ranges of the cutting conditions specified, i.e. cutting speed (12.8 - 20m/min), feed rate (82 - 127 mm/min) and depth of cut (1 - 4 mm).

- An increase in the cutting speed causes a corresponding decrease in the surface finish.
- An increase in the feed rate results in an increase in the surface finish.
- An increase in the depth of cut results in an increase in the surface finish.
- The cutting speed is the most significant factor affecting surface finish, followed by the feed rate, with depth of cut having a negligible effect on the outcome.

From the three graphs showing the contours of surface finish for varying cutting speed and feed rate it can be concluded that for optimum surface finish it is advisable to machine at a high a cutting speed as possible, coupled with a low feed rate and low depth of cut. However, although a better surface is produced at low depths of cut, the increase in surface finish with increasing depth of cut is not very significant. For example, at a cutting speed of 16.5 m/min, a feed rate of 105 mm/min and a depth of cut of the 1 mm, the surface finish produced is 4.6 μm. At a depth of cut 4 mm, the surface finish only rises to 5.8 μm. When you compare this to the 400% increase in metal removal rate obtained at 4 mm depth of cut, the resulting increase in surface finish is disregarded. Therefore, optimum conditons for running coated Strassmann H.S.S. end mills for improved surface finish are as follows;

- **Cutting Speed = 17.5 - 20 m/min**
- **Feed Rate = 82 - 95 mm/min**
- **Depth of Cut = 2.5 - 4 mm**

7.5.2 Cemented Carbide

Experiment

The experiments were carried out on a Bridgeport Vertical Machining Centre (milling machine), in the up-milling mode using full immersion of the cutter (slot milling) and in the dry condition, i.e. without any coolant or lubricant. The Sandvik cutting tools were 25mm in diameter, had 3 inserts and a weldon shank, a more detailed specification of the tool is given in chapter 5, section 1. A new cutting tool was used on every second test. The surface finish was measured using a Mutitoyo Surftest 403 [12], in 4 different locations on the machined surface and the average value was then calculated. As was the case for the tool life tests, the first block of six tests (i.e. 1, 2, 6, 7 and 10) were performed in a random manner. After analyzing these results, the second block of experiments (i.e. 2, 3, 5, 8, 11 and 12) were also conducted in a random manner. The combined set of experimental data is shown in table 7.5.2a together with the actual cutting conditions and code indentification.

Experimental Results

Trial	Cutting Conditions			Coding			Surface
number	V, m/min	f, mm/min	d, mm	x_1	x_2	x_3	**Finish, R_a**
1	98	512	1	-1	-1	-1	**2.18**
2	112.5	512	1	1	-1	-1	**1.40**
3	98	590	1	-1	1	-1	**2.73**
4	112.5	590	1	1	1	-1	**2.30**
5	98	512	4	-1	-1	1	**3.40**
6	112.5	512	4	1	-1	1	**2.77**
7	98	590	4	-1	1	1	**3.93**
8	112.5	590	4	1	1	1	**3.30**
9	105	550	2	0	0	0	**2.48**
10	105	550	2	0	0	0	**2.50**
11	105	550	2	0	0	0	**2.60**
12	105	550	2	0	0	0	**2.40**

Analysis of Results

Using the technique shown in section 7.3, the results of the experiments can be transformed into an equation of surface finish when milling using Sandvik TiCN-coated end mills under the conditions described earlier in this section. This equation is as follows;

$$\therefore \quad R_a = 7.419488 \times 10^{-2} \left(V^{-1.80054} * f^{1.85426} * d^{0.334019}\right) \quad (7.5.1)$$

and is valid over the range;

- $98 \leq V \leq 112.5$ m/min
- $512 \leq f \leq 590$ mm/min
- $1 \leq d \leq 4$mm

From the equation it can be deduced that an increase in feed rate or depth of cut results in an increase in the surface finish produced, while an increase in the cutting speed results in a decrease in the surface finish.

The surface finish equation (7.5.2) can be plotted, as contours for each of the response surfaces at three selected levels of depth of cut. These selected levels were chosen as 1mm, 2mm and 4mm and are shown in figures 7.4.2a, b and c.

Adequacy of the postulated model

The analysis of variance (ANOVA) was used to check the adequacy of the developed model. As per this technique the calculated F_{rat} of the model was found to be 16.34 while the F_{rat} 5,2 for 95% confidence is 19.30 as obtained from statistical table. Hence the model is valid. The results of the ANOVA for the total block of 12 tests are shown in appendix B.

Surface Finish Contour for Sandvik Inserts

Depth of Cut = 1 mm

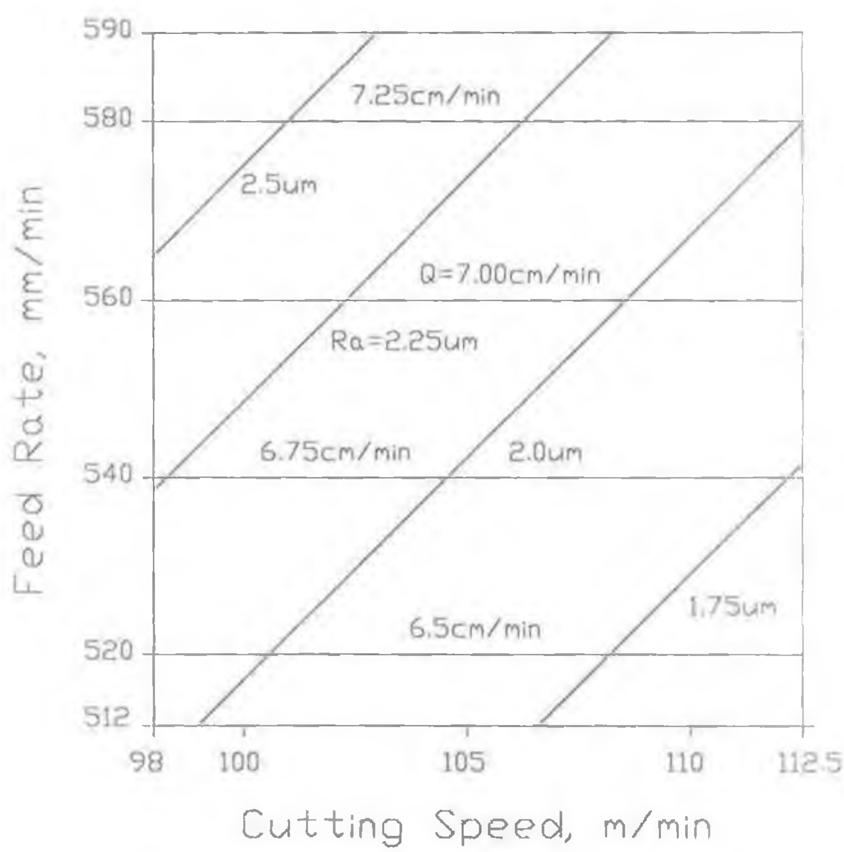

Figure 7.5.2a, Tool life contours (first-order model)

Surface Finish Contour for Sandvik Inserts

Depth of Cut = 2 mm

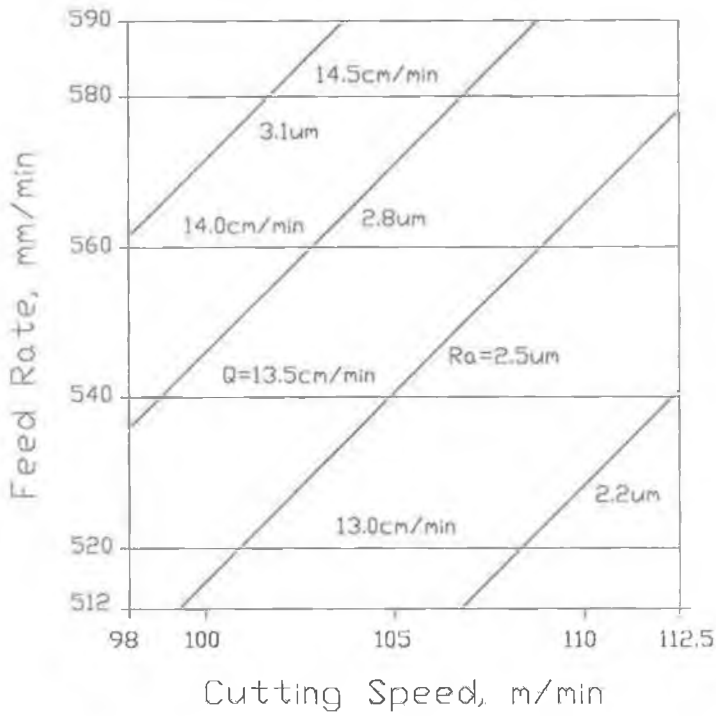

Figure 7.5.2b, Tool life contours (first-order model)

Surface Finish Contour for Sandvik Inserts

Depth of Cut = 4 mm

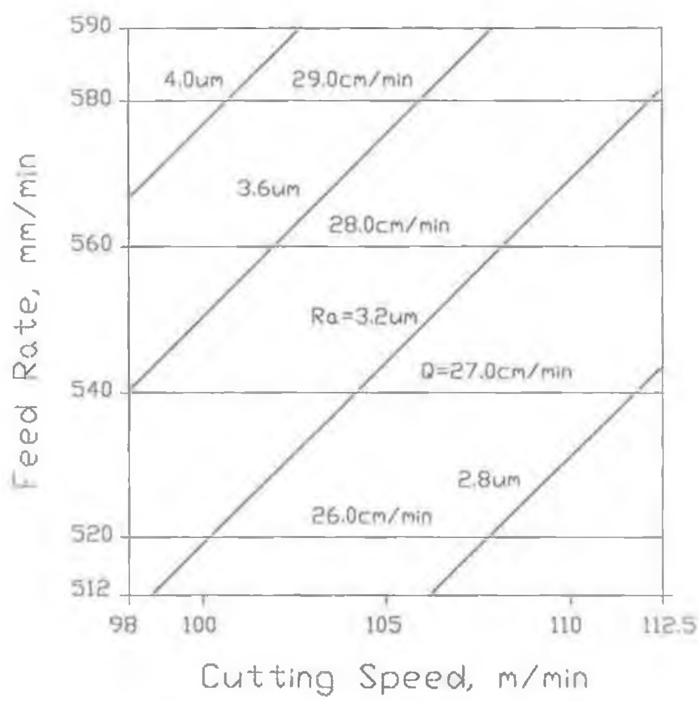

Figure 7.5.2c, Tool life contours (first-order model)

Conclusions

The predicting tool life equation can accurately estimate the surface finish for any set of conditions within the boundaries of the cutting conditions specified, i.e. cutting speed (98 - 112.5 m/min), feed rate (512 - 590 mm/min) and depth of cut (1 - 4 mm).

- An increase in the cutting speed results in a decrease in the surface finish.
- An increase in the feed rate produces an increase in the surface finish.
- An increase in the depth of cut results in an increase in the surface finish.
- The cutting speed is the most significant factor affecting surface finish of a machined component, with feed rate and depth of cut having a reduced effect on the outcome.

From the graphs showing the surface finish contours with varying cutting speed and feed rate it can be concluded that for the best surface finish, it is advisable to machine at a high a cutting speed as possible, coupled with low feed rate. Although increasing depth of cut results in an increase in the surface finish produced, the increase is negligible when compared to the increase in metal removal rates that are obtainable at large depths of cut. Therefore the optimum cutting conditions for producing a good surface finish are as follows;

- **Cutting Speed = 106- 112.5 m/min**
- **Feed Rate = 512 - 540 mm/min**
- **Depth of Cut = 4 mm**

CHAPTER 8

CONCLUSIONS

Following this research into the machinability of tool steel (Din 1.2311) using the end milling process, the following conclusions can be made;

8.1 High Speed Steel

8.1.1 Cutting Forces

In end milling, the feed force (x-axis) is the largest of the three cutting forces, followed by the normal force (y-axis) and finally the vertical force (z-axis).

As the cutting speed increases the cutting forces decrease, while an increase in the feed rate or depth of cut results in an increase in the cutting forces.

From the cutting force tests it can be concluded that for uncoated H.S.S. cutting tools, the optimum range of cutting conditions to minimize the cutting forces produced is as follows.

Cutting Speed = 12 - 18 m/min
Feed Rate = 55 - 100 mm/min
Depth of Cut = 1.0 - 2.5mm

8.1.2 Tool Life

From the tool life tests on H.S.S. end mills the following conclusions on their behaviour and performances can be made.

- For both uncoated and coated H.S.S. cutting tools an increase in the cutting speed results in a corresponding decrease in the tool life.

- For both uncoated and coated H.S.S. cutting tools an increase in the feed rate results in a decrease in the tool life.

- For uncoated H.S.S. tools an increase in the depth of cut results in decrease in the tool life, while for coated tools an increase in the depth of cut results in an increase in the tool life.

The difference between the behaviour of the uncoated and coated H.S.S. cutting tools can be explained as follows. As the depth of cut increases the temperature in the cutting zone increases. However, the size of the chip produced also increases and the proportion of the overall temperature transmitted to the chip and workpiece increases. The rise in temperature with increasing depth of cut is greater for uncoated tools than for coated tools. The increase in the depth of cut also results in an increase in chip load and therefore cutting pressure, which increases the abrasive wear on the tools.

For the uncoated cutting tools the increase in temperature result is an increase the diffusion wear. The increase in pressure results in an increase in the abrasive wear on the tool. Therefore for uncoated tools an increase in the depth of cut results in an increase in the total wear on the uncoated tool due to increases in both diffusion and abrasive wear and consquently a reduction in the tool life.

On the other hand, for coated tools although the overall temperature in the cutting zone increases with increasing depth of cut, the increase in the cutting tool temperature is very small. This can be attributed to the fact that the ceramic coating is thermally stable and acts as a thermal barrier causing the majority of the temperature that is produced to be transmitted to the chip/workpiece. This increase in temperature of the chip/workpiece has the effect of reducing the hardness of the workpiece material making it less abrasive on the cutting tool, therefore reducing the amount of abrasive wear present on the cutting tool. The small rise in the tool temperature increases the diffusion wear but not significantly. The overall effect of the increase in cutting temperature is that the abrasion wear decreases, more than the diffusion wear increases, and therefore there is a net reduction in overall tool wear on coated tools with increasing depth of cut.

It can also be concluded that the performance of the coated tools is far superior to that of the uncoated tools, with the coated tools out-performing the uncoated tools by at least 50 % across the entire cutting range. The performance of the coated tools over the uncoated tools is more apparent for increasing depth of cut. The tool life of the coated tools rises from 60% longer than uncoated at 1mm depth of cut to over 300% longer than uncoated at 4mm depth of cut.

Another important factor affecting the tool life that was observed during the tool life tests is the effect of the clearance on the rake face of the cutting tool. In my opinion it is the uniformity of these clearances that is the underlining reason for the enhanced performance of one cutting tool manufacturer over another.

Figure 8.1.2a is a representation of a new cutting tool, which has a small clearance on the rake face. Figure 8.1.2b is a representation of a worn tool and shows wear on the flank.

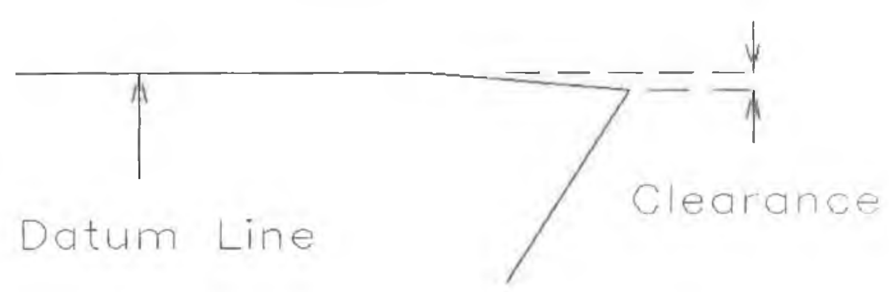

Figure 8.1.2a, A new cutting tool

The clearance that is present on the rake face of the cutting teeth is not constant, it varies from tooth to tooth and from one end mill to another. This affects the wear of the tool in that teeth on the same tool wear at different rates. This is because the chipload varies on cutters with different clearance values The teeth with the least clearance confront more chipload than the teeth with higher clearance. However this does not balance out tool life; rather, a domino effect ensues. As one tooth fails prematurely the tooth following it carries an excessive chipload, repeating the wear cycle. The end result is inevitably shorter tool life.

