PERFORMANCE ASSESSMENT OF COATED CEMENTED CARBIDE TOOLS IN TURNING AISI 1018 STEEL

A Thesis

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Mohamad Nouilati
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Abstract

In this study, the machining performance of a series of commercially available coated tungsten based cemented carbides, with 55° diamond shape, were investigated during finish turning of AISI 1018 steel under dry conditions. The inserts tested had a coating of TiN, Al_2O_3, TiN/Al_2O_3 and TiC/Al_2O_3/TiN respectively. For comparison, uncoated cemented tungsten carbide was also tested under the same cutting conditions.

The coated tools exhibited superior wear resistance over the uncoated tool. The TiC/Al_2O_3/TiN coated tool had the lowest flank wear due to the high abrasive resistance of the TiC layer. The Al_2O_3 coated tool showed superior wear-resistance over the TiN/Al_2O_3 coated tool due to the TiN coating that deteriorated the effect of the Al_2O_3 outer layer. The TiN coated tool showed the least wear resistance with respect to the other coated tools.

Surface roughness appeared to increase with flank wear while oscillating for all the tested tools except for the TiN coated tool. The TiN coated tool produced a relatively consistent surface roughness that was not significantly affected by the flank wear under the conditions tested. The coated tools produced lower surface roughness compared to the uncoated tool, except for the TiN/Al_2O_3 coated tool, which produced considerably higher surface roughness. The reason for this however was the geometry of the chip breaker, rather than the coating materials, which produced longer chips that came in contact with the work piece during the machining process. The TiC/Al_2O_3/TiN coated tool produced the lowest surface roughness of all the tools tested.

Chapter 1 Introduction

1.1 General

The manufacturing industry is constantly striving to decrease its cutting costs and increase the quality of the machined parts as the demand for high tolerance manufactured goods is rapidly increasing. The increasing need to boost productivity, to machine more difficult materials and to improve quality in high volume by the manufacturing industry has been the driving force behind the development of cutting tool materials [1]. Numerous cutting tools have been developed continuously since the first cutting tool material suitable for use in metal cutting, carbon steel, was developed a century ago [2].

First introduced around 1926, cemented carbides are the most popular and most common high production tool materials available today [3]. The productivity enhancement of manufacturing processes imposes the acceleration of the design and evolution of improved cutting tools with respect to the achievement of a superior tribological attainment and wear-resistance [4].

One important aspect that is being vigorously researched and developed is the hard coating for cutting tools. These hard coatings are thin films that range from one layer to hundreds of layers and have thickness that range from few nanometers to few millimeters. These hard coatings have been proven to increase the tool life by as much as 10 folds through slowing down the wear phenomenon of the cutting tools. This increase in tool life allows for less frequent tool changes, therefore increasing the batch sizes that could be manufactured and in turn, not only reducing manufacturing cost, but also reducing the setup time as well as the setup cost.

In addition to increasing the tool life, hard coating deposited on cutting tools allows for improved and more consistent surface roughness of the machined work piece. The surface roughness of the machined work piece changes as the geometry of the cutting tool changes due to wear, and slowing down the wear process means more consistency and better surface finish.

The majority of carbide cutting tools in use today employ chemical vapor deposition (CVD) or physical vapor deposition (PVD) hard coatings. The high hardness, wear resistance and chemical stability of these coatings offer proven benefits in terms of tool life and machining performance [5-7]. The first technique is the CVD. This method deposits thin films on the cutting tools through various chemical reactions. Most tool coatings were traditionally deposited using the CVD technique until the recent development of PVD. This method deposits thin films on the cutting tools through physical techniques, mainly sputtering and evaporation.

The reason PVD is becoming increasingly favorable over CVD is the fact that the coating process occurs under much lower temperature. The high temperature during the CVD process causes deformation and softening of many cutting tool substrates and especially hard steel speed (HSS). Another advantage of applying the PVD technique is the ability to deposit much thinner films. And so, it is much more promising for the deposition of multi-layered coatings, which have been found to reduce wear considerably.

The use of coolant to increase tool life has been an issue with different views [8]. The inherent brittleness of carbides makes them susceptible to severe damage by cracking if sudden loads of thermal gradients are applied to their edge [9]. However, environmental and economic considerations of developed countries led to implementation of dry machining. Conventional machining uses 300-4000 l/h of coolants during machining. Environmental considerations mandate use of minimal coolant in the range of 6-70 ml/h. This is termed dry machining [10].

Today, there are two obvious trends in cutting tool developments. Dry machining is desirable to avoid the extra costs and environmental problems associated to cutting fluids. High speed machining of hardened steel has the potential of giving sufficiently high quality of the machined surface to make finishing operations such as grinding and polishing unnecessary [11]. Both cases tend to intensify the heat generation along the tool surfaces, and consequently the tools must possess further improved, thermal and chemical stability.

Since Taylor's time [12], considerable research and development have been directed at improving the technological performance measures as well as developing means for establishing equations relating the various technological performance measures to the many influencing variables for quantitative prediction purposes. While significant improvements in the technological performance of machining operations have been continually achieved through new tool geometrical designs as well as new tool materials, reliable quantitative predictions of the various technological performance measures remains a formidable task which has yet to be fully achieved.

A general theory covering all relevant properties and parameters involved in the design and application of tribological coating composites is very far from being realized. Such a theory would have to treat the long chain of relations ranging from the coating deposition parameters to the tribological response of the coated components [13].

Usually it is not possible to reproduce in full-scale the machining contact conditions through lab experiments such as using pin-on-disc testing because the wear mechanisms involved are not relevant to that observed in machining [14].

Generally, the end users of coated components are recommended to make the final evaluation of the tribological response in field tests or in component tests, i.e. Tests where the actual component is evaluated under realistic conditions. Simplified laboratory tests often deviate from the actual situations to nominal and real contact pressure, sliding speed, heat conductivity and capacity, ambient cooling, etc., which makes correlation to the real case hazardous [11].

1.2 Goal

The goal of this study was to improve the understanding of the effect of different types of coating materials on the performance of carbide cutting tools. To achieve this goal, turning tests were conducted with a CNC lathe using commercially available carbide cutting inserts with different coating materials. The performance of the cutting tools is evaluated by considering the progression of tool wear and the surface finish of the work piece.

The specific objectives of this research study included:

1. Study the flank wear progression on each of the cutting tools used.
2. Study the change of surface finish throughout the tool life of each cutting tool.
3. Assess and analyze the results obtained for each tool, and evaluate their performance based on the effects of the coating materials used.

Chapter 2 Literature Review

In order to achieve the objectives of this research a literature review was conducted. The literature included information on carbide cutting tools used in turning, coating materials for cutting tools, wear observed during turning operations and surface finish of the machined work piece. This information served as a guideline in the course of this study.

The use of coating materials to enhance the performance of cutting tools is not a new concept. The first coated cemented carbide indexable inserts for turning were introduced in 1969 and had an immediate impact on the metal cutting industry [15]. The boost in wear resistance gave room for a significant increase in cutting speed and thereby improved productivity at the machine shop floor. And today, 70% of the cemented carbide tools used in the industry are coated [16].

In development of modern materials, the functionality is often improved by combining several materials of different properties into composites. Many classes of composites exist, most of which are addressing improved mechanical properties such as stiffness, strength, toughness and resistance to fatigue. Coating composites are designed to specifically improve tribological and chemical functions. It is thus natural to select the bulk of a component to meet the demands for stiffness, strength, toughness, formability, cost, etc. and then modify or add another material as a thin surface layer. This surface layer or coating is the carrier of virtually all other functional properties. Application of coatings on tools and machine elements is, therefore, a very efficient way of improving their friction and wear resistance properties [17].

The combined substrate-coating properties ultimately determine the important properties such as wear, abrasion resistance and adhesion strength of a coating. A hard wear resistant coating cannot perform well unless complimented by a hard and tough substrate. Thus, a hard coating deposited on a soft substrate leads to poor properties [10].

Due to their significantly higher hardness, carbide-cutting tools are more widely used in the manufacturing industry today than high-speed steels. Coated and uncoated carbides are widely used in the metal working industry and provide the best alternative for most turning operations [8]. Due to their heat resistance, cemented carbides can be used in very hot applications and all types of PVD and CVD processes can be used to deposit coatings [11].

Physically and chemically vapor deposited coatings offer today a powerful alternative to improve further the cutting performance of the cutting materials [4].

2.1 Wear

The prediction and control of wear is one of the most essential problems emerging in the design of cutting operations [18]. A useful definition for a worn out tool is: “A tool is considered to be worn out when the replacement cost is less than the cost for not replacing the tool” [19]. Tool failure is said to occur when the tool no longer performs the desired function whereas total failure (ultimate failure) is defined as the complete removal of the cutting edge, a condition obtaining when catastrophic failure occurs [20]. Therefore, in machining operations, tools are considered to be worn out and are changed long before total failures to avoid incurring high costs associated with such catastrophic failures.

Some of the tool life rejection criteria presented in ISO 3685 are listed below [21]:

1. Average flank wear ≥ 0.4 mm
2. Maximum flank wear ≥ 0.6 mm
3. Notching ≥ 1.0 mm
4. Nose wear ≥ 0.5 mm
5. Surface roughness (R_a) ≥ 6.0 µm.

Machining of metals is a complex process. The cutting tool environment features high-localized temperatures (~1000 ºC) and high stress (~700 MPa). The tool may experience repeated impact loads during interrupted cuts, and the work piece chips may chemically interact with the tool materials. The useful life of a cutting tool may be limited by a variety of wear processes such as crater wear, flank wear or abrasive wear, built up edge, depth of cut notching and nose wear [10]. The main types of wear on a carbide-cutting tool are shown in Figure 2-1 below.

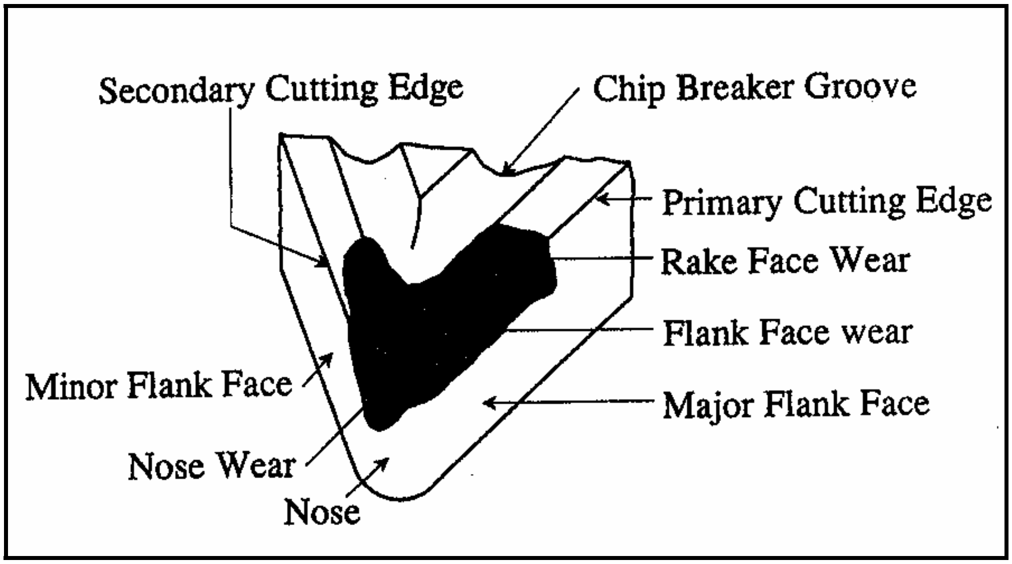


Figure 2- 1 Typical wear pattern and pertinent terminology [28].