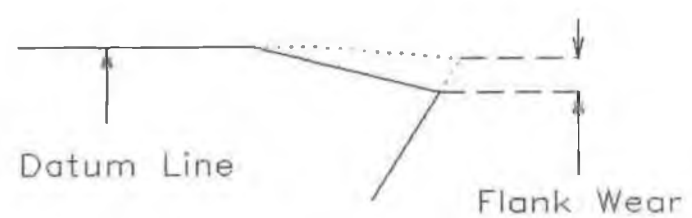

Figure 8.1.2b, A worn cutting tool

Most end milling cutters tend to have teeth with different rake clearance values which results in different wear rates on the same cutting tool. However, during the investigation one particular tool in the batch was found, that had no rake clearance on any of its teeth. This particular tool had a significantly longer tool life than was expected. Although this tool was a standard tool, it had the geometry of a qualified cutting tool and although the findings are inconclusive it has nonetheless raised some interesting points on the benefits of using qualified tools. In light of these findings it is suggested that further research work could be conducted into the performance of qualified tools compared to standard tools.

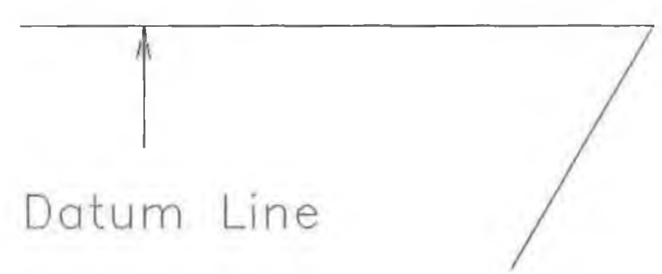

Figure 8.1.2c, A tooth with no rake clearance

Design of Experiment Model

From the tool life tests conducted using the design of experiment method using coated Strassmann H.S.S. tools, the following equation for tool life was calculated.

$$\therefore \quad T = 6472.71\,(V^{-0.271843} * f^{-0.65621} * d^{0.38307}) \qquad (8.1)$$

where,

T	=	tool life, minutes
V	=	cutting speed, m/min
f	=	feed rate, mm/min
d	=	depth of cut, mm

this equation is valid over the range;

- $12.8 \le V \le 20$ m/min
- $82 \le f \le 127$mm/min
- $1 \le d \le 4$mm

Once again it was concluded that the depth of cut is the most important factor influencing the tool life of the cutting tool.

The graphs showing the tool life contours for varying cutting speed, feed rate and depth of cut where used to find the optimum conditions for improved tool life and economic metal removal rate.

The optimum cutting conditions for end milling tool steel (P20) with a Brinell hardness of 300, under dry machining while using Strassmann TiN coated cutters where found to be the following.

- **Cutting Speed = 13 - 14m/min**
- **Feed Rate = 90 - 120mm/min.**
- **Depth of Cut = 4mm**

8.1.3 Surface Finish

- An increase in the cutting speed causes a corresponding decrease in the surface finish.
- An increase in the feed rate results in an increase in the surface finish.
- An increase in the depth of cut results in an increase in the surface finish.
- The cutting speed is the most significant factor affecting surface finish, followed by the feed rate, with depth of cut having a negligible effect on the outcome.

The outcome of the design of experiment tests is an equation for measuring the surface roughness while using Strassmann TiN-coated end mills. This equation is as follows;

$$\therefore \quad R_a = 1.55737\,(V^{-0.78454} * f^{0.70525} * d^{0.18277}) \qquad (7.4.1)$$

The surface finish equation can be used to accurately predict the surface finish that is produced for any set of conditions within the ranges of the cutting conditions that were used for the design of experiment tests. The valid range of the equation is cutting speed (12.8 - 20 m/min), feed rate (82 - 127mm/min) and depth of cut (1 - 4mm).

From the graphs showing the contours of surface finish for varying cutting speed and feed rate it can be concluded that for optimum surface finish it is advisable to machine at a high a cutting speed as possible, coupled with a low feed rate and low depth of cut. However, although a better surface is produced at low depths of cut, the increase in surface finish with increasing depth of cut is not very significant. For example, at a cutting speed of 16.5 m/min, a feed rate of 105 mm/min and a depth of cut of the 1 mm, the surface finish produced is 4.6 μm. At a depth of cut 4 mm, the surface finish only rises to 5.8 μm. When you compare this to the 400% increase in metal removal rate obtained at 4 mm depth of cut, the resulting increase in surface finish is disregarded. Therefore, optimum conditons for running coated Strassmann H.S.S. end mills for improved surface finish are as follows;

- **Cutting Speed** = **17.5 - 20 m/min**
- **Feed Rate** = **82 - 95 mm/min**
- **Depth of Cut** = **2.5 - 4 mm**

8.2 Cemented Carbide

8.2.1 Tool Life

From the tool life tests on cemented carbide end mills the following conclusions on their behaviour and performances can be made.

- For both uncoated and coated cemented carbide cutting tools an increase in the cutting speed results in a corresponding decrease in the tool life.
- For both uncoated and coated cemented cutting tools an increase in the feed rate results in a decrease in the tool life.
- For uncoated cemented tools an increase in the depth of cut results in decrease in the tool life, while for coated tools an increase in the depth of cut results in an increase in the tool life.

It can be concluded that the performance of the coated inserts are far superior to the uncoated inserts, with the coated inserts lasting approximately 100% longer than the uncoated inserts at low depths of cut. As well as lasting longer than the uncoated inserts, the coated inserts also operate at 60% higher metal removal rates. At higher depths of cut the coated inserts perform over 500% longer than their uncoated counterparts while operating at higher metal removal rates.

The reasons for the difference in the behaviours of the uncoated and coated tools for varying depths of cut are the same as those for H.S.S. cutting tools and is explained in section 8.1.2.

From the design of experiment method an equation for predicting the tool life of coated Sandvik end mill cutters was calculated. This equation is valid for predicting the tool life while milling tool steel (P20) under dry cutting conditions while using a 25mm cutter.

$$\therefore \quad T = 8.366155 \times 10^{7} (V^{-1.4923} * f^{-1.1382} * d^{0.0681}) \qquad (7.4.1)$$

The equation is valid over the range, cutting speed (98 - 112.5 m/min), feed rate (512 - 590 mm/min) and depth of cut (1 - 4 mm).

From the graphs showing tool life contours for varying cutting speed, feed rate and depth of cut, the optimum conditions for tool life and metal removal rate where found and are as follows.

- **Cutting Speed = 98 -100 m/min**
- **Feed Rate = 540 - 580 mm/min**
- **Depth of Cut = 4 mm**

8.2.2 Surface Finish

- An increase in the cutting speed results a decrease in the surface finish.
- An increase in the feed rate results in an increase in the surface finish.
- An increase in the depth of cut results in an increase in the surface finish.
- The cutting speed is the most significant factor affecting surface finish, followed by the feed rate, with depth of cut having a negligible effect on the outcome.

The outcome of the design of experiment tests is an equation for measuring the surface roughness while using Sandvik coated end mills. This equation is as follows;

$$\therefore \quad R_a = 7.419488 \times 10^{-2} (V^{-1.80054} * f^{1.85426} * d^{0.334019}) \qquad (7.5.1)$$

The equation is valid over the range, cutting speed (98 - 112.5 m/min), feed rate (512 - 590 mm/min) and depth of cut (1 - 4 mm).

From the graphs showing the surface finish contours with varying cutting speed and feed rate it can be concluded that for the best surface finish, it is advisable to machine at a high a cutting speed as possible, coupled with low feed rate. Although increasing depth of cut results in an increase in the surface finish produced, the increase is negligible when compared to the increase in metal removal rates that are obtainable at large depths of cut. Therefore the optimum cutting conditions for producing a good surface finish are as follows;

- **Cutting Speed = 106- 112.5 m/min**
- **Feed Rate = 512 - 540 mm/min**
- **Depth of Cut = 4 mm**

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APPENDIX A

TOOL LIFE TESTS-TOOL WEAR DATA

Uncoated Clarkson High Speed Steel

a) Effect of Cutting Speed

Machining Time	Tool Wear, mm		
minutes	10 m/min	15 m/min	20 m/min
0	0	0	0
10	0.056	0.062	0.067
20	0.081	0.091	0.100
30	0.104	0.118	0.127
40	0.129	0.144	0.159
50	0.150	0.173	0.196
60	0.173	0.201	0.220
70	0.195	0.228	0.253
80	0.219	0.258	0.313
90	0.241	0.307	-
100	0.320	-	-

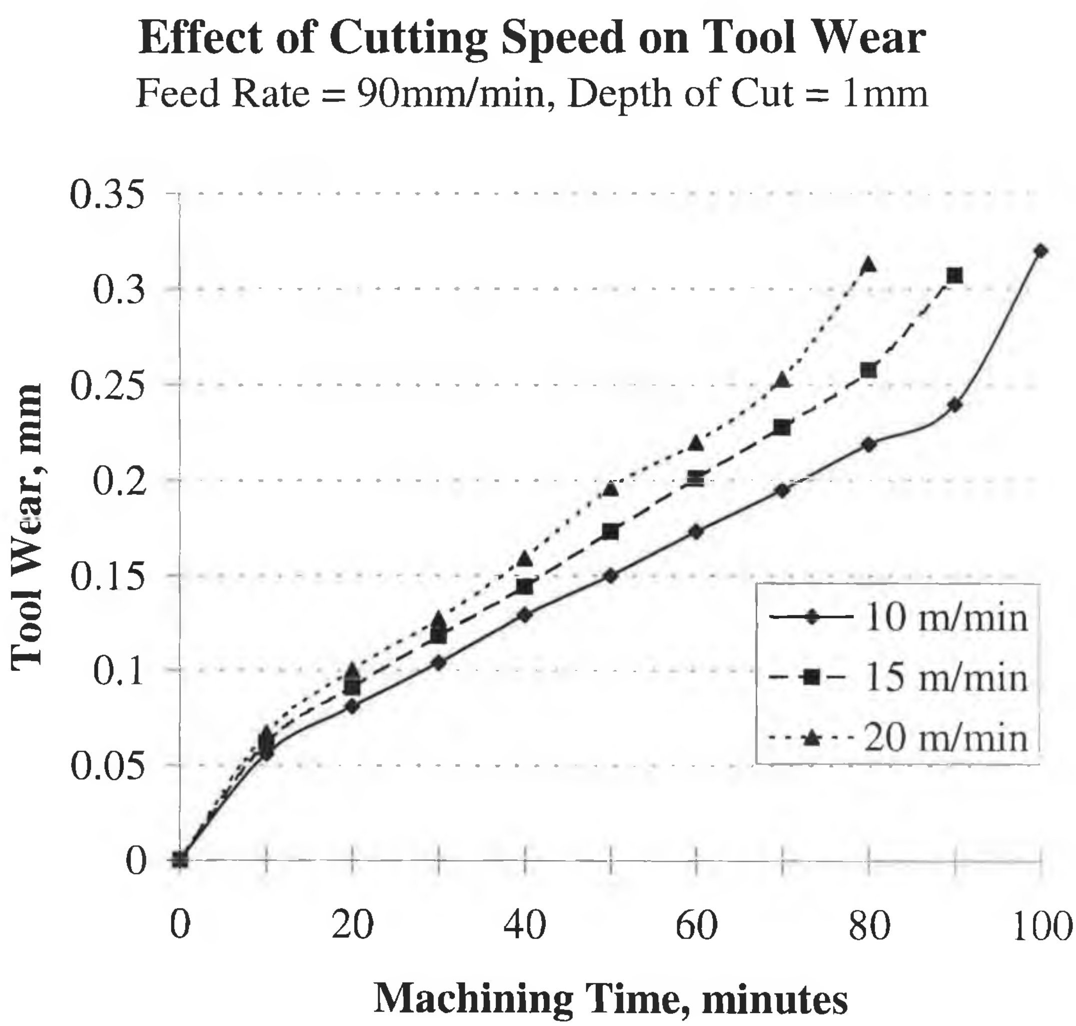

Figure A1, Effect of Cutting Speed on Tool Wear, Uncoated Clarkson H.S.S.

b) Effect of Feed Rate

Machining Time	Tool Wear, mm		
minutes	60 mm/min	90 mm/min	120 mm/min
0	0	0	0
10	0.044	0.062	0.057
20	0.065	0.091	0.094
30	0.092	0.118	0.129
40	0.117	0.144	0.163
50	0.143	0.173	0.198
60	0.168	0.201	0.243
70	0.195	0.228	0.299
80	0.221	0.258	-
90	0.254	0.307	-
100	0.301	-	-

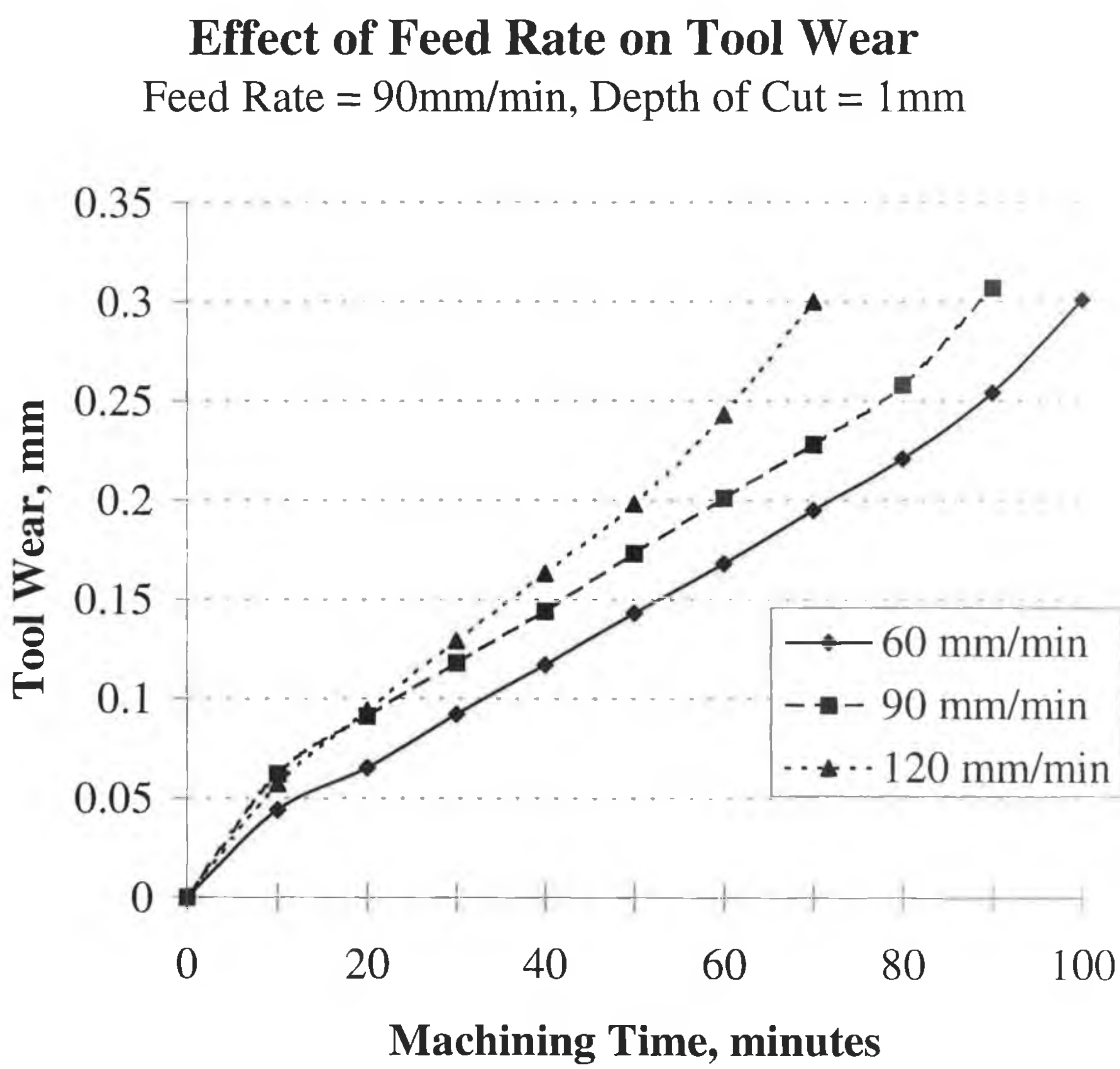

Figure A2, Effect of Feed Rate on Tool Wear, Uncoated Clarkson H.S.S.

c) Effect of Depth of Cut

Machining Time	Tool Wear, mm		
minutes	1 mm	2 mm	4 mm
0	0	0	0
10	0.062	0.068	0.080
20	0.091	0.102	0.121
30	0.118	0.129	0.157
40	0.144	0.155	0.198
50	0.173	0.183	0.236
60	0.201	0.207	0.302
70	0.228	0.246	-
80	0.258	0.299	-
90	0.307	-	-

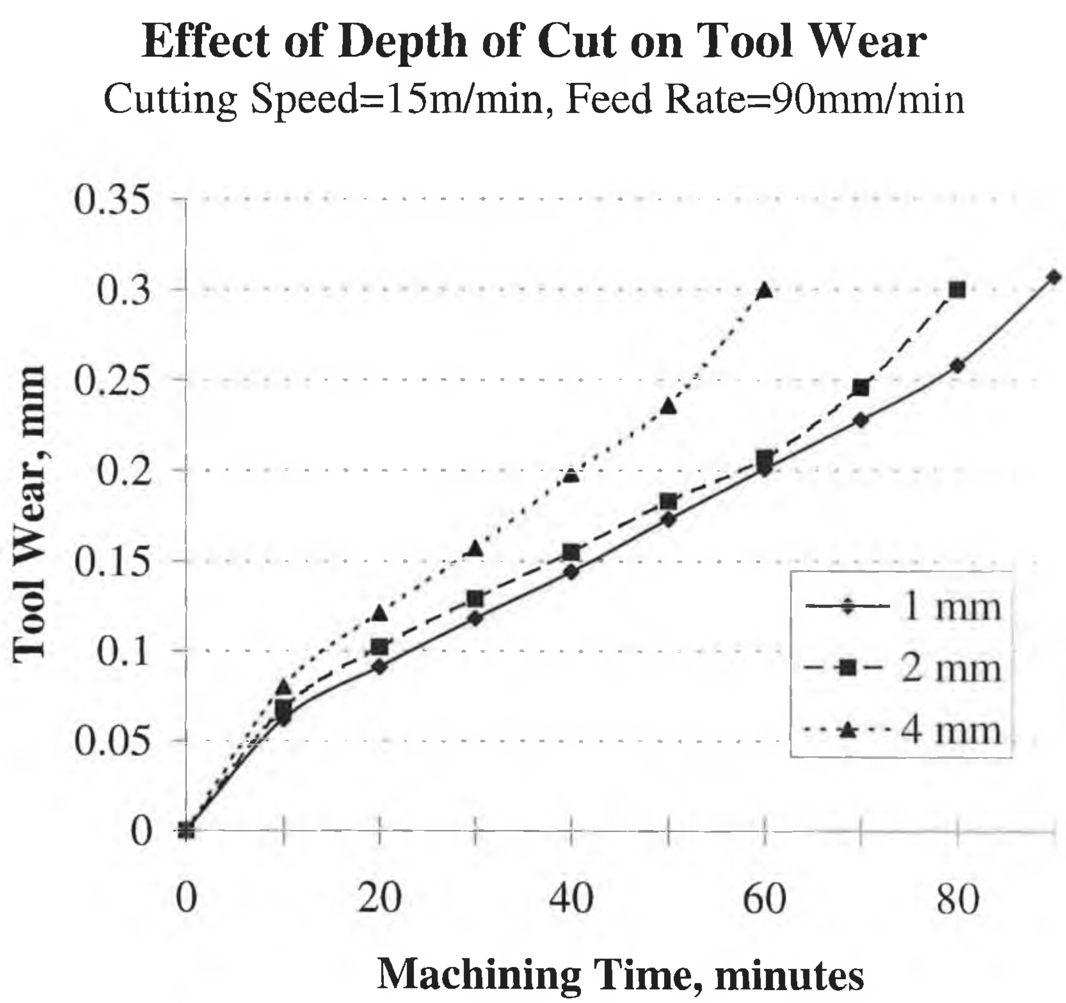

Figure A3, Effect of Depth of Cut on Tool Wear, Uncoated Clarkson H.S.S.

Uncoated Strassmann High Speed Steel

a) Effect of Cutting Speed

Machining Time	Tool Wear, mm		
minutes	10 m/min	15 m/min	20 m/min
0	0	0	0
10	0.063	0.068	0.060
20	0.089	0.094	0.088
30	0.109	0.114	0.115
40	0.130	0.130	0.141
50	0.151	0.153	0.167
60	0.172	0.176	0.194
70	0.193	0.198	0.223
80	0.214	0.220	0.259
90	0.236	0.243	0.303
100	0.264	0.272	-
110	0.292	0.302	-
120	0.324	-	-

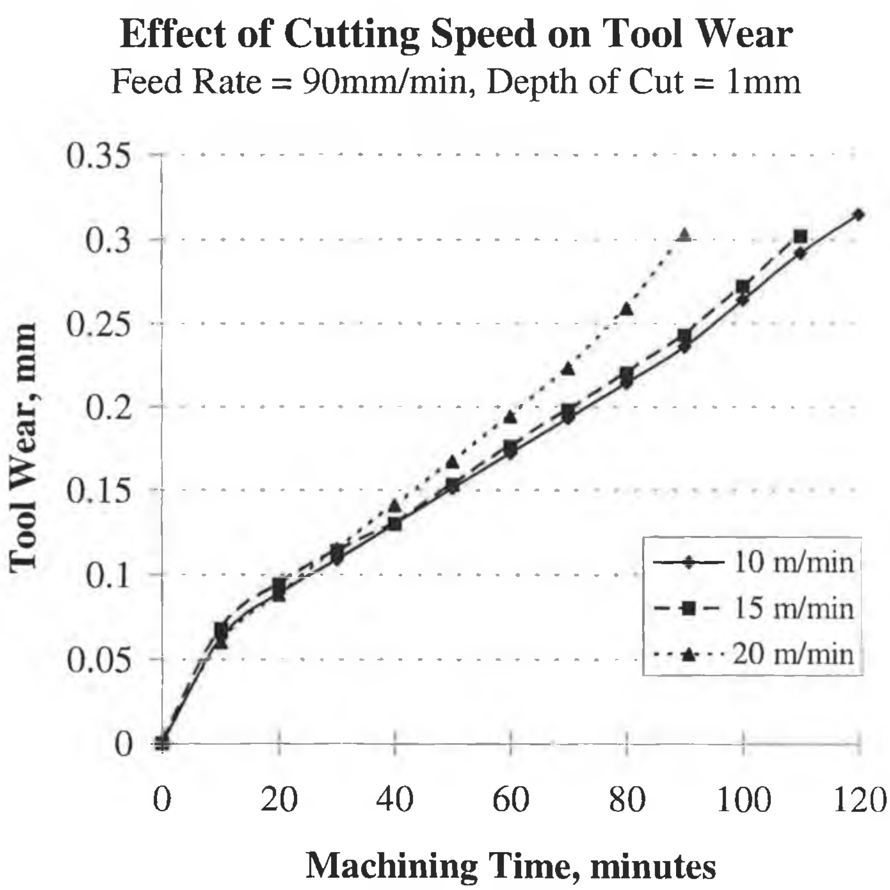

Figure A4, Effect of Cutting Speed on Tool Wear, Uncoated Strassmann H.S.S.

b) Effect of Feed Rate

Machining Time	Tool Wear, mm		
minutes	60 mm/min	90 mm/min	120 mm/min
0	0	0	0
10	0.042	0.068	0.045
20	0.064	0.094	0.068
30	0.082	0.114	0.088
40	0.100	0.130	0.108
50	0.118	0.153	0.128
60	0.136	0.176	0.148
70	0.155	0.198	0.169
80	0.174	0.220	0.188
90	0.194	0.243	0.208
100	0.220	0.272	0.240
110	0.253	0.302	0.308
120	0.305	-	-

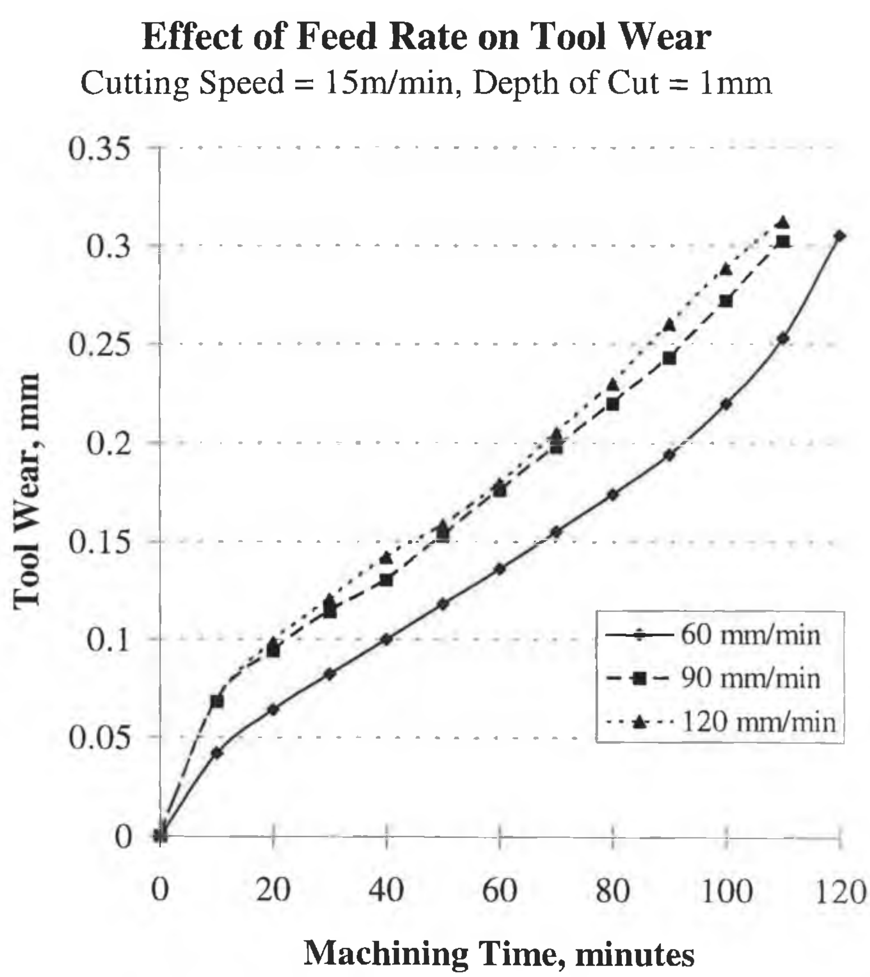

Figure A5, Effect of Feed Rate on Tool Wear, Uncoated Strassmann H.S.S.

c) Effect of Depth of Cut

Machining Time	Tool Wear, mm		
minutes	1 mm	2 mm	4 mm
0	0	0	0
10	0.068	0.043	0.070
20	0.094	0.070	0.111
30	0.114	0.097	0.139
40	0.130	0.126	0.165
50	0.153	0.152	0.191
60	0.176	0.180	0.22
70	0.198	0.207	0.255
80	0.220	0.236	0.303
90	0.243	0.282	-
100	0.272	0.334	-
110	0.302	-	-

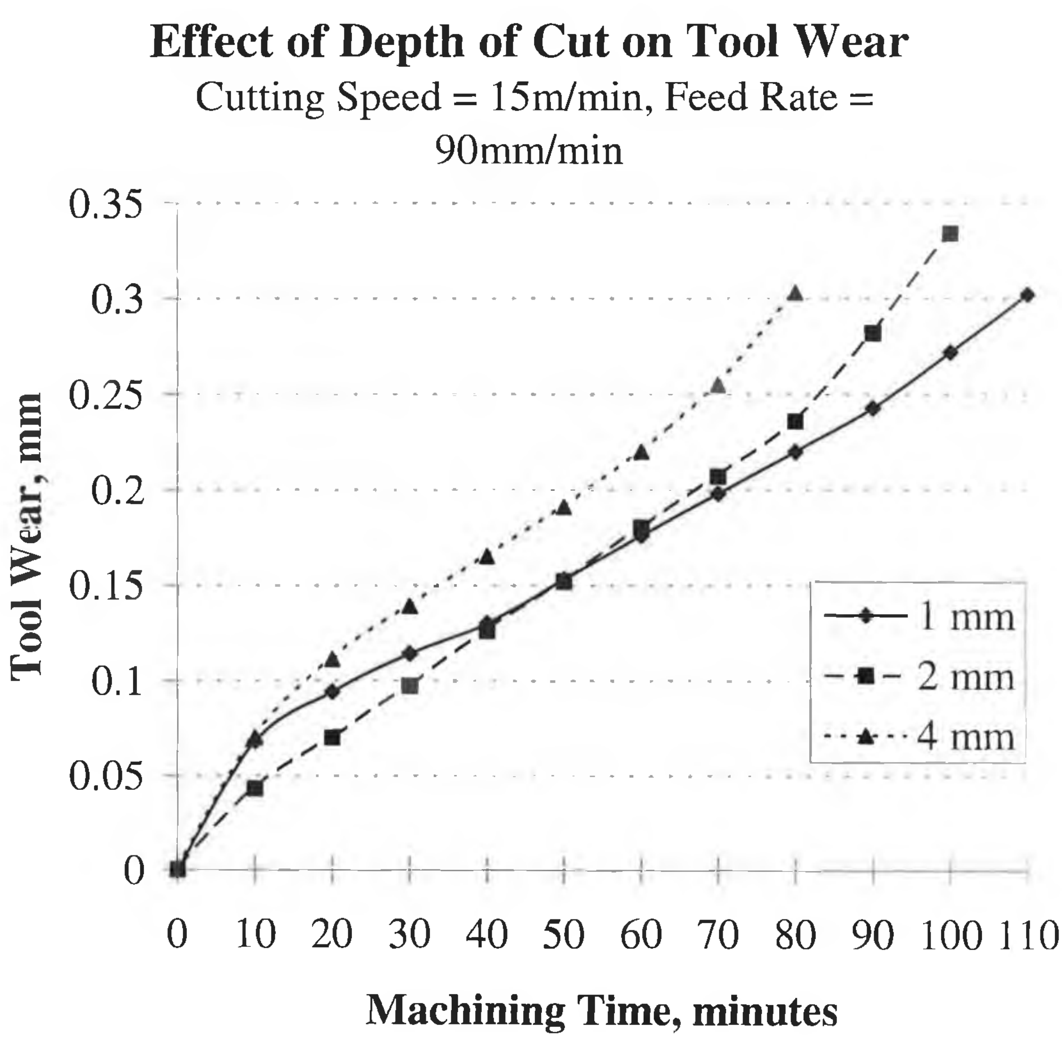

Figure A6, Effect of Depth of Cut on Tool Wear, Uncoated Strassmann H.S.S.