Flank wear is observed on the flank or clearance face of a metal cutting insert and is caused mainly by abrasion of the flank face by the hard constituents of the workpiece [22]. This failure mechanism is commonly observed during machining of cast irons and steels where the abrasive particles are mainly Fe_3C and non-metallic inclusions [10].

Crater wear is observed on the rake face of cutting tools and is caused by chemical interactions between the rake face of a metal cutting insert and the hot metal chip flowing over the tool. Depth of cut notching is attributed to the oxidation of the tool material. Nose wear or tool tip blunting results from insufficient deformation resistance of the tool material [10].

Fracture is the least desirable mode of tool failure because it is unpredictable and catastrophic. When machining using carbides under typical cutting conditions, the gradual wear of the flank and rake faces is the main process by which a cutting tool fails [8]. However, flank wear is the preferred mode because it progresses gradually and can easily be monitored [10]. Most tool material development work is focused on minimizing flank wear and preventing unwanted tool failure modes such as catastrophic fracture, gross plastic deformation, built up edge and crater wear.

Some authors affirm that the flank wear in carbide tools initially occurs due to abrasion and as the wear process progresses, the temperature increases causing diffusion to take place [23-27]. Severe abrasion occurs at the flank face because of the lower temperature, the more rigid work piece relatively to the chip, and the constraint in the movement of the work piece and tool [28]. The intimate contact between the flank of the tool and work piece, high compressive and shear contact stresses acting on the flank of the tool and cutting temperature of around 850 ^{o}C can encourage atomic dissolution-diffusion wear [29].

At relatively high machining rates, high flow rates and elevated temperatures (600-1000ºC) at the chip/tool interface where seizure occurs, atoms from the tool material may diffuse into the flowing chip [30]. Also, the tool and work material may dissolve in each other, if the free energy of the material pair decreases by the formation of a solution [31,32]. Cemented carbide tools worn off by dissolution/diffusion exhibit smoothly worn through carbide grains [24,26,30]. In many previous studies, a very smooth surface at the worn flank face possessing voids between carbide grain boundaries was observed on a carbide insert. This smoothly worn surface topography is a characteristic of dissolution/diffusion wear. Inter-diffusion between cobalt in the tool and iron in the steel and decarburization of the tool have been reported as the major diffusion reactions that occur [33,34].

According to Jiang and Xu [35], the tool wear process can be divided into five stages: initial stage of wear, regular stage of wear, micro breakage stage, fast wear stage and tool breakage. Other studies have divided the tool wear process into three stages in which rapid flank wear occurred at the beginning of machining at cutting speeds of 200-250 m/min, followed by a gradual and steady wear growth, and finally by an accelerated wear towards the point of tool rejection [36].

2.2 Coating

Machining efficiency is improved by reducing the machining time with high speed machining. When cutting ferrous and hard to machine materials such as steels, cast iron and super alloys, softening temperature and the chemical stability of the tool material limits the cutting speed. Therefore, it is necessary for tool materials to possess good high-temperature mechanical properties and sufficient inertness.

While many ceramic materials such as TiC, Al_2O_3 and TiN possess high temperature strength, they have lower fracture toughness than that of conventional tool materials such as high-speed steels and cemented tungsten carbides. The machining of hard and chemically reactive materials at higher speeds is improved by depositing single and multi layer coatings on conventional tool materials to combine the beneficial properties of ceramics and traditional tool materials [28].

Schintlmeister et al. [37] had summarized the effect of coatings in the following statements:

1. Reduction in friction, in generation heat, and in cutting forces
2. Reduction in the diffusion between the chip and the surface of the tool, especially at higher speeds (the coating acts as a diffusion barrier)
3. Prevention of galling, especially at lower cutting speeds.

2.2.1 Types of Coating Technology

Surface coating of tribological applications is associated with deposition temperatures ranging from room temperature to over 1000 °C as shown in Figure 2-2. The coating thickness ranges from microns to several millimeters. Typically, the atomistic methods produce the thinnest coatings. Some methods involve high deposition temperatures that may give undesired phase transformations, softening or shape changes of the coated component [11]. An important benefit of PVD and CVD processes is the high flexibility as to composition and structure of the coatings, and these processes are today successfully utilized to coat a large variety of mechanical components.

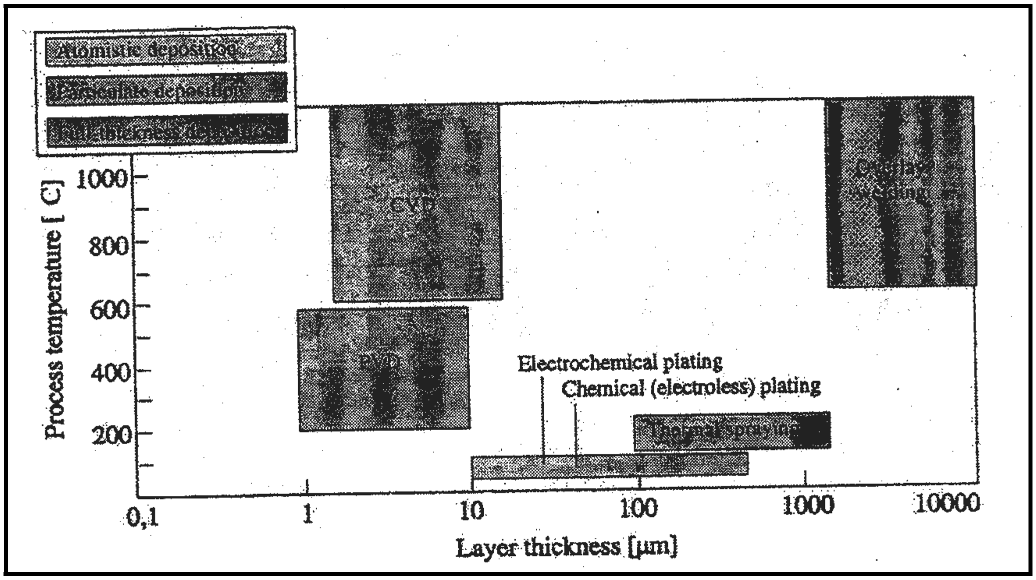


Figure 2- 2 Typical value of coating thickness and process temperature of today's tribological coating methods [17]

CVD coated cemented carbides have been a huge success since their introduction in the late 1960's [38]. Since then, chemical vapor deposition technologies have advanced from single layer to multi layer versions combining TiN, TiCN, TiC and Al_2O_3 [39-41]. Modern CVD coatings combine high temperature and medium temperature processes in complex cycles that produce excellent wear resistant coatings with a total thickness of 4-20 μm [42].

However, the high deposition temperature (950-1059 ^{o}C) during CVD results in diffusion of chemical elements from the carbide substrate to the coating during growth. The main effect is an embrittlement of the coating edge [15]. In addition, the chemistry of the CVD process results in more rapid growth at the cutting edge resulting in an even coating thickness. Therefore, there was a strong driving force to find coatings that could be deposited at lower temperatures in order to allow tools with sharper edges to be coated without any embrittlement effect. The solution was PVD where deposition temperature can be kept at around 500 ^{o}C.

PVD coatings, with deposition temperatures of 400-600 ^{o}C, are gaining greater acceptance in the market place. Over the last decade, they have been successfully applied to carbide metal cutting inserts. They offer performance advantage in applications involving interrupted cuts, those requiring sharp edges, as well as finishing and other applications [22,43,44]. Depending on the intended application, different PVD technologies such as electron beam evaporation, sputtering and arc evaporation are used. Improvements in these technologies such as high ionization magnetron sputtering and new cathodic arc processes have further improved the performance of PVD coated tools [22,43-45].

The metal cutting performance of PVD coated tools depend strongly on the composition, microstructure, internal stresses and adhesion of the coating to the substrate as well as the substrate composition and tool geometry [46]. PVD process chain includes pre-PVD processes and post PVD-processes. Pretreatment processes such as plasma etching and chemical etching influence adhesion, grain growth, stress at substrate surface and coating structure, whereas post-PVD processes influence smoothness of coating surface and better chip flow [47].

PVD coatings attribute excellent cutting performance to cemented carbide inserts [4]. The reason that PVD has more and more taken over with regards to deposition of many coatings is the advantages that lower coating temperatures give with regard to micro-toughness. In addition, the coatings are crack free as opposed to CVD coatings and have a risidual stress that is beneficial in some applications [15]. Previous studies have shown that cemented carbide cutting tools coated by PVD technology offer proven performance over their CVD coated counterparts [48].

2.2.2 Materials Used in Coatings

The majority of inserts presently used in various metal cutting operations are cemented carbide tools coated with a material consisting of nitrides (TiN, CrN, etc.), carbides (TiC, CrC, W2C, WC/C, etc.), oxides (e.g. alumina) or combinations of these [11,28]. Coating cemented carbide with TiC, TiN and Al_2O_3 dramatically reduces the rate of flank wear [26]. A primary contributor to the wear resistance of the coating materials is that they are all much less soluble in steel than WC at metal cutting temperatures.

The first PVD coating material to have a commercial application was TiN [15]. TiN deposited as a mono-layer holds a dominant position in the field of hard coatings to improve the wear resistance of cutting tools [49,50]. However, a draw back of TiN coating is its limited oxidation resistance at temperatures above 600 ^{o}C where a TiO_2 layer is formed. Due to the large difference in molar volumes between the TiO_2 and TiN, compressive stresses are developed in the oxide layer resulting in spallation and exposure of the nitride to further oxidation [51,52].

TiN coating is usually used as an outermost layer. In addition to adding to the total wear resistance of the insert, the golden color of the TiN coating helps in wear detection by allowing the operator to distinguish between a used and a new cutting edge corner [15]. In addition, TiN often reduces the sticking of the work material [11]. Dissolution–diffusion and discrete plastic deformation are the principal wear mechanisms for TiN coating [29].

In addition to its high wear resistance, TiC accounts for good bonding to the carbide material [11]. The formation of low friction compounds such as titanium oxides, which reduce welding between the tool and chip, has been suggested [53,54]. Dissolution–diffusion and discrete plastic deformation are the principal wear mechanisms for TiC coating [29]. Micro cracking and micro chipping are also major wear modes of TiC coatings [24]. At low cutting speeds, when abrasion is the main wear mechanism, the presence of TiC coating will greatly increase the tool life. As the cutting speed increases, diffusion becomes an important wear mechanism due to the high temperatures, and then the presence of coatings with thermal and chemical stability such as Al_2O_3 is important [29].

Al_2O_3 was used first as a cutting tool material in the form of a bulk ceramic. However, the brittleness of Al_2O_3 ceramics posed a strong limitation to a more general use for metal cutting. A thin Al_2O_3 coating on top of an inner TiC coating was introduced in the 1970's. TiC was used as an inner layer due to the problem of achieving sufficient adhesion directly on the carbide substrate at that time. However, the two coatings have been found to complement each other in limiting wear at the cutting edge and have become an industry standard [15].

Al_2O_3 provides a good wear resistance at elevated temperatures. The low chemical wear rate of Al_2O_3 indicates that this material is so chemically stable with respect to steel that chemical dissociation is unimportant at all temperatures [15]. Hence, unlike WC, mechanically activated wear mechanism such as plastic flow, thermomechanical fatigue, and fracture would be expected to prevail during machining of steels when using Al_2O_3 coating.

High hardness is beneficial in resisting the abrasive wear. Retention of hardness even at higher temperatures is very important since the tool bit experiences a temperature in the range of 300-1000 ˚C depending on the machining parameters and the materials to be machined [10]. Micro hardness values of different coatings measured at different temperatures are shown in Figure 2-3. They all exhibit a decrease with an increase of temperature, and the decrease of hardness was much more pronounced in the case of TiC. Interestingly, the micro hardness of Al_2O_3 was significantly lower than TiC at room temperature but retained almost 40 % of its room temperature hardness at 1000 ˚C.

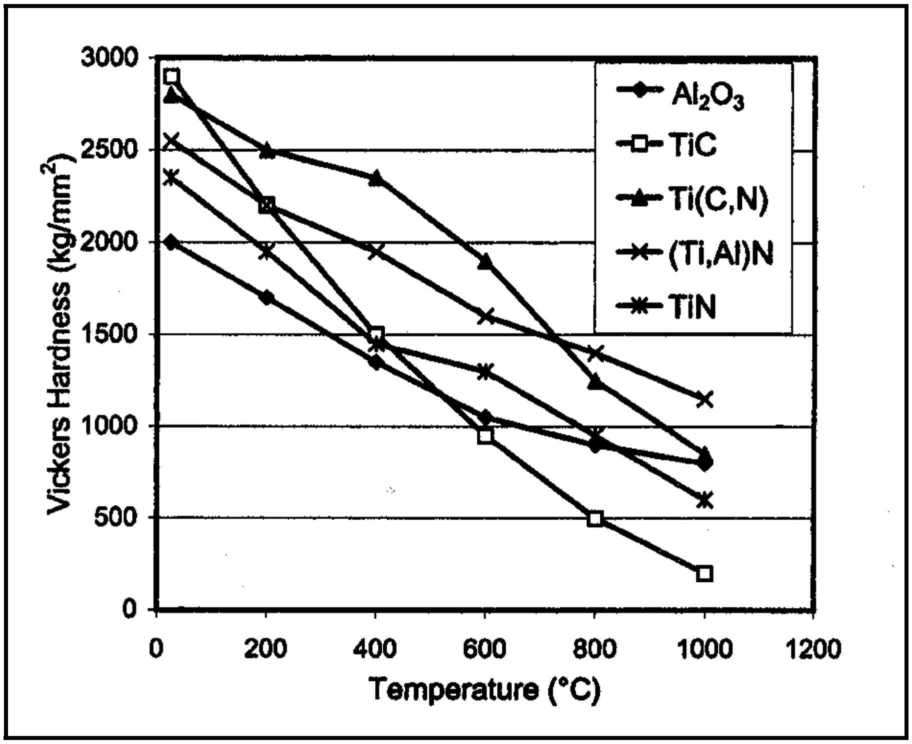


Figure 2- 3 Temperature dependence of micro hardness [22,48]

Al_2O_3 prevents diffusion of oxygen into the coating, and its low thermal conductivity allows dissipation of a considerable amount of heat via chip removal [48]. Oxidation rate of hard coatings is shown in Figure 2-4.

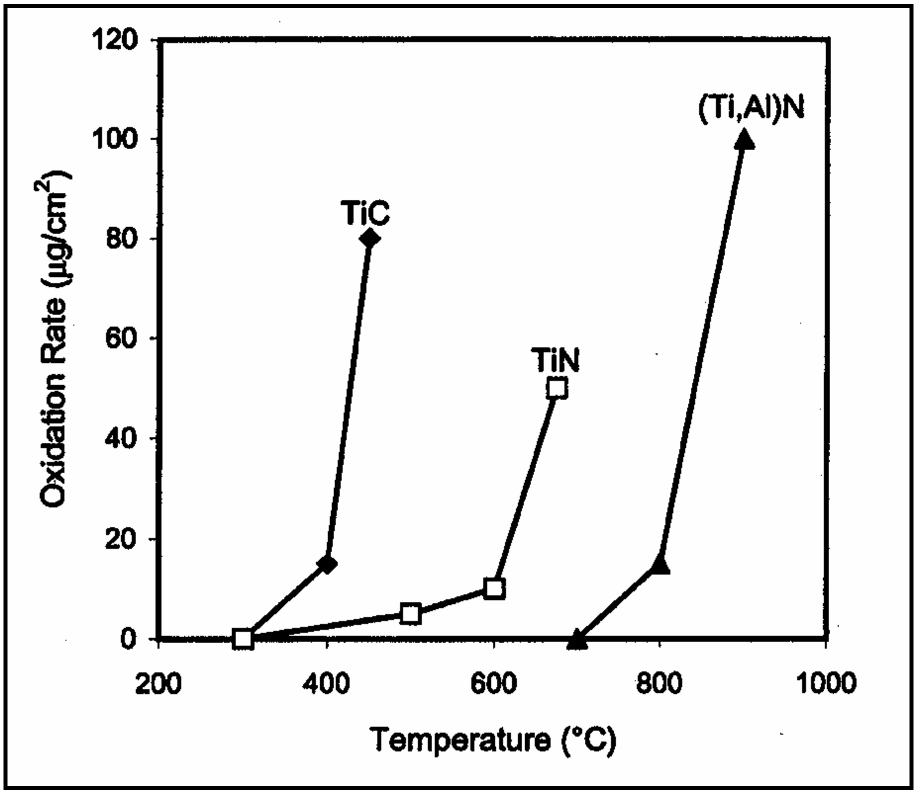


Figure 2- 4 Oxidation rate of hard coatings [10]

Previous studies have shown that surface plastic deformation is the dominant wear mechanism of Al_2O_3 [26,29]. Crack propagation has been reported at the interface between the substrate and the coating of alumina-coated tools, consequently resulting in the delamination of alumina coating at the final stage of wear [26].

A previous study conducted on carbide tools with TiC under-layer and Al_2O_3 outer-layer has observed that the principal wear mechanism of Al_2O_3 is delamination comprising surface and subsurface cracking, and the contribution of surface plastic deformation to the overall tool wear was secondary. Initial wear of the TiC layer occurs by abrasion and surface plastic deformation and at the later stage of wear by demlamination caused by subsurface crack propagation near the brittle TiC/WC-Co interface [28]. The study shows that eventually, the exposed carbide substrate wears out by plucking of carbide grains and dissolution-diffusion wear.

Another previous study was conducted on carbide tools with TiC under-layer, an Al_2O_3 intermediate layer and a TiN outer-layer. In this study the almost invisible wear-land produced in the early stage of cutting suggests that three-layer coated tools have higher wear resistance compared to two-layer coated tools. The study suggests that a delamination process involving the growth of surface and interfacial cracks removes TiN, Al_2O_3 and TiC layers either concomitantly or individually. Abrasive wear was found to be a contributing mechanism for TiN layers [28].

The comparison of the wear performance of two carbides coated with TiC/Al_2O_3 and $TiC/Al_2O_3/TiN$ reveals the better wear resistance of three-layer coated tools over two-layer coated tools [28]. The relatively higher wear resistance of three layer coated tools is attributed to the decrease of the driving force for subsurface and interfacial crack propagation occurring due to the dissipation of external work in plastic shearing of the TiN outer layer, as opposed to the Al_2O_3 outer layer of two layer coated tools which exhibited less plastic deformation.

It has been shown that propagation of cracks approaching an interface between materials with similar elastic properties but differing hardness is dependent on which direction the cracks are coming from [55]. Cracks approaching from the softer material stop at or are diverted from the interface, while cracks coming from the hard side may cross the interface and enter the softer material. Therefore even a thin layer with lower hardness than its surrounding should be able to function as an impedent to crack propagation.

Coating with three layers of TiC-Al_2O_3-TiN as seen from the substrate are widely used for machining of many types of steels [11]. This type of coating improves the wear resistance of the tool by combining the properties of the three materials. The ranking of the solubility products and limits of TiC, TiN and Al_2O_3 in iron, compared to the carbide substrate, is in the order TiC > TiN > Al_2O_3 [26]. Therefore there is less driving force for significant dissolution-diffusion wear of Al_2O_3 to take place.

In a previous study conducted by Dearnley [26], the coated carbides in cutting steels exhibited wear rates in the order of TiN> Al_2O_3 >TiC. It was suggested that wear rate of TiN and Al_2O_3 when cutting steels is rate controlled by discrete plastic deformation, whereas TiC wear was rate controlled by dissolution/diffusion. Also, Al_2O_3 coats at the final stage of wear were frequently removed from the substrate by decohesion at the interface.

Thus, having a coating layer of Al_2O_3 over an under layer of TiC help decrease the dissolution/diffusion wear at the TiC coating layer. This enhances the performance of the cutting tool, by including the TiC layer with a low wear rate and protecting it with a layer of Al_2O_3 to decrease the effect of diffusion/dissolution wear. The softer TiN outer layer helps in reducing the propagation of cracks into the inner coating layers, in addition to decreasing the welding of the chips to the cutting tool. Another reason for having the TiN as an outer layer, as opposed to inner layer, is that at higher temperatures of oxidation, the growth of TiO_2 (rutile) under layer may affect the performance of the protective alumina over layer of the oxide [10].

2.3 Surface Finish

Surface roughness and tolerance are among the most critical quality measures in many mechanical products. As competition grows closer, customers now have increasingly high demands on quality, making surface roughness become one of the most competitive dimensions in today's manufacturing industry [56].

Metal cutting is a common operation in many manufacturing systems. Roughness of the machined surface is an important quality measure in metal cutting, and it is important to monitor and control surface roughness over time during the machining operation. If the surface becomes too rough, the cutting tool has to be changed [57].