Coated Clarkson High Speed Steel

a) Effect of Cutting Speed

Machining Time	Tool Wear, mm		
minutes	10 m/min	15 m/min	20 m/min
0	0	0	0
10	0.066	0.072	0.062
20	0.091	0.090	0.078
30	0.108		0.088
40	0.123	0.110	0.096
60	0.140	0.151	0.132
80	0.163	0.175	0.176
100	0.194	0.199	0.211
120	0.228	0.240	0.256
140	0.266		0.301
150	-	0.300	-
160	0.306	-	-

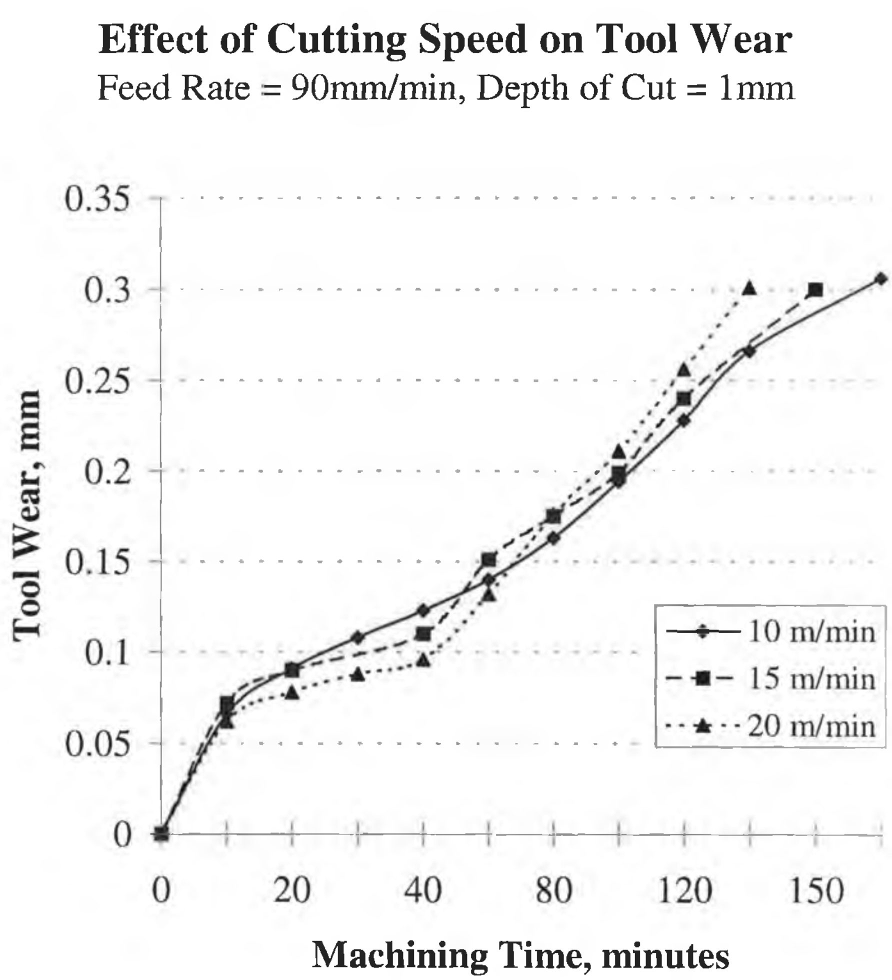

Figure A7, Effect of Cutting Speed on Tool Wear, Coated Clarkson H.S.S.

b) Effect of Feed Rate

Machining Time	Tool Wear, mm		
minutes	60 mm/min	90 mm/min	120 mm/min
0	0	0	0
10	0.046	0.072	0.064
20		0.090	0.101
40	0.093	0.110	0.156
60		0.151	
70	0.124		0.216
80		0.175	
90			0.257
100	0.154	0.199	
110			0.302
120		0.240	-
130	0.202		-
150		0.300	-
160	0.255	-	-
180	0.301	-	-

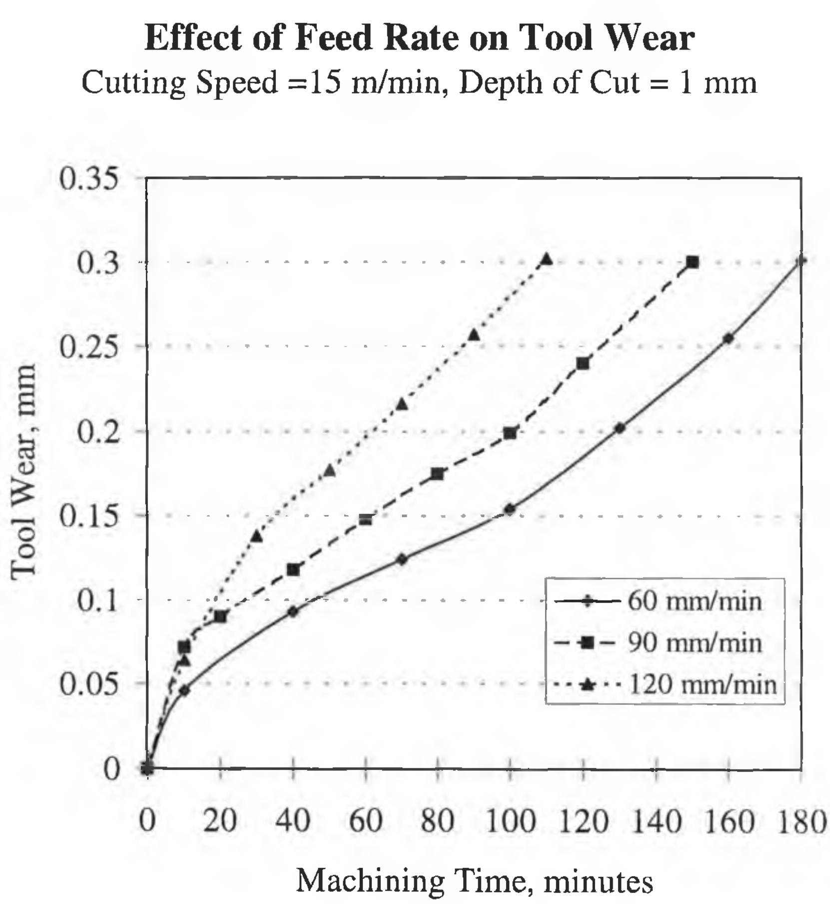

Figure A8, Effect of Feed Rate on Tool Wear, Coated Clarkson H.S.S.

c) Effect of Depth of Cut

Machining Time	Tool Wear, mm		
minutes	1 mm	2 mm	4 mm
0	0	0	0
10	0.072		0.048
20	0.090	0.082	
40		0.109	0.104
60	0.110	0.131	
80	0.151		0.140
100	0.175	0.163	0.155
120	0.199	0.187	0.176
140	0.240		
150	0.300		0.207
160	-	0.233	
180	-	0.263	0.234
200	-	0.300	0.257
220	-	-	0.280
240			0.308

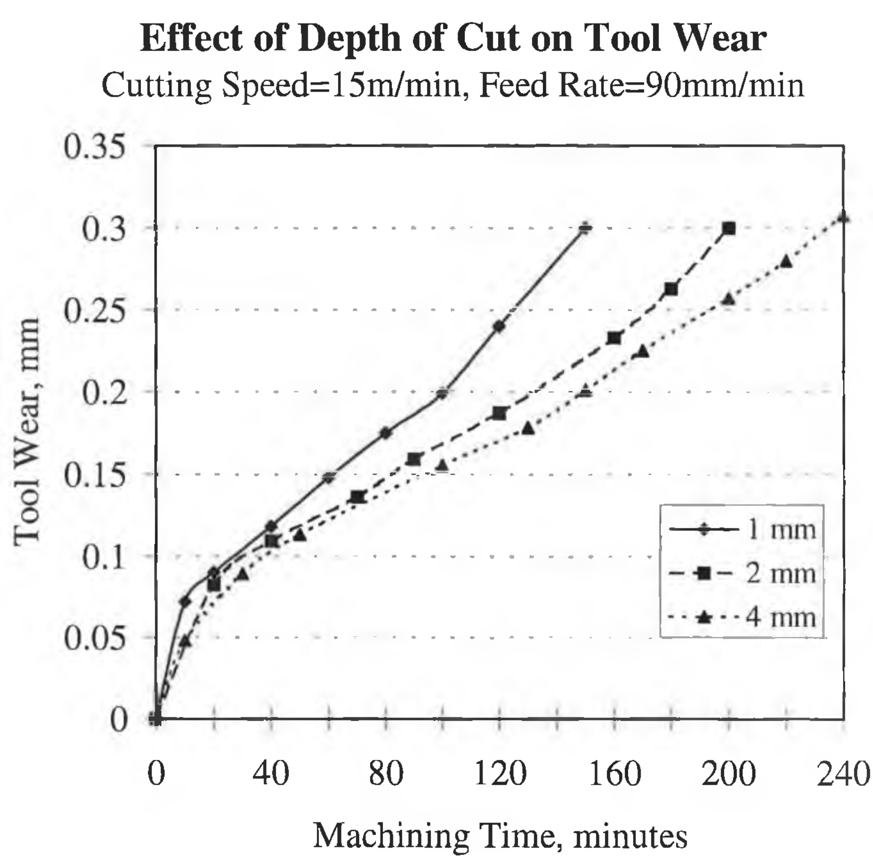

Figure A9, Effect of Depth of Cut on Tool Wear, Coated Clarkson H.S.S.

Coated Strassmann High Speed Steel

a) Effect of Cutting Speed

Machining Time	Tool Wear, mm		
minutes	10 m/min	15 m/min	20 m/min
0	0	0	0
10	0.025	0.032	0.028
20	0.042	0.052	0.043
30	0.058	0.065	0.067
40	0.065	0.073	0.085
60	0.089	0.105	0.118
80	0.118	0.130	0.148
100	0.146	0.155	0.185
120	0.176	0.189	0.240
140	0.206	0.231	0.288
160	0.234	0.288	0.332
180	0.269	0.309	-
190	0.303	-	-

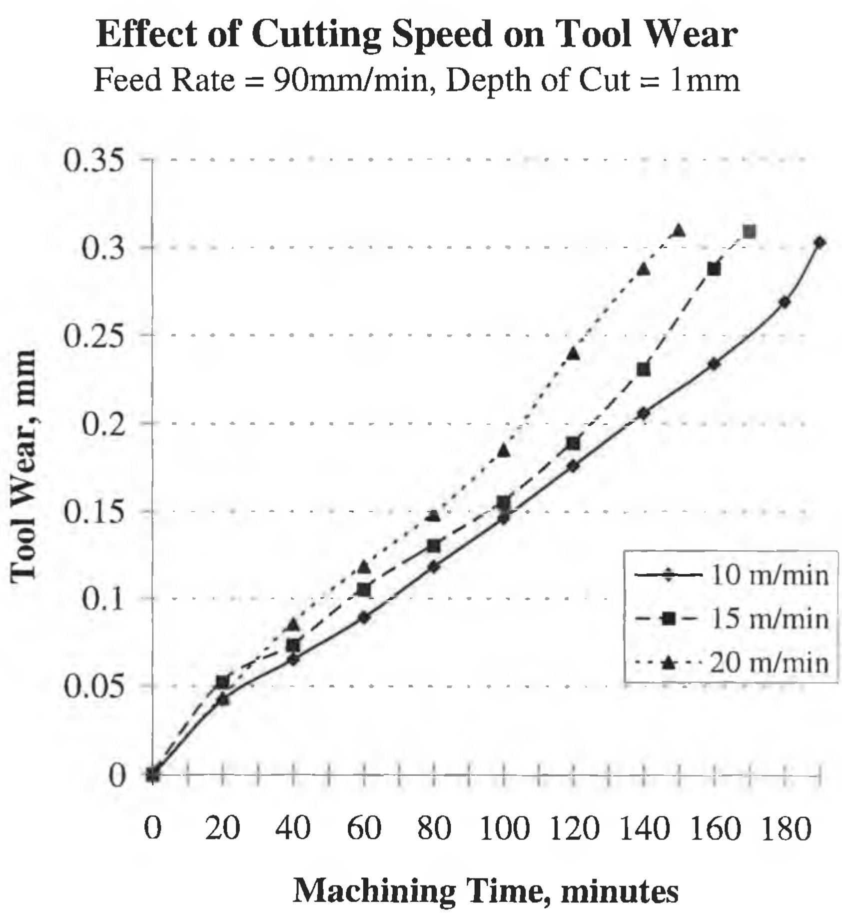

Figure A10, Effect of Cutting Speed on Tool Wear, Coated Strassmann H.S.S.

b) Effect of Feed Rate

Machining Time	Tool Wear, mm		
minutes	60 mm/min	90 mm/min	120 mm/min
0	0	0	0
10	0.023	0.031	0.043
20	0.042	0.052	0.077
40	0.070	0.073	0.111
60	0.098	0.105	0.138
80	0.125	0.130	0.165
100	0.153	0.155	0.192
120	0.181	0.189	0.222
140	0.208	0.231	0.257
160	0.234	0.288	0.302
180	0.269	0.319	-
200	0.310	-	-

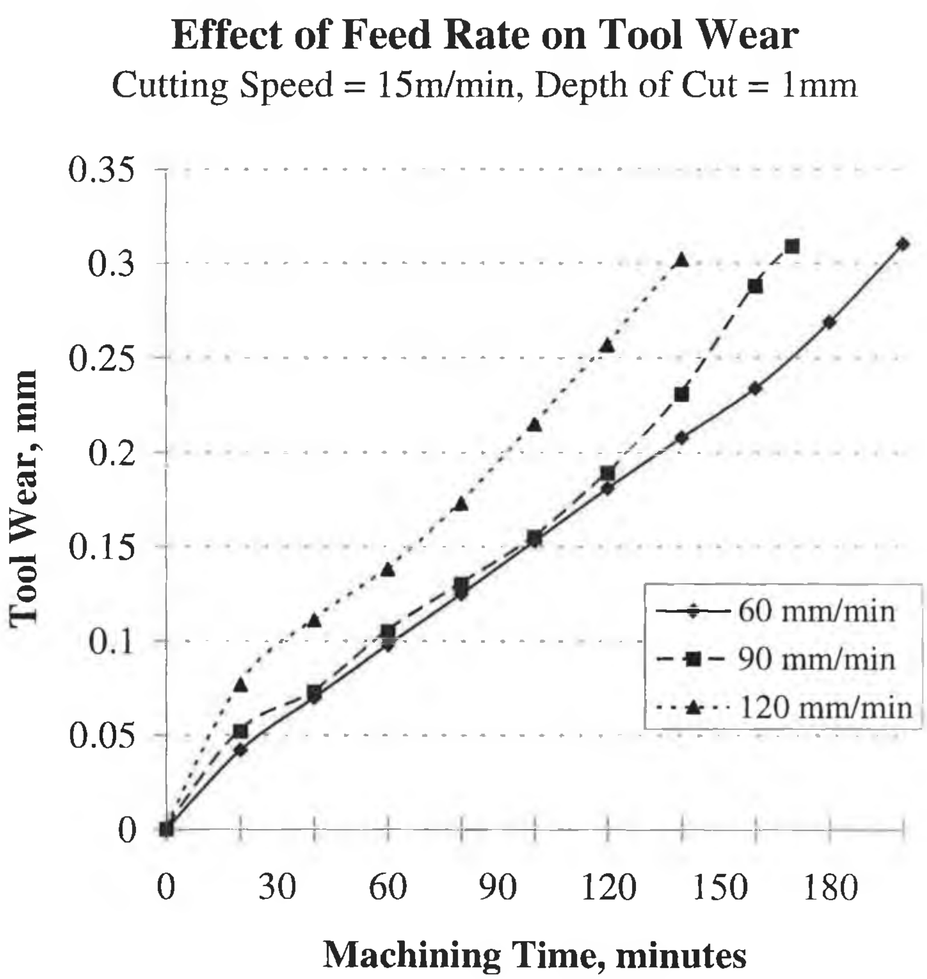

Figure A11, Effect of Feed Rate on Tool Wear, Coated Strassmann H.S.S.

c) Effect of Depth of Cut

Machining Time	Tool Wear, mm		
minutes	1 mm	2 mm	4 mm
0	0	0	0
10	0.031	0.027	0.025
20	0.052	0.048	0.048
40	0.073	0.067	0.064
60	0.105	0.081	0.076
80	0.130	0.096	0.089
120	0.189	0.124	0.115
160	0.288	0.155	0.140
180	0.309	0.205	0.166
200	-	0.261	0.192
240	-	0.300	0.226
280	-	-	0.258
300	-	-	0.281
320	-	-	0.310