Any machined surface has errors that are broadly classifiable as either macro errors or micro errors [58]. Macro errors are due to imperfections in the machine tool whereas micro errors are mainly due to feed marks left by the cutting tool. Vibrations during machining may affect both types of errors. The micro errors are commonly known as surface roughness.

There are several measurements that describe the roughness of a machined surface. One of the most common is the arithmetic average (AA) value usually known as R_a. [59]. The AA value is obtained by measuring the height and depth of the valleys on a surface with respect to an average centerline. The higher the AA value is, the rougher the machined surface. Figure 2-5 shows a magnified cross section of a typical machined surface.

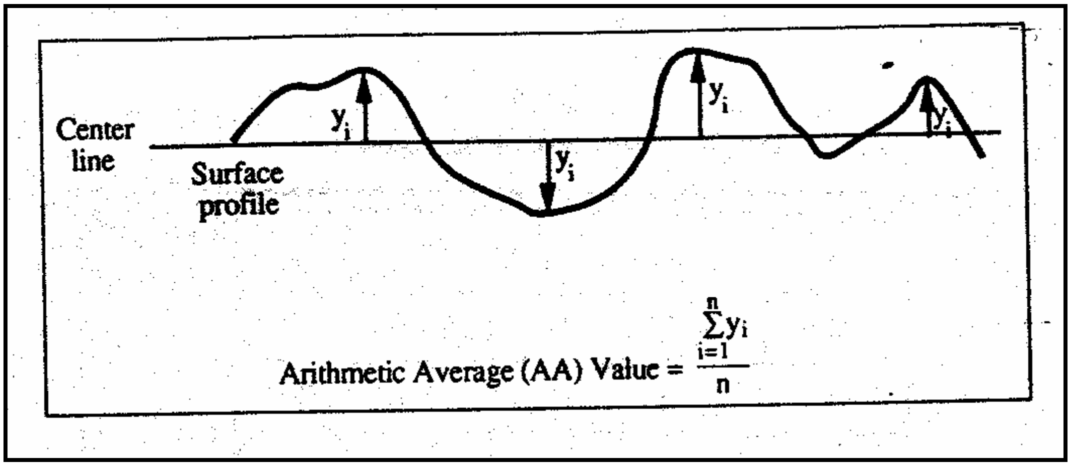


Figure 2- 5 Illustration of surface roughness [57]

Many factors influence the formation of surface roughness in the turning process. These factors include chip deformation and side flow, vibration of the machine-tool-fixture work piece system, geometrical contribution of the feed and tool nose radius.

Classical surface roughness related equations calculate geometrical contribution:

$$h \approx \frac{f^2}{8R},\ h_{CLA} \approx \frac{f^2}{18\sqrt{3}R}$$

Where h is the peak to valley height, h_{CLA} the center line average roughness, f the feed and R the nose radius. This shows that surface roughness is primarily dependent on feed rate and tool nose radius. However, the above equations give ideal surface finish values under satisfactory cutting conditions [60].

The tool wear influences the surface roughness of the work piece and the value of surface roughness is one of the main parameters used to establish the moment to change the tool in finish turning [27]. Carbide tool wear may occur by the mechanical detachment of relatively large fragments of tool material (attrition wear). This causes the surface roughness to increase significantly and promote the formation of ridges [26,30].

The geometry of tool wear also causes a change in surface roughness as machining time elapses. Flank wear is along with groove wear are the types of wear that most influence this change in surface roughness [61]. Some studies have claimed that the change in surface roughness is primarily caused by cutting-tool flank wear [59].

Many authors have studied the relationship between surface roughness and flank wear. Sundaram and Lambert [62] studied turning of steel with uncoated carbide tools. The results are shown in Figure 2-6. The graph shows an increased amplitude of the surface roughness at the beginning of cut, a decreased tendency in the middle and again an increased tendency at the end of wear.

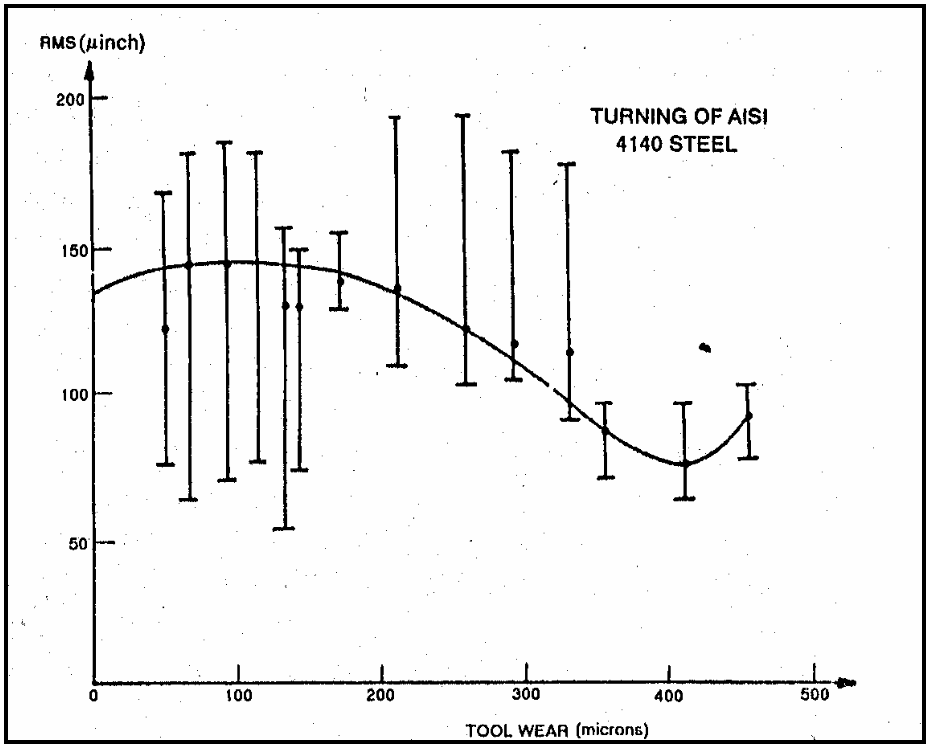


Figure 2- 6 Surface roughness vs. tool wear [62]

The relationships between R_{max}, R_a and V_b with cutting length, lc, was studied by Petropoulos [63] and the results for machining steel are shown in Figure 2-7, where R_{max}

is the maximum peak to valley roughness and V_b is the flank wear. The Figure shows that R_{max} and R_a increase until V_b reaches 0.2 mm. Above this value, R_{max} oscillates around a constant value and R_a oscillates as it increases. Flank-wear increases continuously.

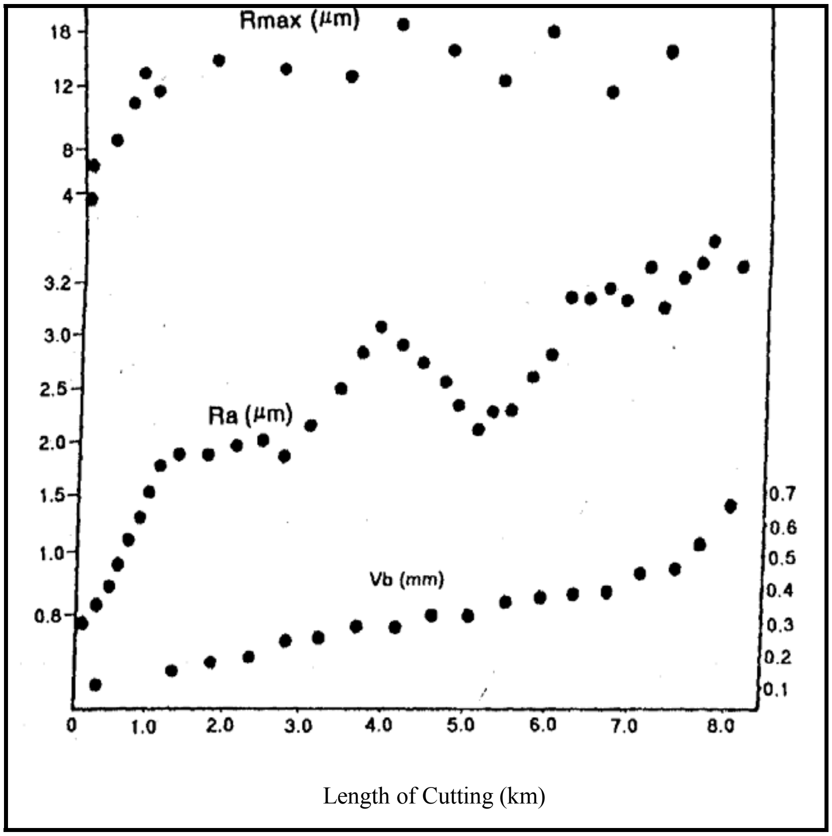


Figure 2- 7 Surface roughness (Ra and Rmax) and flank wear vs. length of cutting [63]

Bonifacio and Diniz [27] also studied the relationship between tool wear and surface roughness. The data obtained from the study is shown in Figure 2-8. The results show that roughness increased after some time of cut for all cutting conditions tried, indicating the end of tool life.

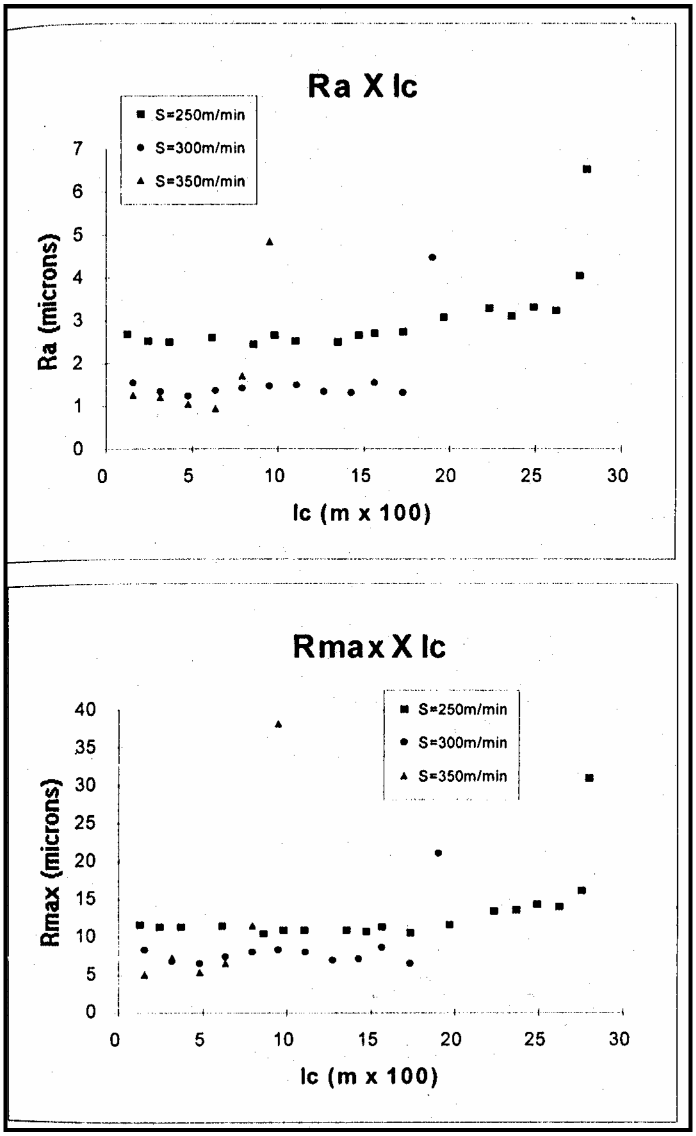


Figure 2- 8 Surface roughness vs. cutting length (lc) for different cutting speeds [27]

The surface roughness values decrease slightly after a short cutting time due to the chamfering of the edge radius [27]. The large increase of wear at the end of tool life, which causes a large increase of surface roughness may be due to the fact that the insert is losing its coating and begins to cut with its substrate.