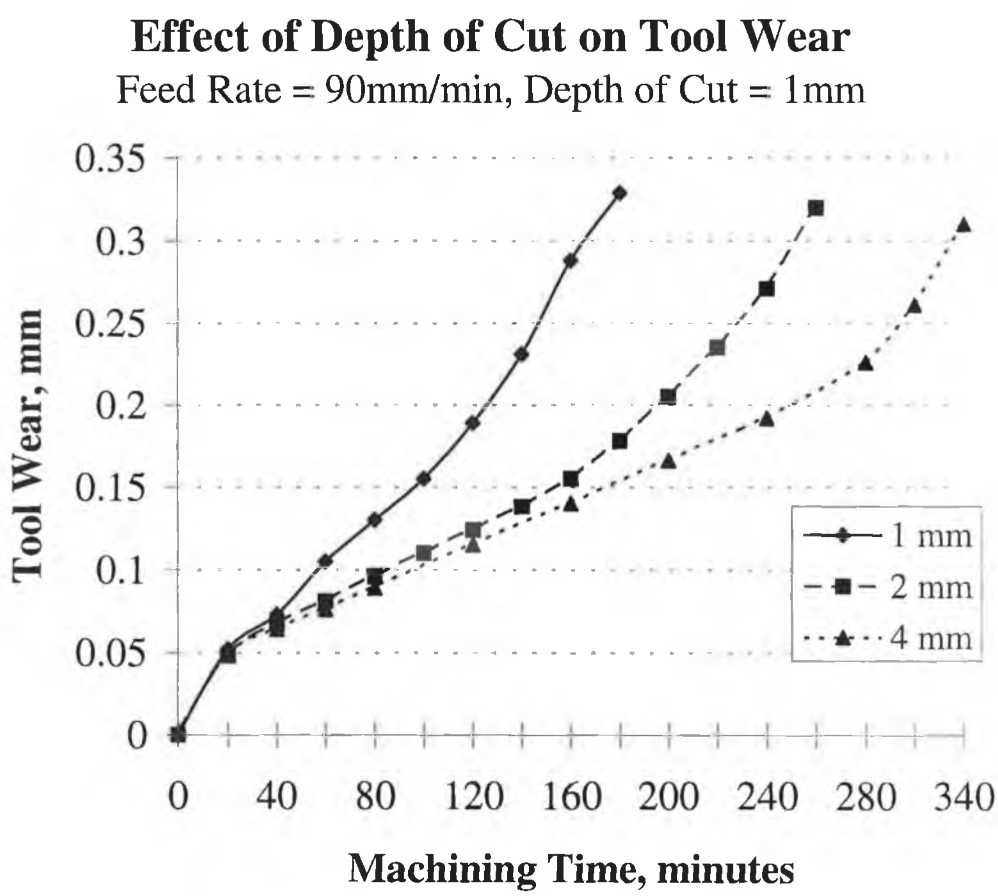

Figure A12, Effect of Depth of Cut on Tool Wear, Coated Strassmann H.S.S.

Coated Kestag High Speed Steel

a) Effect of Cutting Speed

Machining Time	Tool Wear, mm		
minutes	10 m/min	15 m/min	20 m/min
0	0	0	0
10	0.057	0.041	0.040
20	0.086	0.077	0.069
30	0.103	0.104	0.094
40	0.118	0.126	0.118
50	0.133	0.148	0.145
60	0.145	0.166	0.170
70	0.161	0.182	0.195
80	0.175	0.200	0.221
90	0.190	0.216	0.246
100	0.204	0.234	0.273
110	0.220	0.251	0.304
120	0.237	0.275	-
130	0.259	0.308	-
140	0.284	-	-
150	0.314	-	-

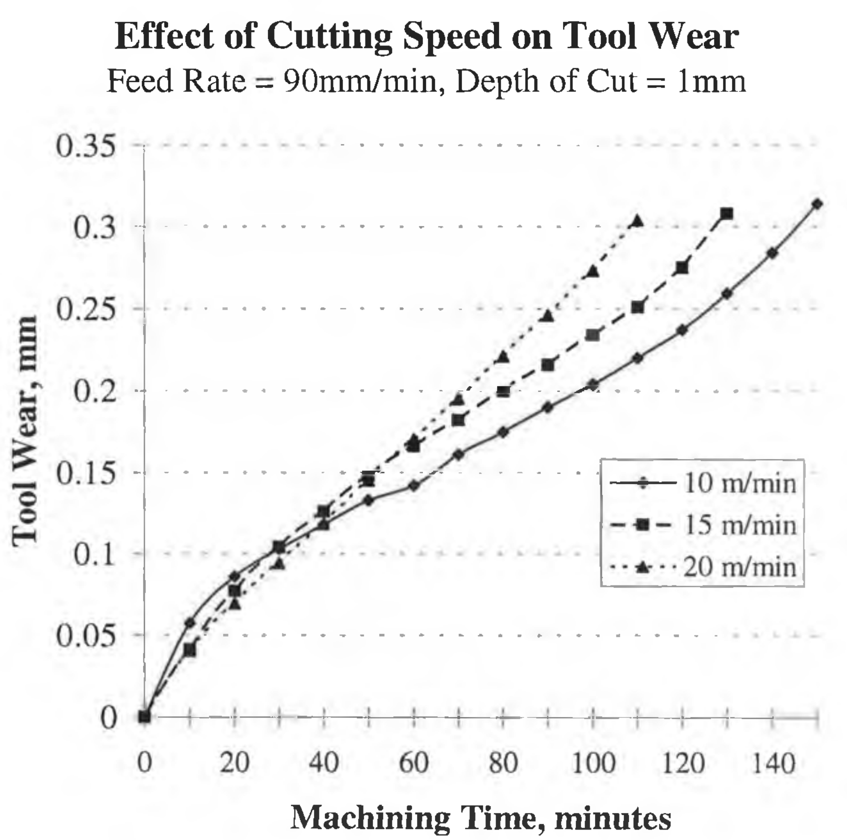

Figure A13, Effect of Cutting Speed on Tool Wear, Coated Kestag H.S.S.

b) Effect of Feed Rate

Machining Time	Tool Wear, mm		
minutes	60 mm/min	90 mm/min	120 mm/min
0	0	0	0
10	0.058	0.041	0.067
20	0.089	0.077	0.104
30	0.104	0.104	0.129
40	0.122	0.126	0.157
50	0.136	0.148	0.182
60	0.151	0.166	0.208
70	0.165	0.182	0.234
80	0.180	0.200	0.260
90	0.194	0.216	0.286
100	0.208	0.234	0.319
110	0.223	0.251	-
120	0.237	0.275	-
130	0.251	0.308	-
140	0.265	-	-
150	0.285	-	-
160	0.320	-	-

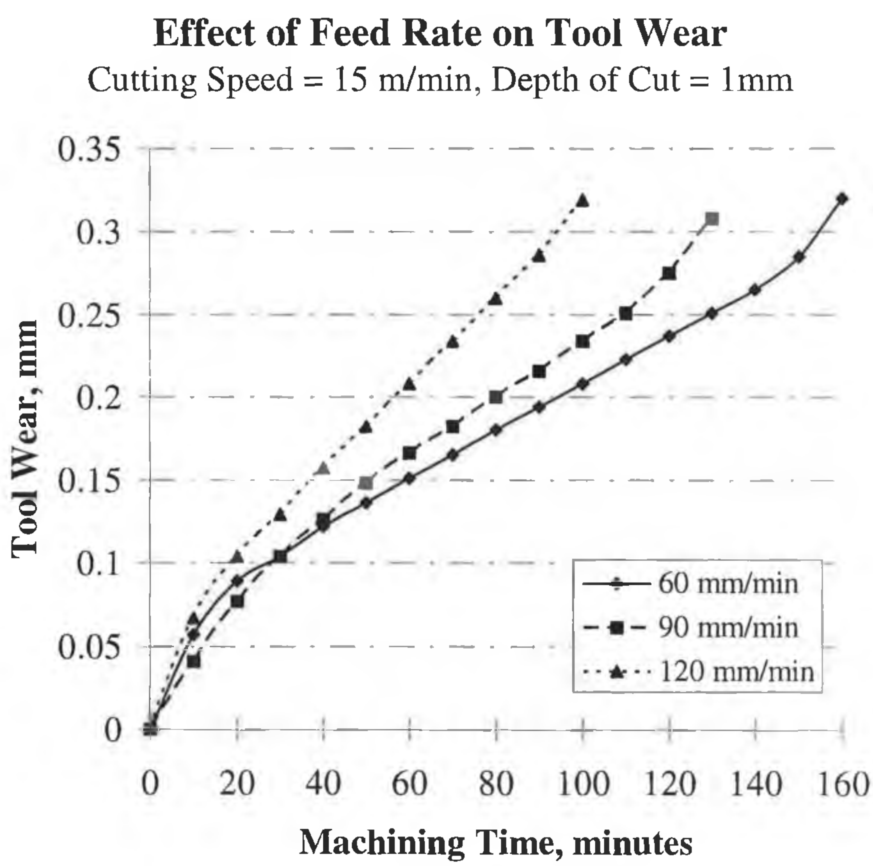

Figure A14, Effect of Feed Rate on Tool Wear, Coated Kestag H.S.S.

c) Effect of Depth of Cut

Machining Time	Tool Wear, mm		
minutes	1 mm	2 mm	4 mm
0	0	0	0
20	0.077	0.055	0.068
40	0.126	0.078	0.090
60	0.166	0.100	0.113
80	0.200	0.123	0.135
100	0.234	0.145	0.159
120	0.275	0.164	0.179
130	0.308		
140	-	0.191	0.202
160	-	0.227	0.230
180	-	0.286	0.264
190	-	0.317	
200	-	-	0.315

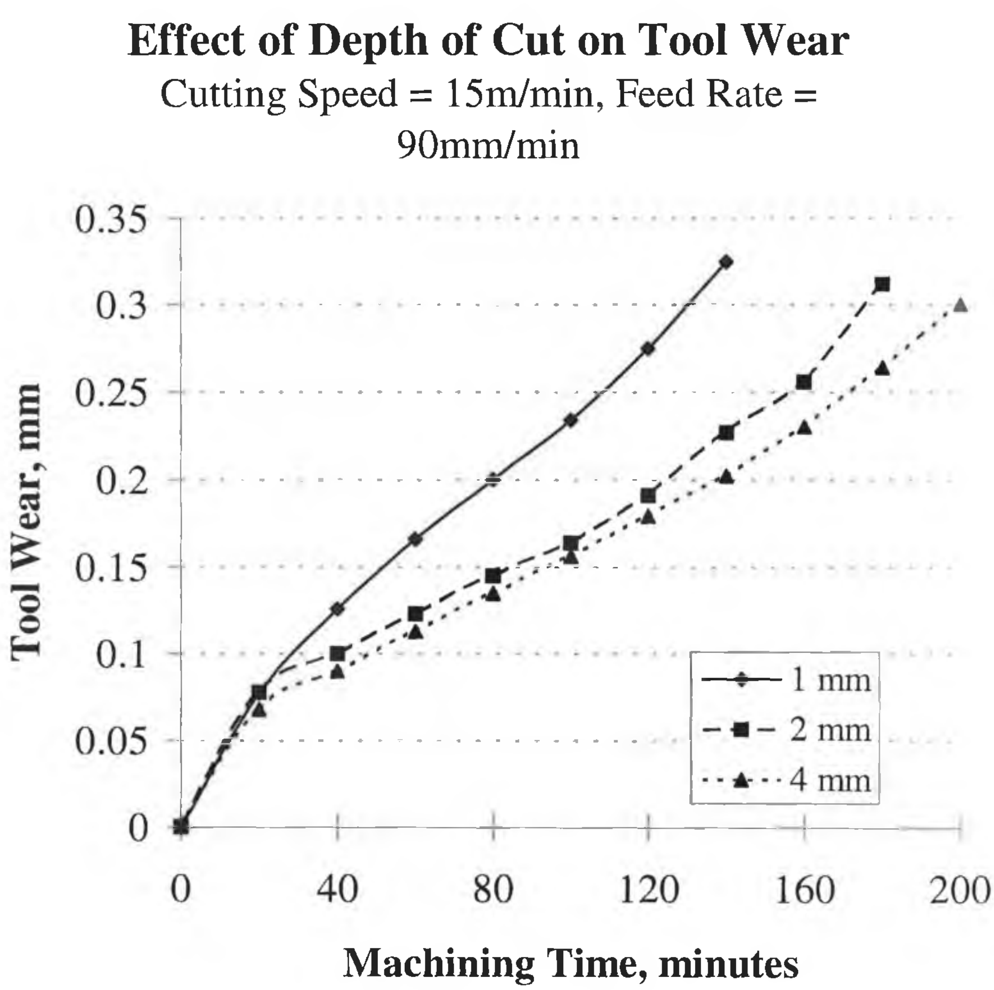

Figure A15, Effect of Depth of Cut on Tool Wear, Coated Kestag H.S.S.

Uncoated Iscar Cemented Carbide

a) Effect of Cutting Speed

Machining Time	Tool Wear, mm		
minutes	75 m/min	85 m/min	95 m/min
0	0	0	0
4	0.099	0.108	0.131
8	0.157	0.169	0.196
12	0.200	0.214	0.258
16	0.244	0.265	0.319
20	0.289	0.321	-
24	0.326	-	-

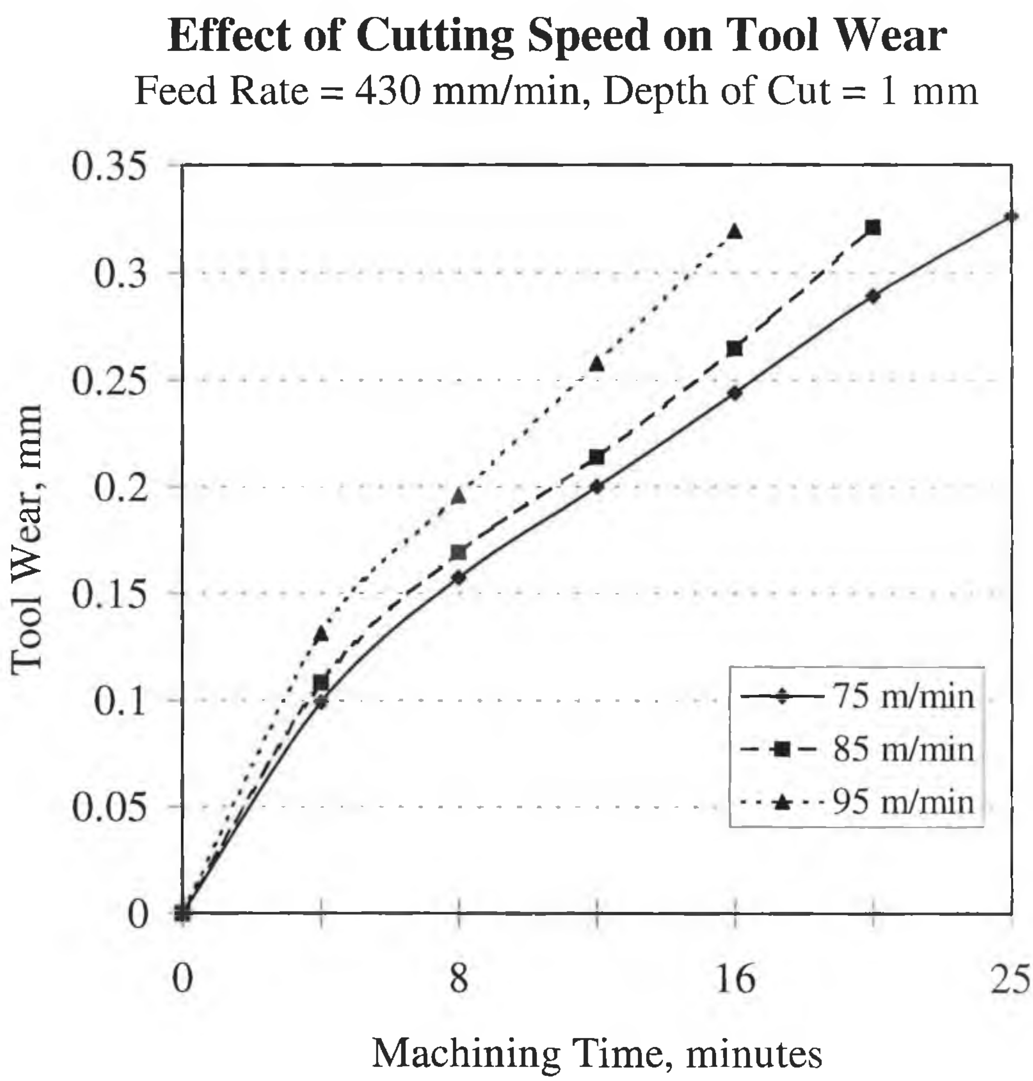

Figure A16, Effect of Cutting Speed on Tool Wear, Uncoated Iscar C. Carbide

b) Effect of Feed Rate

Machining Time	Tool Wear, mm		
minutes	60 mm/min	90 mm/min	120 mm/min
0	0	0	0
4	0.095	0.108	0.131
8	0.141	0.169	0.212
12	0.187	0.214	0.298
16	0.240	0.265	
20	0.299	0.321	

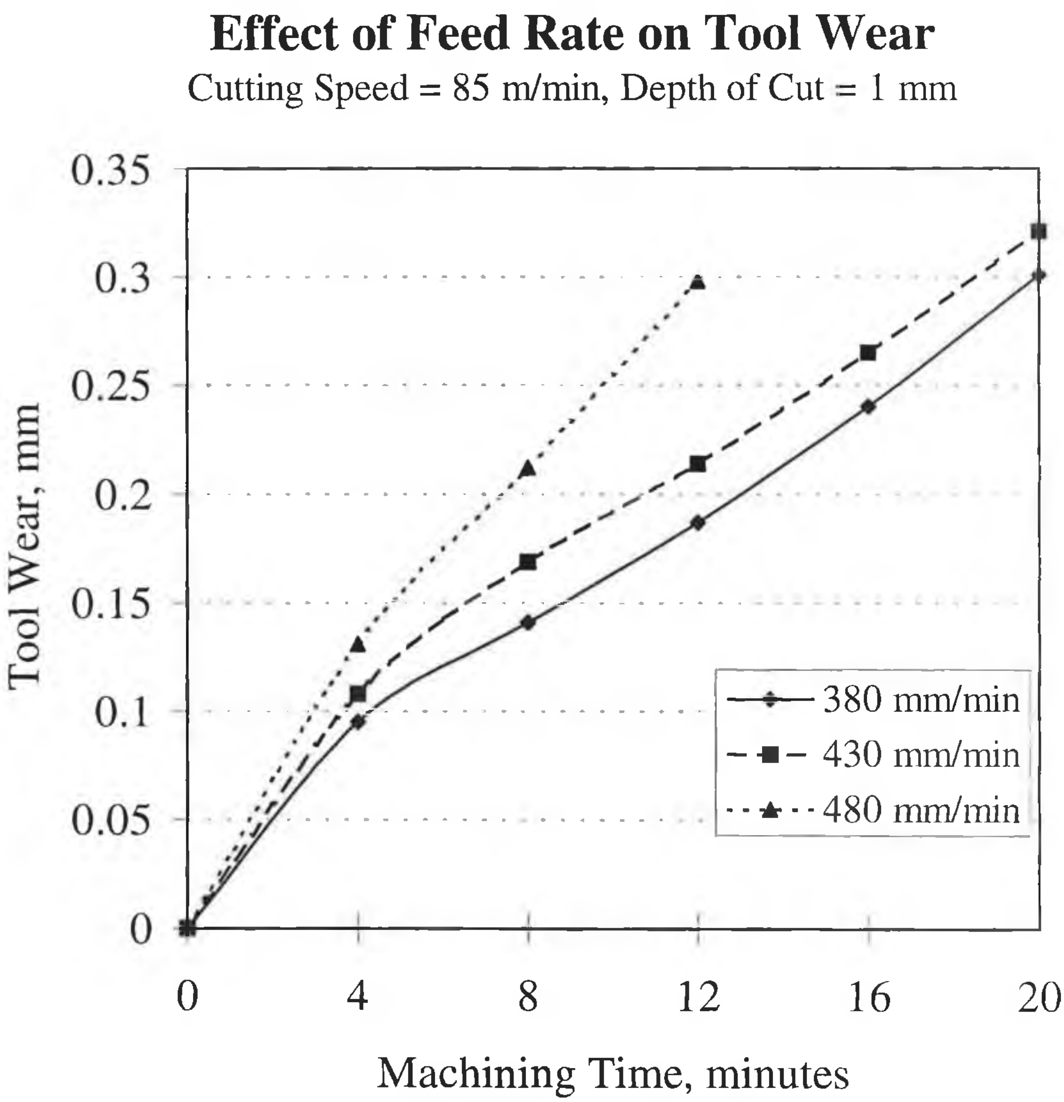

Figure A17, Effect of Feed Rate on Tool Wear, Uncoated Iscar C. Carbide

c) Effect of Depth of Cut

Machining Time	Tool Wear, mm		
minutes	1 mm	2 mm	4 mm
0	0	0	0
4	0.108	0.136	0.145
8	0.169	0.194	0.224
12	0.214	0.254	0.316
16	0.265	0.323	-
20	0.321	-	-

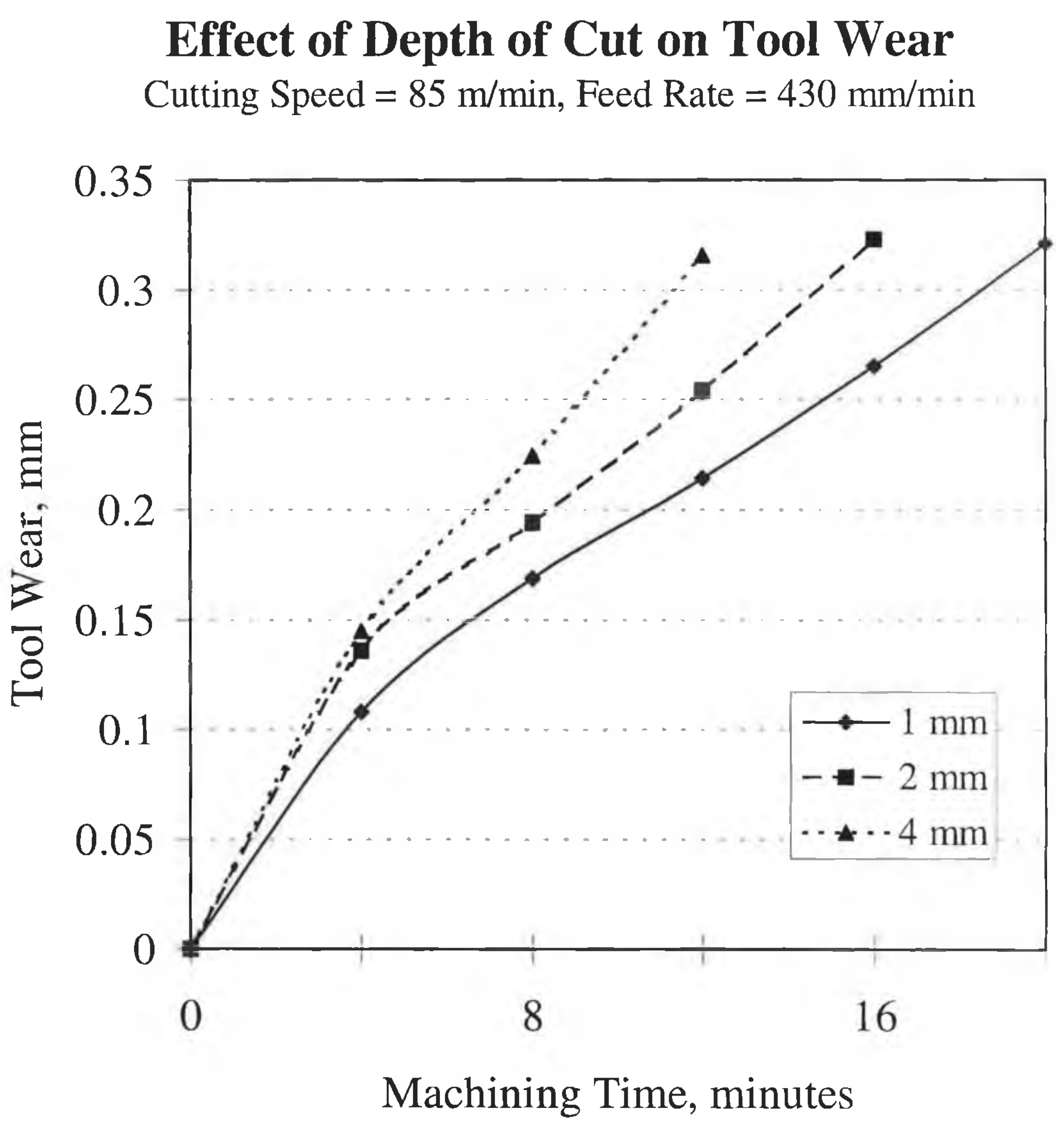

Figure A18, Effect of Depth of Cut on Tool Wear, Uncoated Iscar C. Carbide

Uncoated Sandvik Cemented Carbide

a) Effect of Cutting Speed

Machining Time	Tool Wear, mm		
minutes	55 m/min	65 m/min	75 m/min
0	0	0	0
5	0.088	0.113	0.135
10	0.150	0.194	0.195
15	0.182	0.222	0.240
20	0.230	0.253	0.300
25	0.252	0.282	-
30	0.275	0.318	-
35	0.310	-	-

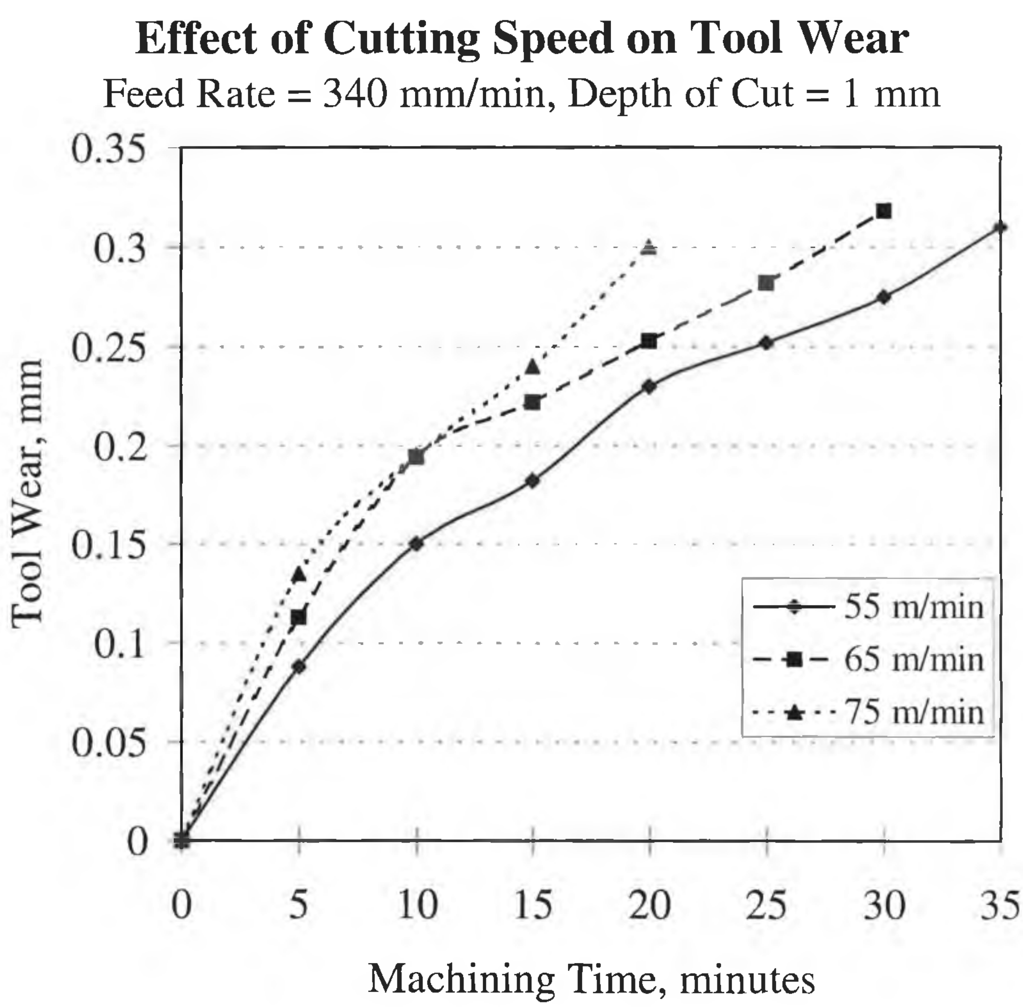

Figure A19, Effect of Cutting Speed on Tool Wear, Uncoated Sandvik C. Carbide

b) Effect of Feed Rate

Machining Time	Tool Wear, mm		
minutes	310 mm/min	340 mm/min	370 mm/min
0	0	0	0
5	0.108	0.113	0.124
10	0.150	0.194	0.170
15	0.185	0.222	0.228
20	0.205	0.253	0.270
25	0.230	0.282	0.325
30	0.260	0.318	-
35	0.293	-	-

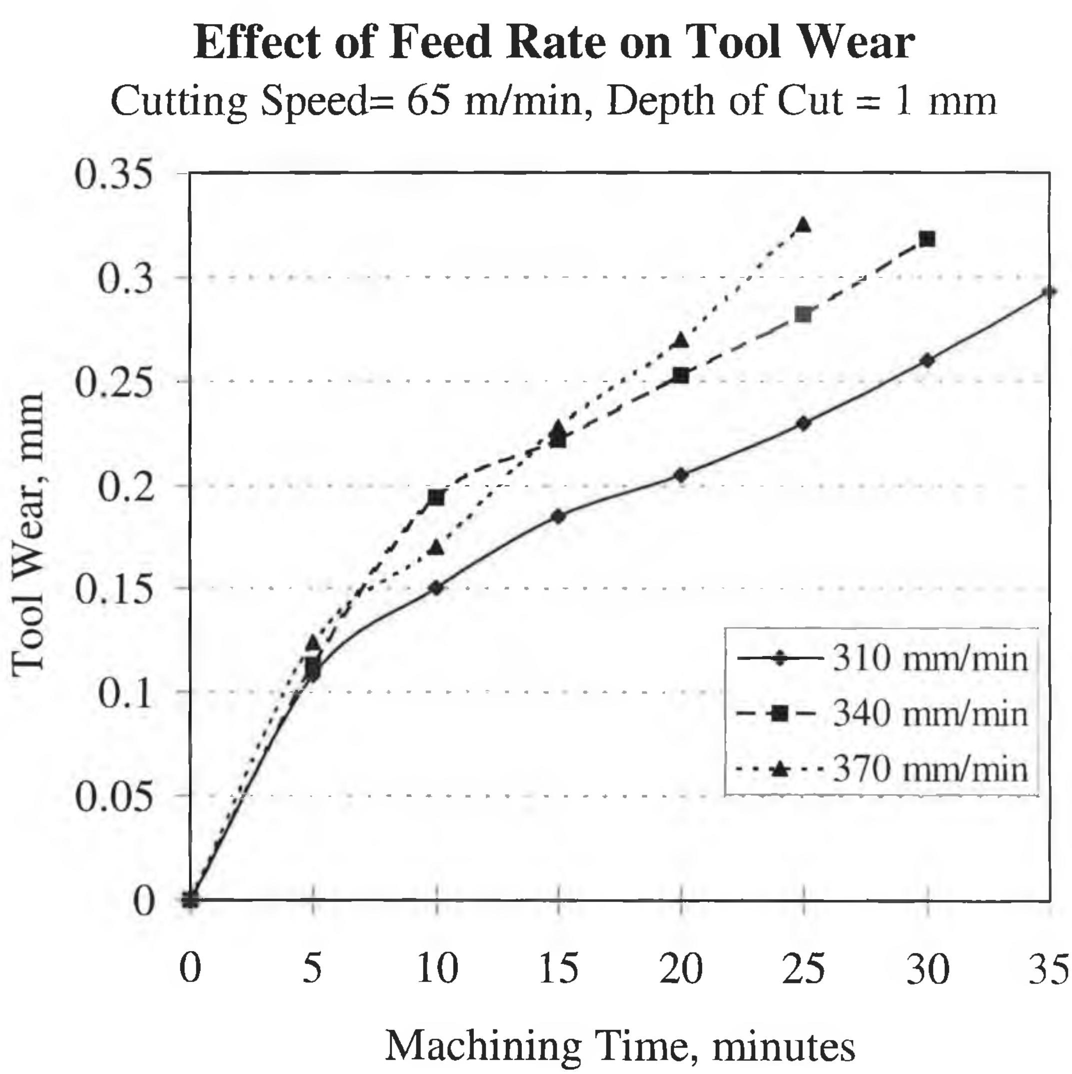

Figure A20, Effect of Feed Rate on Tool Wear, Uncoated Sandvik C. Carbide

c) Effect of Depth of Cut

Machining Time	Tool Wear, mm		
minutes	1 mm	2 mm	4 mm
0	0	0	0
5	0.113	0.117	0.145
10	0.194	0.197	0.224
15	0.222	0.241	0.295
20	0.253	0.281	-
25	0.282	0.325	-
30	0.318	-	-