In a previous study, the surface finish obtained when using TiN coated carbides and Al_2O_3 coated carbides as compared to uncoated carbides showed that TiN coated carbides had best surface finish followed by Al_2O_3 coated carbides and finally uncoated carbides [60]. These results are shown in Figure 2.9, in which insert 1 is Al_2O_3 coated tool, insert 2 is TiN coated tool and insert 3 is uncoated tool.

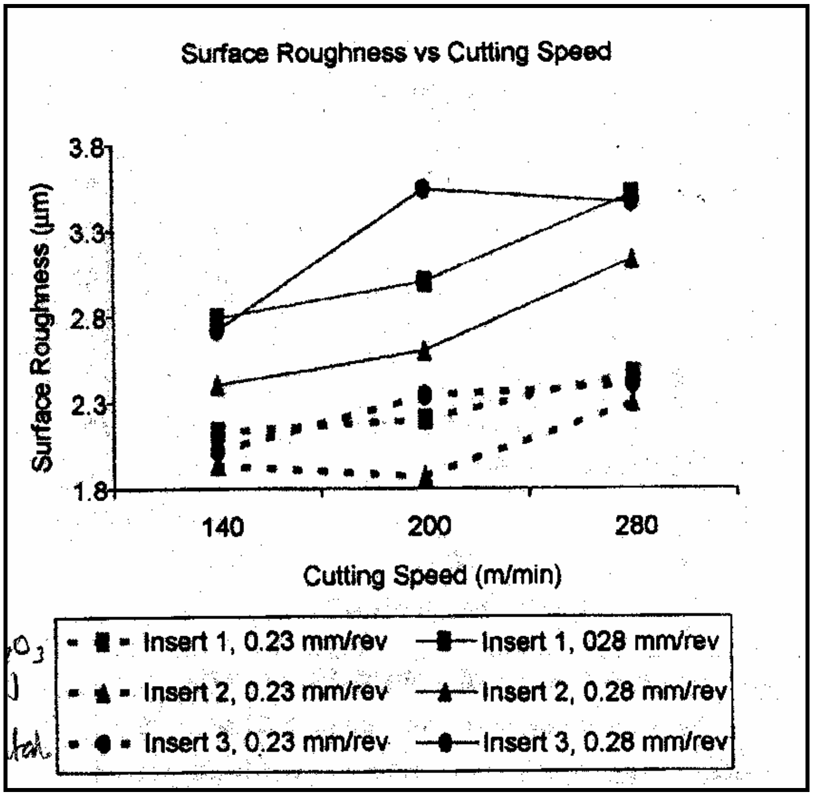


Figure 2- 9 Surface roughness measurements vs. cutting speed [60]

Chapter 3 Methodology

Based on the literature review and an examination of prior experimental studies, a methodology was developed to study the progression of flank wear of the cutting tools and the change in the surface roughness of the machined part in turning. Since the present trend in the manufacturing industry is high speed dry machining, it was suggested to apply dry machining and high turning speed to simulate the machining conditions that are observed in typical manufacturing industries.

This chapter describes the steps that were taken to achieve the objectives of this study. Commercially available cutting tools that are used by numerous manufacturing industries were ordered from cutting tools distributors, and the appropriate machining parameters were selected so that the machining experiment would simulate the conditions in the manufacturing industry.

3.1 Cutting Conditions

Cutting tests were carried out on a computer numerically controlled (CNC) lathe machine under dry conditions. The lathe machine, located in the industrial engineering lab, was of type EZ Path by Bridgeport and is shown in Figure 3-1. The tools were tested under a spindle speed of 1500 RPM. However, the actual spindle speed differs from the selected speed and was 1536 RPM. The feed rate used was 0.01 in/rev, which is equivalent to 0.254 mm/rev. This high feed rate was used for high productivity. And a depth of cut of 0.015 inch was used, which is equivalent to 0.381 mm. This small depth of cut was used for finish turning. The cutting conditions were kept constant for each of the tools tested throughout the experiment.

Figure 3- 1 Bridgeport EZ Path CNC lathe machine.

3.2 Cutting Inserts

Five types of commercially available tungsten based cemented carbide inserts were tested. The cutting inserts tested were uncoated – insert 1, TiN coated – insert 2, Al_2O_3 coated – insert 3, TiN/Al_2O_3 coated – insert 4 and TiN/Al_2O_3/TiC coated – insert 5, respectively. All the inserts had a grade C6, suitable for machining different kinds of steels at high speeds and high feed rates.

All the inserts have identical geometry designated by the American National Standard Institute (ANSI) as DNMG – 432, where

D: Insert shape of 55^o diamond.

N: Relief angle of 0^o.

M: Tolerance of the inscribed circle and thickness of ± .002 and ± .005 respectively.

G: Insert with a hole and chip breaker on both faces.

4: Inscribed circle of ½ inch.

3: Thickness of the insert of 3/16 inch.

2: Nose radius of 1/32 inch.

The inserts were rigidly mounted on a right hand style tool holder with a cutting rake and a back rake of –6°. The tool holder is designated by ANSI as MDJNR – 12 – 4B, where

M: Multiple lock assembly composed of pin lock and clamp lock.

D: Insert shape of 55° diamond.

J: Offset shank with –3° side cutting edge angle.

N: Rake attitude is negative.

R: Right hand tool (cutting is from right to left).

12: Shank size of 12/16 inch.

4: Size of the insert inscribed circle of 4/8 inch.

B: Length of 4.5 inches.

The cutting tool and tool holder assembly are shown in Figure 3-2.

3.3 Composition of the Cutting Tool Substrate

X-ray photoelectron spectroscopy (XPS) was used to find the composition of the tungsten carbide substrate of the cutting tools. An uncoated carbide insert was used and the results after 2760 seconds of etching are shown in Figure 3-3.

In addition, a scanning electron microscope (SEM) was used to observe the surface of the tungsten carbide insert of the cutting tools. A TiN coated tungsten carbide insert was first immersed in epoxy and then it was polished first with SiC abrasive grit and then with diamond abrasives. Polishing was required because the SEM requires that a specimen be both flat and reflective. The substrate is then coated with a layer of Au to provide conduction necessary for the SEM. The SEM micrograph taken of the tungsten carbide shows a WC grain size of around 2 μm as shown in Figure 3-4. Figure 3-5 shows an SEM micrograph of the TiN and tungsten carbide interface, and shows a TiN coating thickness of around 2.7 μm.

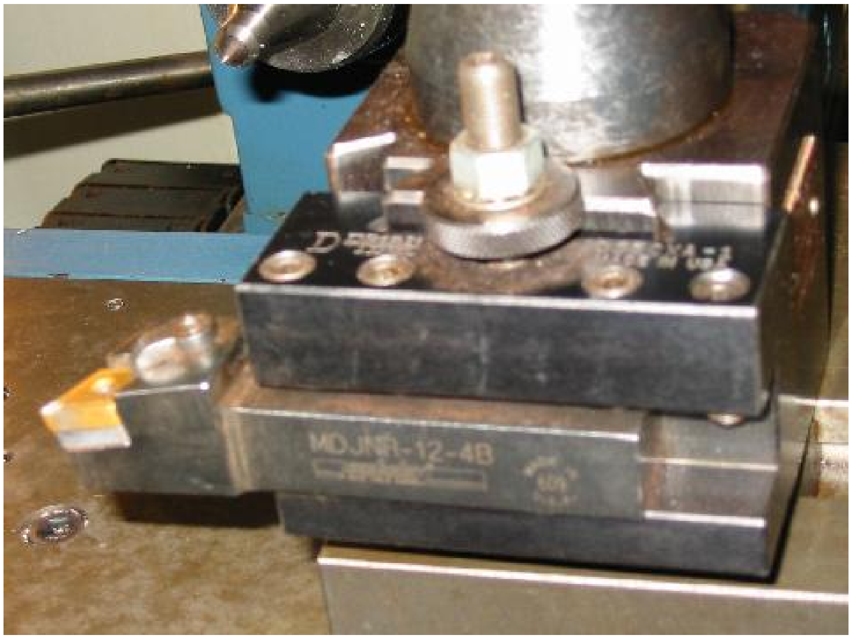
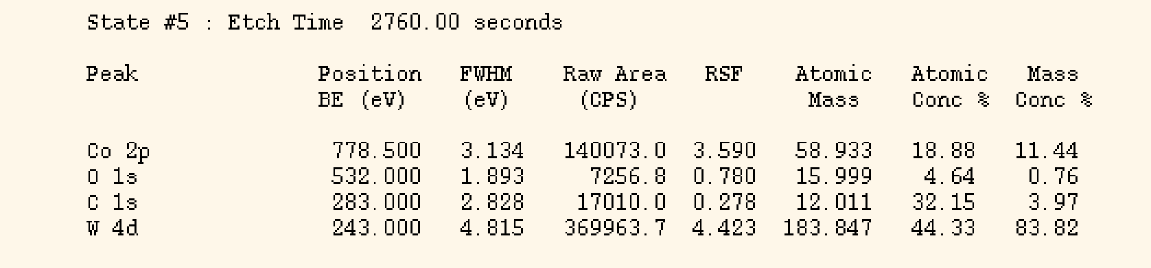


Figure 3- 2 The cutting tool and tool holder.



```
State #5 : Etch Time  2760.00 seconds

Peak            Position  FWHM   Raw Area   RSF    Atomic   Atomic   Mass
                BE (eV)   (eV)    (CPS)             Mass    Conc %  Conc %

Co 2p           778.500   3.134  140073.0  3.590   58.933   18.88   11.44
O 1s            532.000   1.893    7256.8  0.780   15.999    4.64    0.76
C 1s            283.000   2.828   17010.0  0.278   12.011   32.15    3.97
W 4d            243.000   4.815  369963.7  4.423  183.847   44.33   83.82
```

Figure 3- 3 Composition of the uncoated carbide insert.