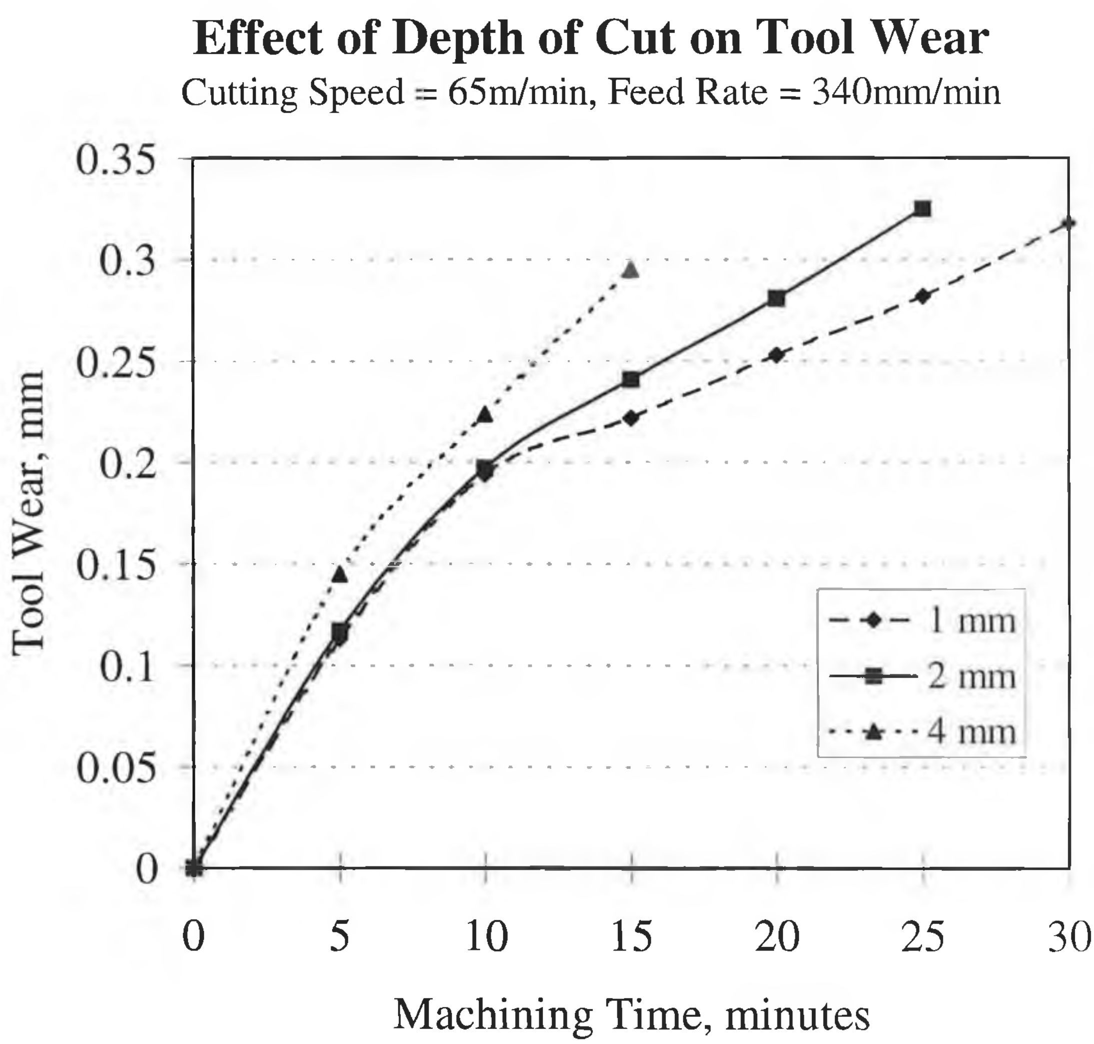

Figure A21, Effect of Depth of Cut on Tool Wear, Uncoated Sandvik C. Carbide

Coated Iscar Cemented Carbide

a) Effect of Cutting Speed

Machining Time	Tool Wear, mm		
minutes	125 m/min	140 m/min	155 m/min
0	0	0	0
5	0.069	0.081	0.101
10	0.108	0.123	0.145
20	0.146	0.158	0.198
30	0.187	0.206	0.254
35			0.278
40	0.226	0.245	0.301
45	0.254	0.268	-
50	0.280	0.315	-
55	0.305	-	-

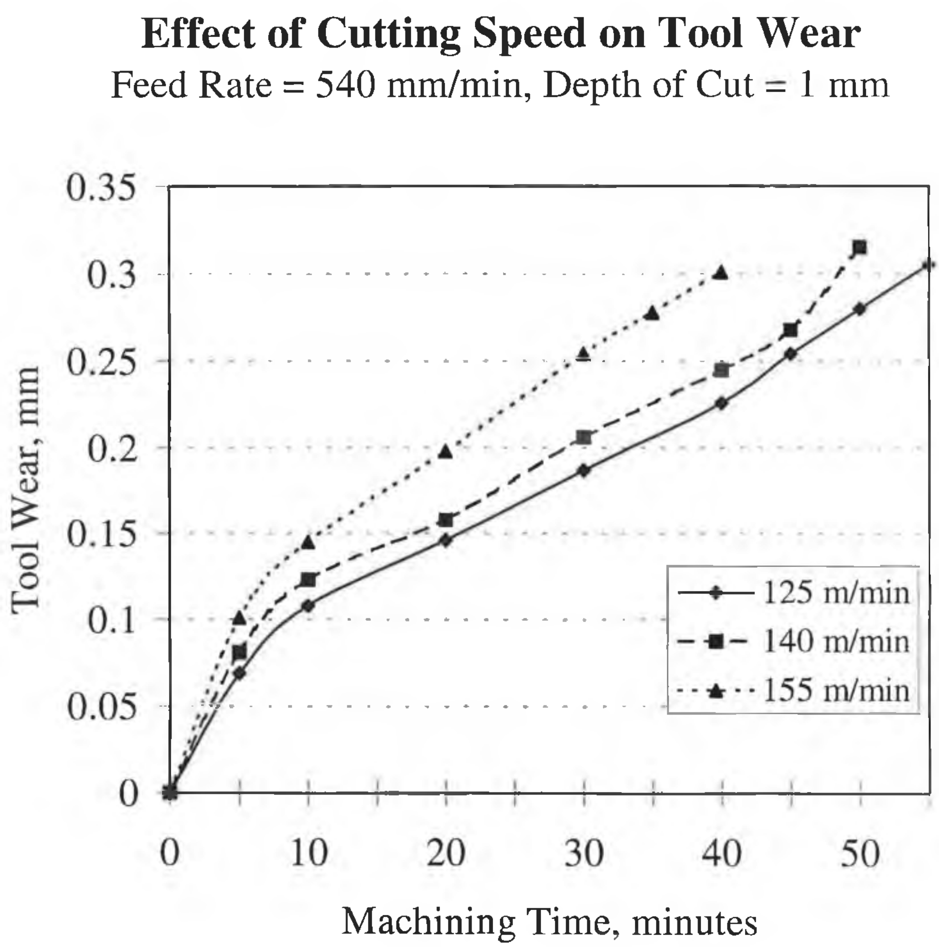

Figure A22, Effect of Cutting Speed on Tool Wear, Coated Iscar C. Carbide

b) Effect of Feed Rate

Machining Time	Tool Wear, mm		
minutes	500 mm/min	540 mm/min	570 mm/min
0	0	0	0
5	0.075	0.081	0.096
10	0.110	0.123	0.147
20	0.138	0.158	0.202
30	0.179	0.206	0.256
35			0.286
40	0.216	0.245	0.309
45	0.248	0.268	-
50	0.283	0.315	-
55	0.322	-	-

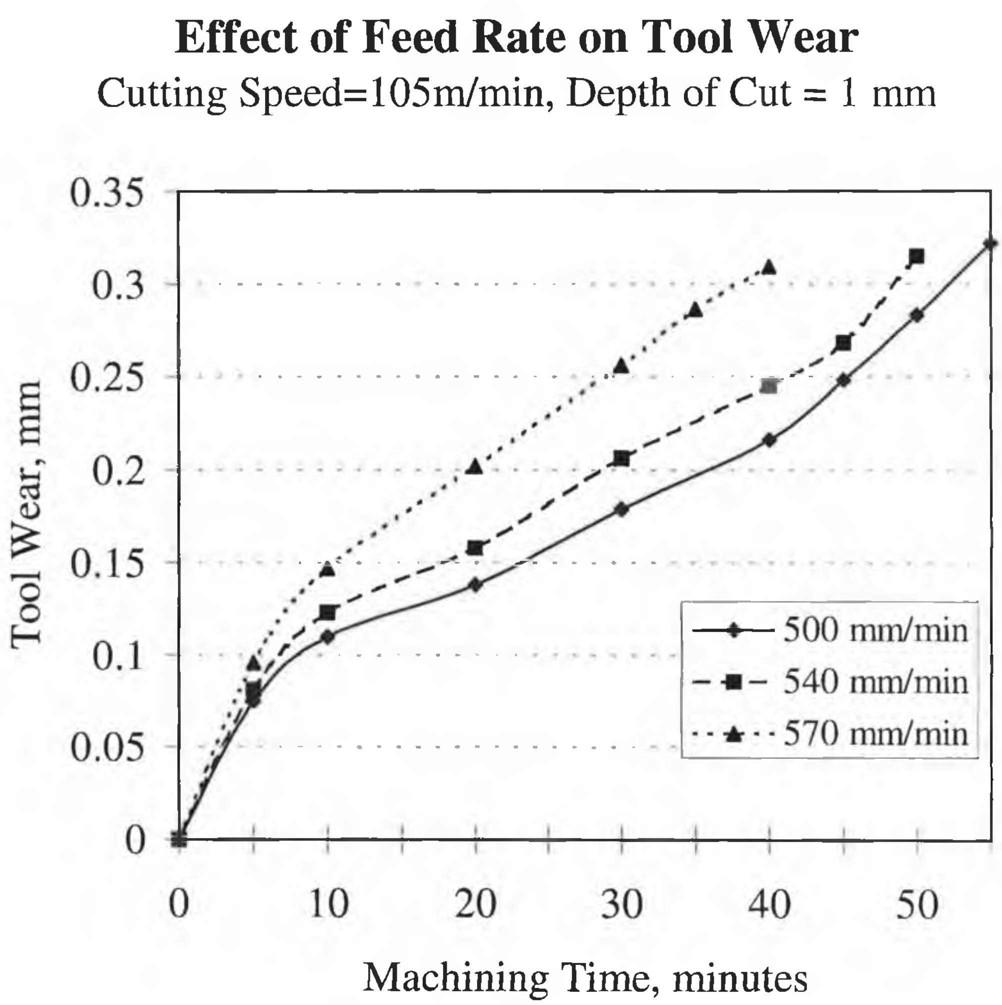

Figure A23, Effect of Feed Rate on Tool Wear, Coated Iscar C. Carbide

c) Effect of Depth of Cut

Machining Time	Tool Wear, mm		
minutes	1 mm	2 mm	4 mm
0	0	0	0
5	0.081	0.59	0.061
10	0.123	0.098	0.086
20	0.158	0.135	0.119
30	0.206	0.174	0.151
40	0.245	0.219	0.194
45	0.268		
50	0.315	0.267	0.236
55	-	0.301	0.278
60	-	-	0.311

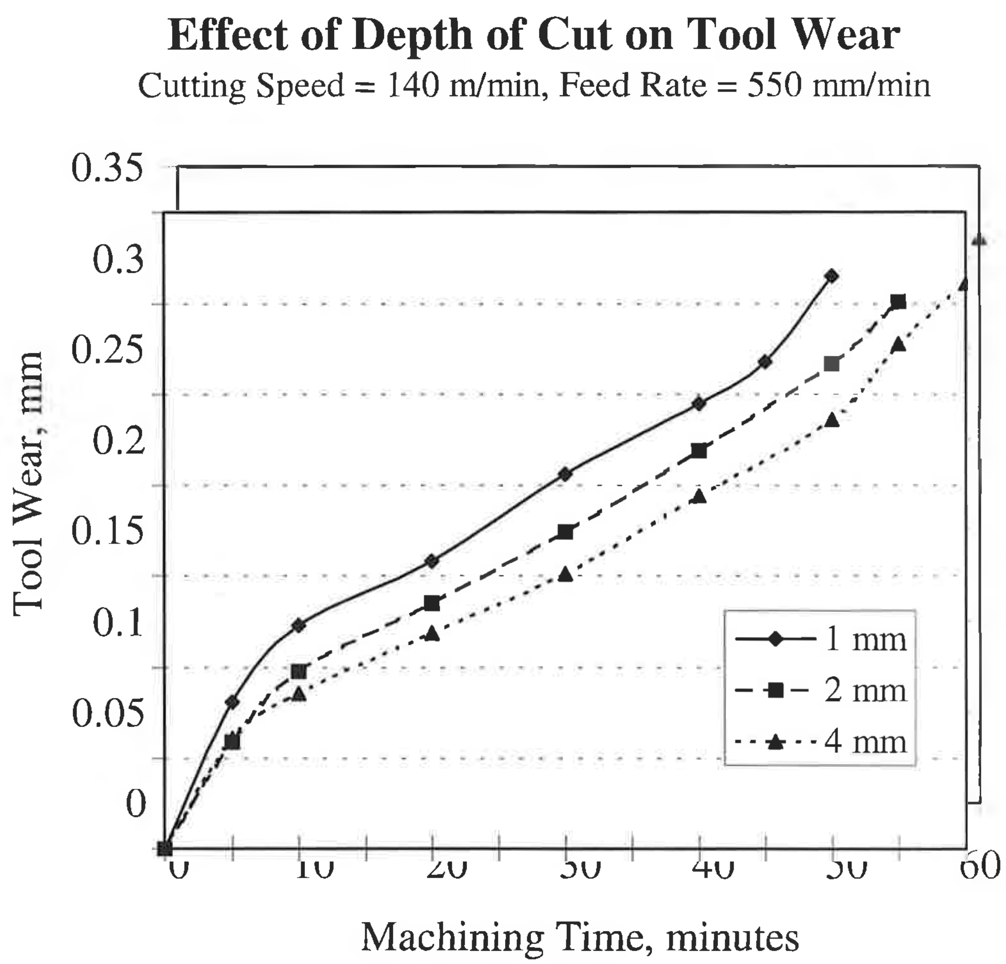

Figure A24, Effect of Depth of Cut on Tool Wear, Coated Iscar C. Carbide

Coated Sandvik Cemented Carbide

a) Effect of Cutting Speed

Machining Time	Tool Wear, mm		
minutes	98 m/min	105 m/min	112 m/min
0	0	0	0
5	0.030	0.047	0.054
10	0.062	0.077	0.077
20	0.110	0.137	0.147
30	0.148	0.175	0.202
40	0.185	0.216	0.252
45			0.304
50	0.235	0.271	-
55		0.301	-
60	0.262	-	-
65	0.291	-	-