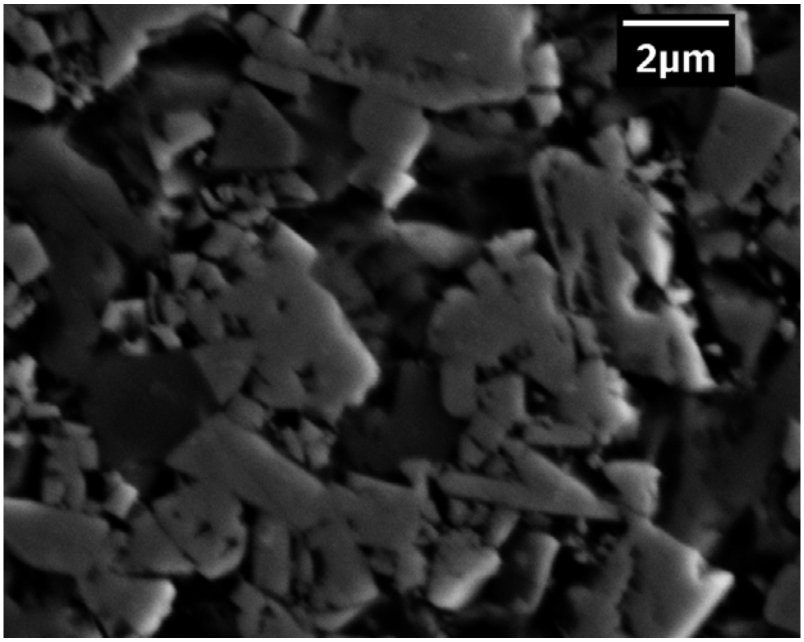


Figure 3- 4 SEM micrograph showing the WC grains on the uncoated tool.

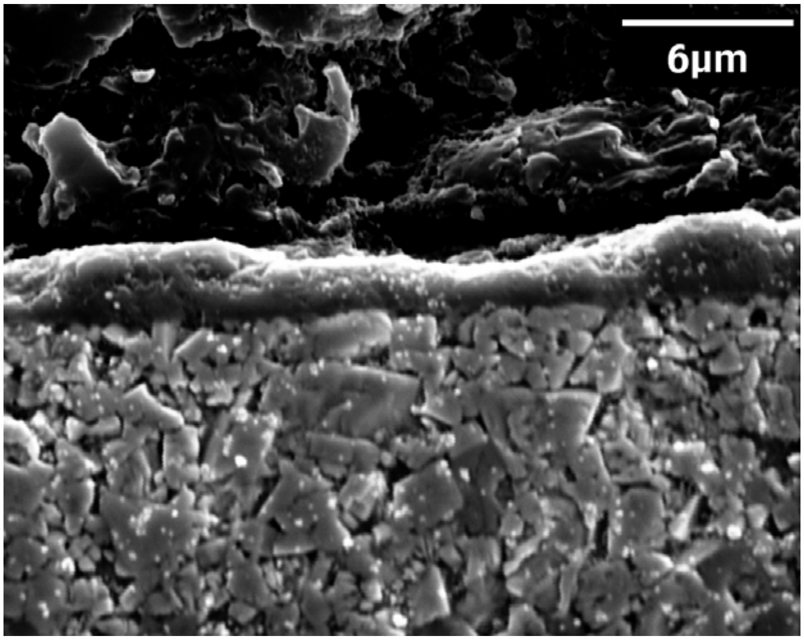


Figure 3- 5 SEM micrograph showing the coating/substrate interface.

3.3 Work-piece Material

The cutting performance tests were performed on AISI 1018 cold rolled steel. Based on the AISI-SAE standard carbon steel table, it is a non-resulphurized grade steel and its composition is 0.15-0.2% C, 0.6-0.9% Mn, maximum of 0.04% P and maximum of 0.05% S.

The work piece material used was 1.5 inch in diameter and 20 feet long. However, in order to meet the requirement of the ISO 3685 [21] that the length/diameter ratio of the work piece material to be used should be less than 10 during testing, the bar was cut into 20 pieces (12 inch length) using the metal cutter shown in Figure 3-6 which is located in the machine shop of the Industrial Engineering department.

Figure 3- 6 Metal-cutter for cutting the work piece material.

3.4 Experimental Techniques

Each work piece was first center-drilled on one side as shown in Figure 3-7. This was necessary in order to support the work piece from both sides while turning on the lathe, and in turn, reducing the vibration of the work piece material and minimizing any impact forces on the cutting tool.

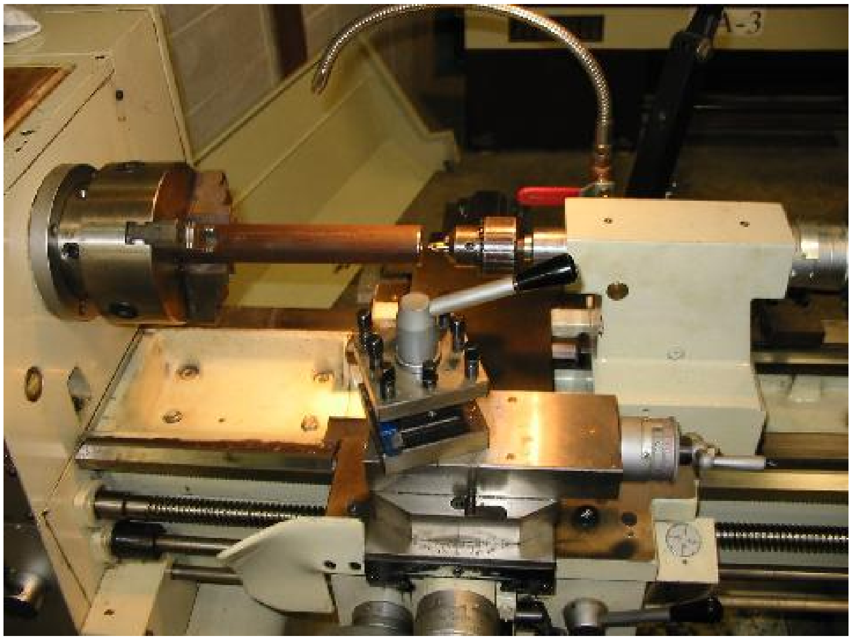


Figure 3- 7 Center drilling the work pieces.

The work piece was then set up on the CNC lathe machine as shown in Figure 3-8. The work-piece was attached to the lathe by the chuck, which is attached to the spindle. A tailstock assembly was used to support the work piece center drilled end.

The cutting tool was allowed to slightly touch the right side of the work piece material shown in Figure 3-8, and the coordinates of the start of the work piece were set on the CNC lathe. The cutting tool was then allowed to slightly touch the surface of the work piece material, and the diameter of the work piece was set in the CNC lathe.

The work piece length to be machined was 8 inches. This was to allow 3 inches in the chuck for support, and 1-inch clearance between the end of the machined surface and the chuck to avoid any interference with the chip flow.

Figure 3- 8 The work piece setup

A pre cut with a 0.01 depth of cut was performed on each work piece prior to the actual turning tests using a different TiN coated tool. This was done in order to remove the rust layer from the outside surface and to minimize any effect of inhomogeneity on the experimental results.

The cutting performance tests involved 60 cuts for each of the cutting inserts – 30 cuts on each work piece. The response variables measured were flank wear and the surface roughness. Flank wear on each cutting tool was measured after every 3 cuts using a light-section microscope as shown in Figure 3-9 and the measurement made was of the maximum depth of mark on the flank face. Surface roughness of the turned surface was measured after every cut using a portable surface roughness tester (Hommel Tester T 500), as shown in Figure 3-10.

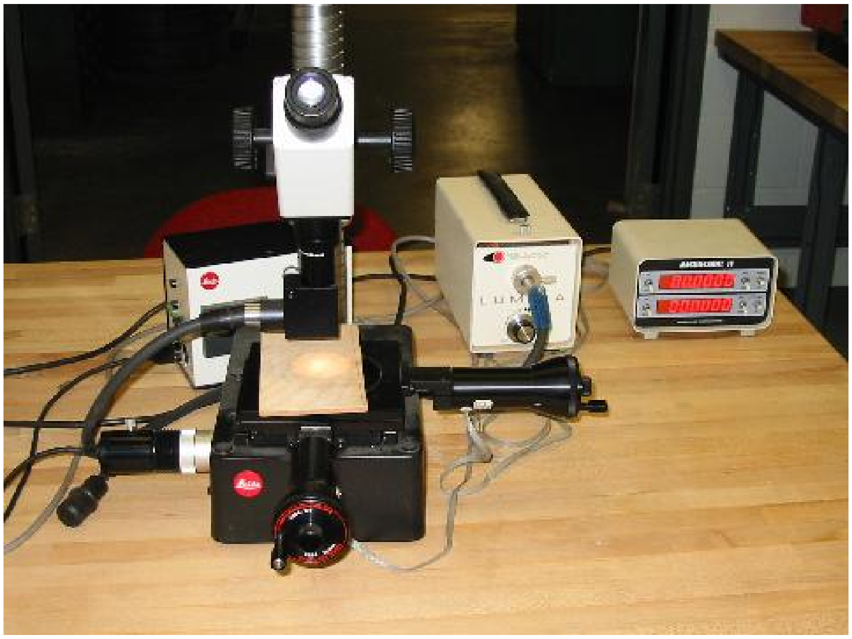


Figure 3- 9 Light section microscope used for wear measurements.

Figure 3- 10 Hommel surface roughness tester.

The tool holder was first removed from the CNC lathe, and the cutting tool was removed from the tool holder, by loosening the pin and clamp locks, in order to examine the flank wear under the microscope. The surface roughness measurement was taken on each side of the work piece and an average surface roughness value was obtained for each cut. Also, following every cut, chips produced while turning had to be removed so that they did not interfere with the next cut.

Chapter 4 Results and Analysis

This chapter presents the results for the machining performance of the four different coated cutting tools and the uncoated cutting tool in turning AISI 1018 steel. The results for the flank wear of the uncoated tool and the surface roughness of the machined AISI 1018 work-piece are first presented. The results of the other coated tools are then shown and are compared to those obtained using the uncoated tool in order to obtain the effectiveness of the different coatings on the flank wear and the surface roughness.

The flank-wear and the obtained surface roughness results for each of the coated tools are then compared in order to confirm the machining performance rankings of the different coatings considered.

4.1 Uncoated Carbide Insert

4.1.1 Flank wear

The flank-wear as a function of the number of cuts for the uncoated tool is shown in Figure 4-1. From the figure, the flank wear appears to increase with the number of cuts as expected.