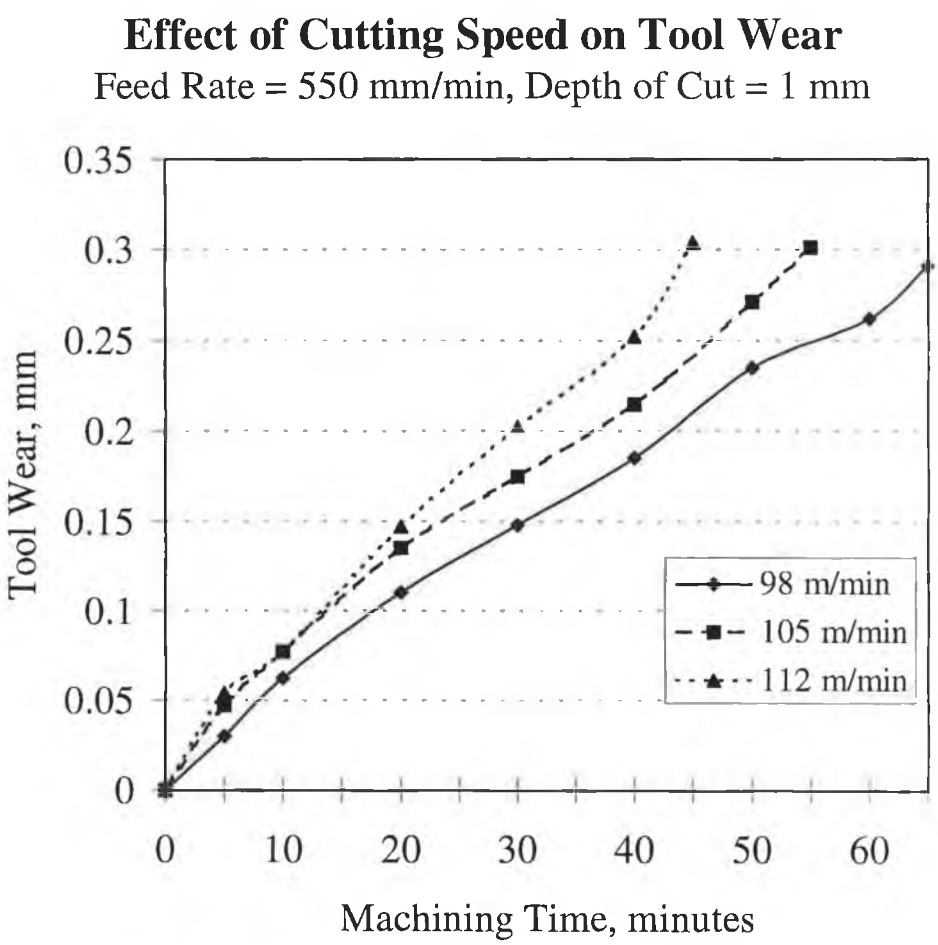

Figure A25, Effect of Cutting Speed on Tool Wear, Coated Sandvik C. Carbide

b) Effect of Feed Rate

Machining Time	Tool Wear, mm		
minutes	500 mm/min	540 mm/min	570 mm/min
0	0	0	0
5	0.044	0.047	0.054
10	0.085	0.077	0.077
20	0.131	0.137	0.147
30	0.165	0.175	0.202
40	0.202	0.216	0.252
45			0.304
50	0.239	0.271	-
55		0.301	-
60	0.290	-	-
65	0.320	-	-

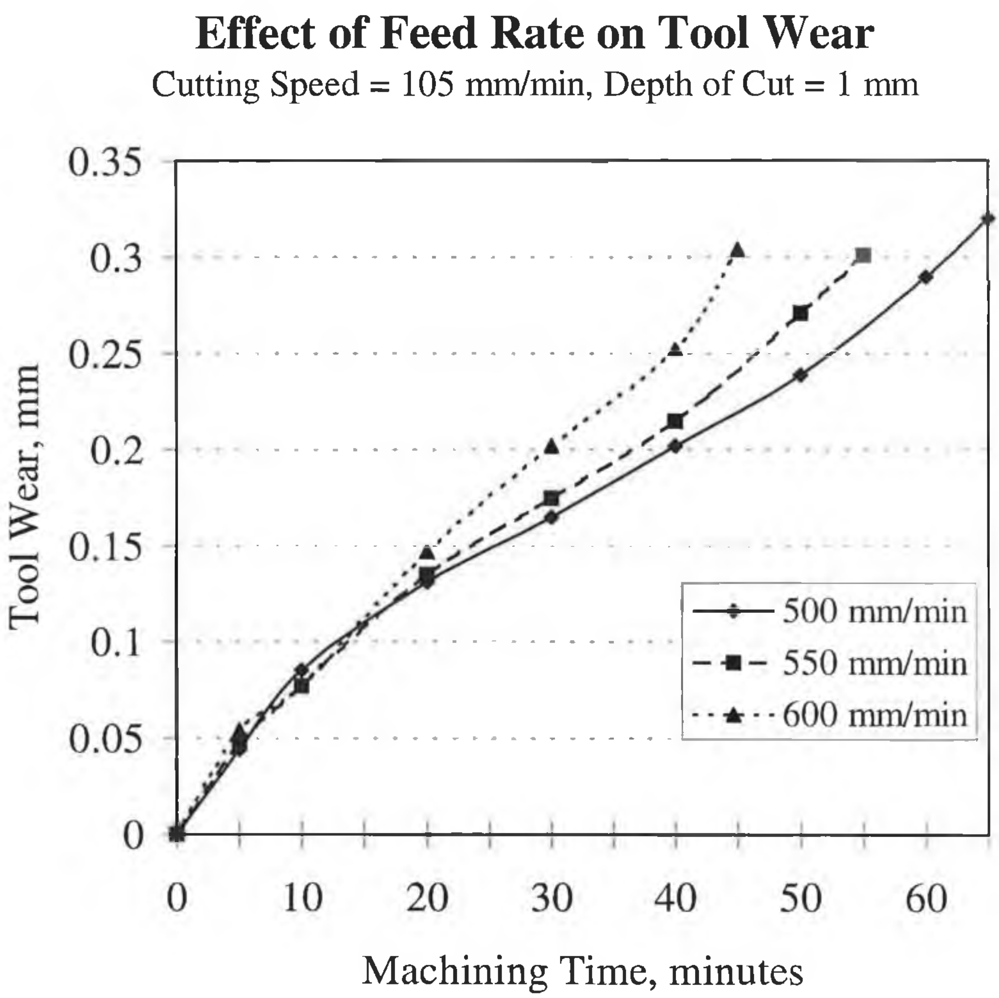

Figure A26, Effect of Feed Rate on Tool Wear, Coated Sandvik C. Carbide

c) Effect of Depth of Cut

Machining Time	Tool Wear, mm		
minutes	1 mm	2 mm	4 mm
0	0	0	0
5	0.047	0.024	0.043
10	0.077		
15		0.091	0.075
20	0.137		
25		0.133	0.119
30	0.175		
35		0.175	0.158
40	0.216		
45		0.211	0.196
50	0.271		
55	0.301	0.255	0.236
60	-		
65	-	0.308	0.270
70	-	-	0.306

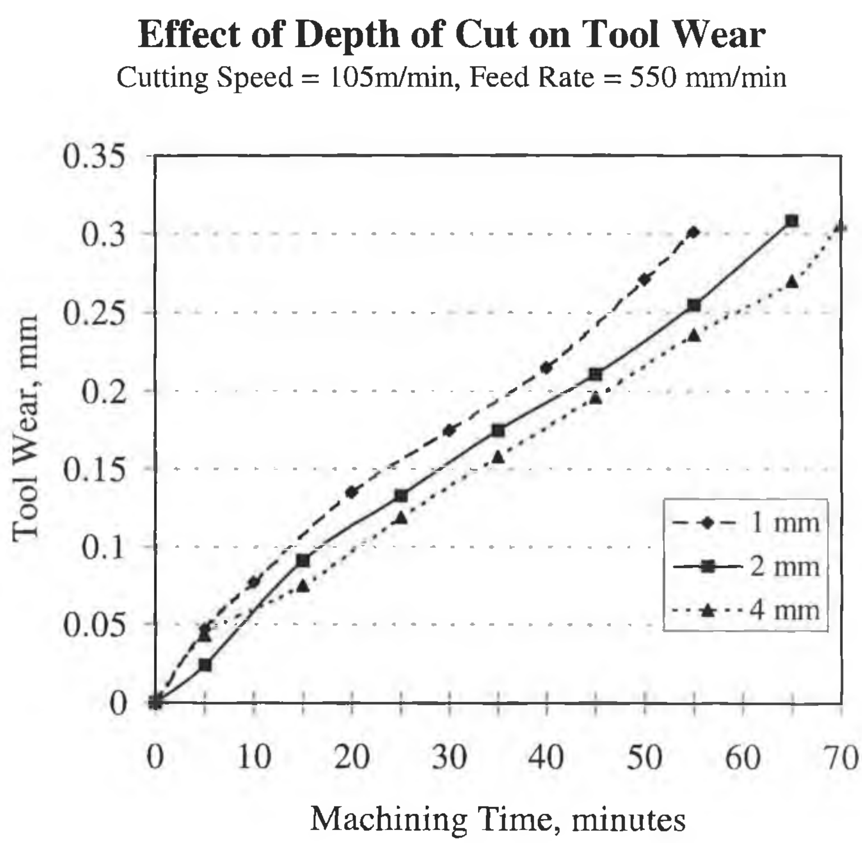

Figure A27, Effect of Depth of Cut on Tool Wear, Coated Sandvik C. Carbide

APPENDIX B

ANOVA TABLES

a) Tool Life model for H.S.S. end mills

Source	SS	DF	MS	F_{cal}	F_{tab}
Zero order term	324.204	1	324.204		
First-order term	0.37366	3	0.12455		
Lack of Fit	0.05831	1	0.05831	11.38	19.30
Pure Error	0.00512	1	0.00512		

b) Tool Life model for Cemented Carbide end mills

Source	SS	DF	MS	F_{cal}	F_{tab}
Zero order term	207.928	1	207.928		
First-order term	0.07685	3	0.025617		
Lack of Fit	0.004862	1	0.004862	7.609	19.30
Pure Error	0.000639	1	0.000639		

c) Surface Finish model for H.S.S. end mills

Source	SS	DF	MS	F_{cal}	F_{tab}
Zero order term	30.458	1	30.458		
First-order term	0.27873	3	0.09291		
Lack of Fit	0.081435	1	0.081435	10.15	19.30
Pure Error	0.00802	1	0.00802		

d) Tool Life model for Cemented Carbide end mills

Source	SS	DF	MS	F_{cal}	F_{tab}
Zero order term	10.856	1	10.856		
First-order term	0.34393	3	0..11464		
Lack of Fit	0.054354	1	0.054354	7.609	19.30
Pure Error	0.003325	1	0.003325		

Abbreviations

SS Sum of Squares

DF Degrees of Freedom

MS Mean of Squares

F_{cal} Calculated from the model

F_{tab} Obtained from statistical tables

APPENDIX C

COMPUTER PROGRAMME FOR CUTTING FORCE MEASUREMENT

‘Computer program for converting the data from the A/D converter into cutting force measurements’. Written by David Moore, 9/3/1995

```
#include <stdio.h>          ‘Opens the command files’
#include <dos.h>
#include <bios.h>
#include "dash8.h"

void main(void)
{
        ‘Defines all the variables as either a float or an integer’
        float ch0,ch1,ch2,fx,fy,fz;
        float sum1,sum2,sum3,forcex,forcey,forcez;
        int i,freq,ans,scale1,scale2,scale3;

        cls();          ‘clears the screen’

‘Gets the user to input the information in response to a series of
questions’
        puts("\n");
        printf("Enter the desired frequency (Hz):");
        scanf("%d",&freq);

        puts("\n");
        printf("Enter the x-axis scale factor:");
        scanf("%d",&scale1);
        puts("\n");
        printf("Enter the y-axis scale factor:");
```

```
scanf("%d",&scale2);
puts("\n");
printf("Enter the z-axis scale factor:");
scanf("%d",&scale3);

cls ();                     'clears the screen'
setfreq (freq);             'sets the frequency of the test'
getset_dat ();              'runs the program getset.dat'
install ();                 'runs the program install'
das8set ();                 'runs the program das8set'

puts("     DASH8 VOLTAGE & FORCE READINGS\n");
puts("\n\n");
puts("    X-AXIS   Y-AXIS            Z-AXIS");
puts("\n");
puts("     CH 0       CH 1          CH 2  \n");
puts("\n");

'sets all of the variables to zero'
i = 0;
ch0 = 0;
ch1 = 0;
ch2 = 0;
fx = 0;
fy = 0;
fz = 0;
sum1 = 0;
sum2 = 0;
```

```
sum3 = 0;
forcex = 0;
forcey = 0;
forcez = 0;

'starts a loop which will stop the program after 500 steps'
for (i=0;i<500;i++)
{
  while (error == FALSE)
{

'defines the input voltages'
ch0 = int_volt(int_in[0]);
ch1 = int_volt(int_in[1]);
ch2 = int_volt(int_in[2]);

'equations which convert the input voltages into cutting force values'
fx = ch0 * 10 * scale1/4096;
fy = ch1 * 10 * scale2/4096;
fz = ch2 * 10 * scale2/4096;

'prints the data on the screen'
printf("Voltage     %2.2fV      %2.2fV
%2.2fV",ch0,ch1,ch2);
puts("\n\n\n\n");
printf("%5.2fN     %5.2fN      %5.2fN",fx,fy,fz);
```

```
'equations which sum the cutting force readings'
}
sum1 = sum1 + fx;
sum2 = sum2 + fy;
sum3 = sum3 + fz;
}

'equations which finds the average cutting force values'
forcex = sum1/500;
forcey = sum2/500;
forcez = sum3/500;

cls ();          'clears the screen'

'prints the results on the screen'
printf("Actual output frequency is %4.2d Hz.",freq);
printf("Force on x-axis =  %5.2f Newtons.",forcex);
printf("Force on y-axis =  %5.2f Newtons.",forcey);
puts("\n");
printf("Force on z-axis =  %5.2f Newtons.",forcez);
puts("\n");
printf("END OF TEST\n");

cls ();          'clears the screen'

printf("Do you wish to continue, Yes = 1, No = 2:\n");
scanf("%d",&ans);
```

```
        while (ans < 1 || ans > 2)
        {
          printf("Error, please try again");
          printf("Do you wish to continue, Yes = 1, No = 2:\n");
          scanf("%d",&ans);
        }

        if (ans == 1)
        main();                 'returns to the start of the program'

stop ();                        'ends the program'

}
```

APPENDIX D

PUBLICATIONS

Assessment of Cutting Forces in End Milling Tool Steel Bhn 300

David Moore, Dr. M.A. El-Baradie

12th Conference of the Irish Manufacturing Committee (IMC)

University College Cork

September 1995

Tool life Assessment of High Speed Steel End Mills

David Moore, Dr. M.A. El-Baradie

13th Conference of the Irish Manufacturing Committee (IMC)

University of Limerick

September 1996