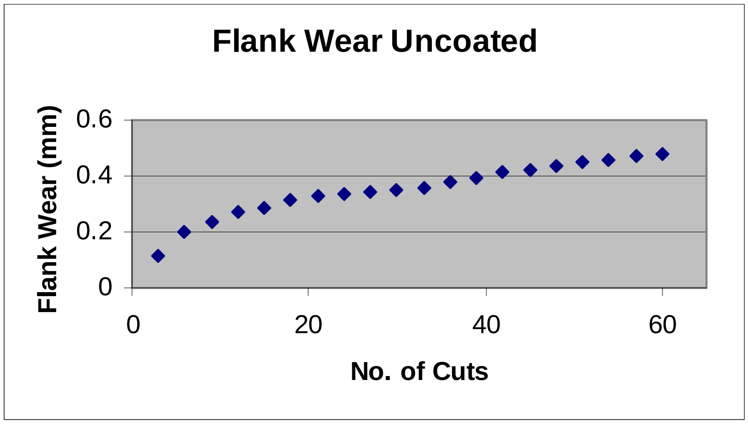


Figure 4- 1 Flank wear vs. number of cuts for uncoated tool.

The wear appears to grow more rapidly at the initial stage up to cut number 15, and then grows at a lower steady rate up to cut number 35, and then grows at a higher rate from cut number 35 on. This result agrees with previous studies where flank wear is said to have three stages, an initial stage with rapid growth, a second stage with steady low growth and a final stage of higher wear growth until tool rejection criteria is reached.

Table 4-1 shows the SAS output for the regression of flank-wear on the number of cuts. A null hypothesis (Ho) that the number of cuts has no effect on wear and an alternative hypothesis (Ha) that the number of cuts has an effect on wear were used.

Table 4- 1 Regression of flank wear on the number of cuts for uncoated tool.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: wear

                             Analysis of Variance

                                    Sum of           Mean
Source                   DF        Squares         Square    F Value    Pr > F

Model                     1        0.16242        0.16242     221.63    <.0001
Error                    18        0.01319     0.00073283
Corrected Total          19        0.17561


Root MSE              0.02707    R-Square     0.9249
Dependent Mean        0.35177    Adj R-Sq     0.9207
Coeff Var             7.69561
```

The P-value for the number of cuts was calculated using SAS for the flank wear vs. number of cuts for the uncoated tool. To reject the null hypothesis, the P-value must be less than the value of α. In this study, a 95 percent confidence is used, and so the value of α is equal to 0.05. This means only 0.05 (five percent) of all values will exceed this interval. The P value for this regression is <0.0001. Since it is less than 0.05, the null hypothesis is rejected. And so it can be concluded that the number of cuts has a significant effect on wear.

4.1.2 Roughness

The machined part surface roughness as a function of number of cuts is shown in Figure 4-2. This figure shows that the surface roughness increased steadily until around cut number 15. After that the surface roughness oscillated while increasing at a lower rate.

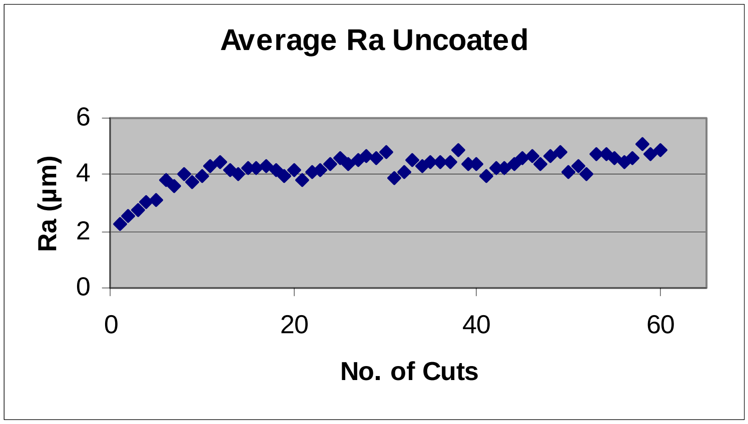


Figure 4- 2 Surface roughness vs. number of cuts for uncoated tool.

This pattern for the change of surface roughness with cutting agrees with previous studies, in which they have suggested that the oscillation of the surface roughness is not only dependent on flank wear, but is dependent on other factors such as groove wear. However, it is interesting to note that the initial steady increase in surface roughness coincides with the initial stage of rapid wear growth for the tool.

Table 4- 2 Regression of surface roughness on the number of cuts for uncoated tool.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: roughness

                             Analysis of Variance

                                    Sum of           Mean
Source                    DF       Squares         Square    F Value    Pr > F

Model                      1       8.59129        8.59129      55.56    <.0001
Error                     58       8.96851        0.15463
Corrected Total           59      17.55980


Root MSE             0.39323    R-Square     0.4893
Dependent Mean       4.20442    Adj R-Sq     0.4805
Coeff Var            9.35277
```

Table 4-2 shows the SAS output for the regression of surface roughness on the number of cuts. A null hypothesis (Ho) that the number of cuts has no effect on the surface roughness and an alternative hypothesis (Ha) that the number of cuts has an effect on surface roughness were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis since the P value for this regression is <0.0001. And so it can be concluded that the number of cuts has a significant effect on surface roughness.

4.1.3 Roughness vs. Wear

The machined part surface roughness as a function of tool flank wear is shown in Figure 4-3. This figure shows the increase of machined surface roughness with increasing tool flank wear.

Table 4-3 shows the SAS output for the regression of surface roughness on the tool flank-wear.

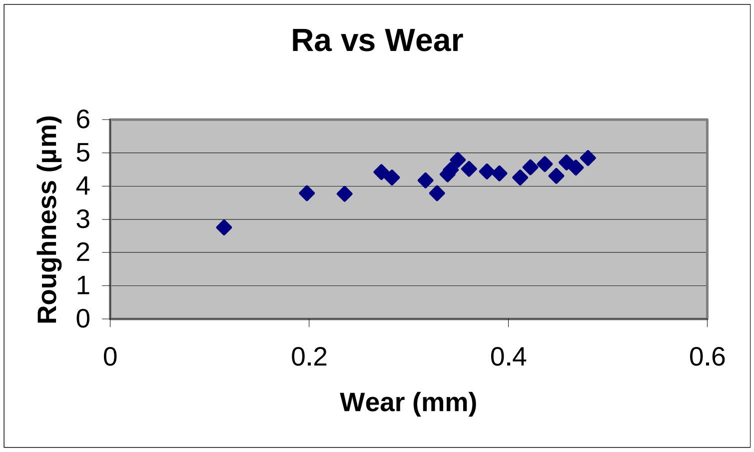


Figure 4- 3 Surface roughness vs. flank wear for uncoated tool.

A null hypothesis (Ho) that the tool flank-wear has no effect on the surface roughness and an alternative hypothesis (Ha) that the tool flank wear has an effect on surface roughness were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis since the P value for this regression is <0.0001. And so it can be concluded that the flank wear has a significant effect on surface roughness.

4.2 TiN Coated Carbide Insert

4.2.1 Wear

The flank-wear as a function of the number of cuts for the TiN coated tool is shown in Figure 4-4. From the figure, the flank wear appears to increase with the number of cuts as expected. The wear appears to grow more rapidly at the initial stage up to around cut number 30, and then grows at a lower steady rate from cut number 30 on. This result shows an initial stage with rapid growth and a second stage with steady lower growth.

Table 4- 3 Regression of surface roughness on flank wear for uncoated tool.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: roughness

                             Analysis of Variance

                                    Sum of           Mean
Source                   DF        Squares         Square    F Value    Pr > F

Model                     1        2.91331        2.91331      36.98    <.0001
Error                    18        1.41791        0.07877
Corrected Total          19        4.33122


Root MSE              0.28066    R-Square     0.6726
Dependent Mean        4.29025    Adj R-Sq     0.6544
Coeff Var             6.54193
```

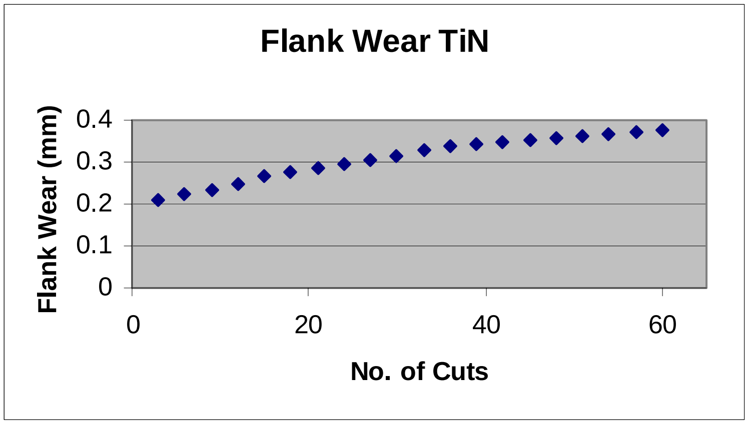


Figure 4- 4 Flank wear vs. number of cuts for TiN coated tool.

Table 4-4 shows the SAS output for the regression of flank-wear on the number of cuts for the TiN coated tool. A null hypothesis (Ho) that the number of cuts has no effect on the flank wear and an alternative hypothesis (Ha) that the number of cuts has an effect on flank wear were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis since the P value for this regression is <0.0001. And so it can be concluded that the number of cuts has a significant effect on tool flank wear for the TiN coated tool.

Table 4- 4 Regression of flank wear on number of cuts for TiN coated tool.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: wear

                             Analysis of Variance

                                    Sum of           Mean
Source                   DF        Squares         Square    F Value    Pr > F

Model                     1        0.05062        0.05062     481.16    <.0001
Error                    18        0.00189     0.00010520
Corrected Total          19        0.05251


Root MSE               0.01026    R-Square     0.9639
Dependent Mean         0.30960    Adj R-Sq     0.9619
Coeff Var              3.31295
```

4.2.2 Wear of TiN Coated vs. Uncoated Tool

To compare the performance of the TiN coating, the flank wear of the TiN coated tool was compared with the flank wear of the uncoated tool. Table 4-5 shows the SAS output for the regression of flank-wear on the number of cuts for both TiN coated and the uncoated tools. A null hypothesis (Ho) that the TiN coating has no effect on the flank wear and an alternative hypothesis (Ha) that the TiN coating has an effect on flank-wear were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis since the P value for this regression is <0.0001. And so it can be concluded that the TiN coating has a significant effect on tool flank wear for the TiN coated tool.

The average wear for the TiN coated tool during the 60 cuts, from Table 4-4, is 0.3096 mm whereas the average wear for the uncoated tool is 0.3518 mm as shown in Table 4-1. And so the tool flank wear decreased with the addition of TiN coating.

Table 4- 5 Regression of flank wear on the type of coating for TiN and uncoated.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: wear

                             Analysis of Variance

                                    Sum of           Mean
Source                   DF        Squares         Square    F Value    Pr > F

Model                     2        0.21497        0.10749     128.58    <.0001
Error                    37        0.03093     0.00083597
Corrected Total          39        0.24591


Root MSE              0.02891    R-Square     0.8742
Dependent Mean        0.33069    Adj R-Sq     0.8674
Coeff Var             8.74340
```

4.2.3 Roughness

The machined part surface roughness as a function of number of cuts for the TiN coated tool is shown in Figure 4-5. This figure shows that the surface roughness was relatively constant until around cut number 15. After that the surface roughness oscillated around a constant value. This pattern for the change of surface roughness with cutting is different from that obtained for the machining using the uncoated tool. The TiN coated tool provided a more consistent surface roughness that did not change much over the increase with the number of cuts.

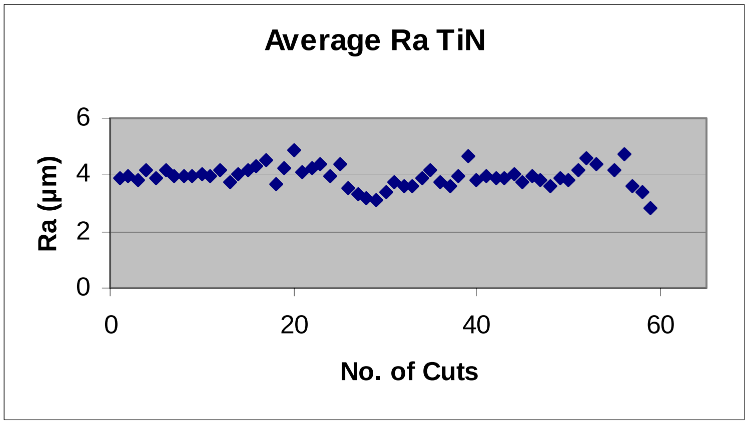


Figure 4- 5 Surface roughness vs. number of cuts for TiN coated tool.

Table 4-6 shows the SAS output for the regression of surface roughness on the number of cuts for the TiN coated tool. A null hypothesis (Ho) that the number of cuts has no effect on the surface roughness and an alternative hypothesis (Ha) that the number of cuts has an effect on surface roughness were used. Again using a α-value of 0.05, the null hypothesis is not rejected in favor of the alternative hypothesis in this case since the P value for this regression is 0.2781, which is larger than 0.05. And so it can be concluded that the number of cuts has no significant effect on surface roughness. This shows that the TiN coated tool provided a consistent surface roughness along the 60 cuts made.

4.2.4 Roughness of TiN Coated vs. Uncoated Tool

To compare the performance of the TiN coating, the machined part surface roughness obtained from the TiN coated tool was compared with the surface roughness obtained from the uncoated tool. Table 4-7 shows the SAS output for the regression of surface roughness on the number of cuts for both TiN coated and the uncoated tools. A null hypothesis (Ho) that the TiN coating has no effect on the surface roughness and an alternative hypothesis (Ha) that the TiN coating has an effect on surface roughness were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis since the P value for this regression is 0.0016. And so it can be concluded that the TiN coating has a significant effect on machined surface roughness for the TiN coated tool.

Table 4- 6 Regression of surface roughness on number of cuts for TiN coated tool.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: roughness

                             Analysis of Variance

                                    Sum of           Mean
Source                   DF        Squares         Square    F Value    Pr > F

Model                     1        0.18148        0.18148       1.20    0.2781
Error                    56        8.47249        0.15129
Corrected Total          57        8.65397


Root MSE              0.38897    R-Square     0.0210
Dependent Mean        3.92974    Adj R-Sq     0.0035
Coeff Var             9.89800
```

The average surface roughness for the TiN coated tool during the 60 cuts, from Table 4-6, is 3.93 μm whereas the average surface roughness for the uncoated tool is 4.20 μm as shown in Table 4-2. And so the surface roughness decreased with the addition of TiN coating.

4.2.5 Roughness vs. Wear

The machined part surface roughness as a function of tool flank-wear for the TiN coated tool is shown in Figure 4-6. This figure shows the oscillation of machined surface roughness around a constant value of approximately 4 µm with increasing tool flank-wear.

Table 4- 7 Regression of surface roughness on the type of coating for TiN and uncoated.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: roughness

                             Analysis of Variance

                                          Sum of           Mean
Source                      DF           Squares         Square    F Value    Pr > F

Model                        2           5.54308        2.77154      13.92    <.0001
Error                      115          22.89573        0.19909
Corrected Total            117          28.43881


Root MSE              0.44620    R-Square     0.1949
Dependent Mean        4.06941    Adj R-Sq     0.1809
Coeff Var            10.96471
```

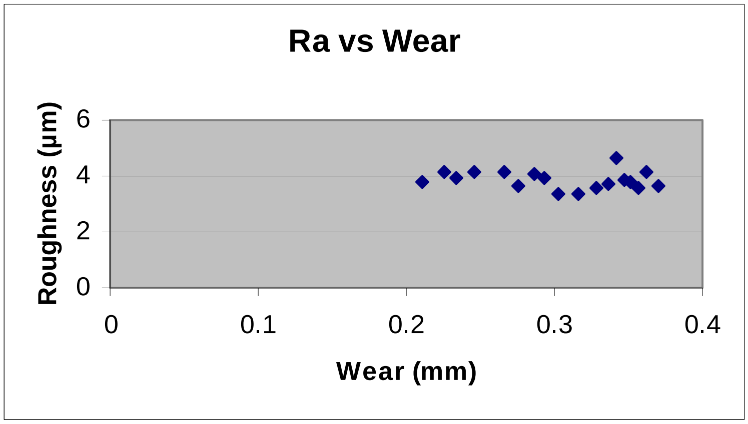


Figure 4- 6 Surface roughness vs. flank wear for TiN coated tool.

Table 4-8 shows the SAS output for the regression of surface roughness on the tool flank-wear for the TiN coated tool. A null hypothesis (Ho) that the tool flank-wear has no effect on the surface roughness and an alternative hypothesis (Ha) that the tool flank wear has an effect on surface roughness were used. Again using a α-value of 0.05, the null hypothesis is not rejected in favor of the alternative hypothesis in this case since the P value for this regression is 0.4206. And so it can be concluded that the flank wear has no significant effect on surface roughness in the case of TiN coated tool.

Table 4- 8 Regression of Surface roughness on flank wear for TiN coated tool.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: roughness

                             Analysis of Variance

                                    Sum of           Mean
Source                    DF       Squares         Square    F Value    Pr > F

Model                      1       0.07296        0.07296       0.68    0.4206
Error                     16       1.70829        0.10677
Corrected Total           17       1.78124


Root MSE             0.32675    R-Square     0.0410
Dependent Mean       3.86444    Adj R-Sq    -0.0190
Coeff Var            8.45538
```

4.3 TiN/Al_2O_3 Coated Carbide Insert

4.3.1 Wear

The flank-wear as a function of the number of cuts for the TiN/Al_2O_3 coated tool is shown in Figure 4-7. From the figure, the flank wear appears to increase with the number of cuts as expected. The wear appears to grow more rapidly at the initial stage up to around cut number 20, and then grows at a lower steady rate from cut number 20 on.

This result shows an initial stage with rapid growth and a second stage with steady lower growth.

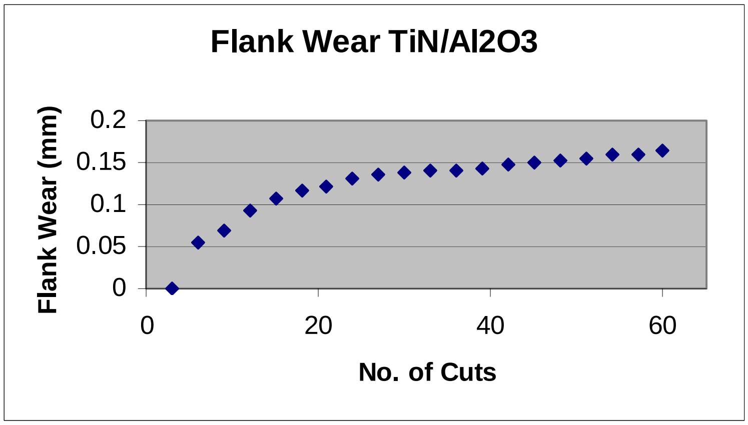


Figure 4- 7 Flank wear vs. number of cuts for TiN/Al_2O_3 coated tool.

Table 4-9 shows the SAS output for the regression of flank-wear on the number of cuts for the TiN/Al_2O_3 coated tool.

Table 4- 9 Regression of flank wear on the number of cuts for TiN/Al_2O_3 coated tool.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: wear

                             Analysis of Variance

                                    Sum of           Mean
Source                   DF        Squares         Square    F Value    Pr > F

Model                     1        0.02479        0.02479      55.34    <.0001
Error                    18        0.00806     0.00044801
Corrected Total          19        0.03286


Root MSE              0.02117    R-Square     0.7546
Dependent Mean        0.12411    Adj R-Sq     0.7409
Coeff Var            17.05507
```

A null hypothesis (Ho) that the number of cuts has no effect on the flank wear and an alternative hypothesis (Ha) that the number of cuts has an effect on flank wear were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis since the P value for this regression is <0.0001. And so it can be concluded that the number of cuts has a significant effect on tool flank wear for the TiN/Al_2O_3 coated tool.

4.3.2 Wear of TiN/Al_2O_3 Coated vs. Uncoated Tool

To compare the performance of the TiN/Al_2O_3 coating, the flank wear of the TiN/Al_2O_3 coated tool was compared with the flank wear of the uncoated tool. Table 4-10 shows the SAS output for the regression of flank-wear on the number of cuts for both TiN/Al_2O_3 coated and the uncoated tools.

Table 4- 10 Regression of flank wear on the type of coating for TiN/Al_2O_3 and uncoated.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: wear

                             Analysis of Variance

                                    Sum of           Mean
Source                   DF        Squares         Square    F Value    Pr > F

Model                     2        0.67538        0.33769     243.07    <.0001
Error                    37        0.05140        0.00139
Corrected Total          39        0.72678


Root MSE              0.03727    R-Square     0.9293
Dependent Mean        0.23794    Adj R-Sq     0.9255
Coeff Var            15.66494
```

A null hypothesis (Ho) that the TiN/Al_2O_3 coating has no effect on the flank wear and an alternative hypothesis (Ha) that the TiN/Al_2O_3 coating has an effect on flank-wear were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis since the P value for this regression is <0.0001. And so it can be concluded that the TiN/Al_2O_3 coating has a significant effect on tool flank wear for the TiN/Al_2O_3 coated tool.

The average wear for the TiN/Al_2O_3 coated tool during the 60 cuts, from Table 4-9, is 0.1241 mm whereas the average wear for the uncoated tool is 0.3518 mm as shown in Table 4-1. And so the tool flank wear decreased with the addition of TiN/Al_2O_3 coating.

4.3.3 Roughness

The machined part surface roughness as a function of number of cuts is shown in Figure 4-8. This figure shows that the surface roughness increased steadily until around cut number 15. After that the surface roughness oscillated while increasing at a lower rate. This pattern for the change of surface roughness with cutting agrees with previous studies and with that obtained for the uncoated tool.

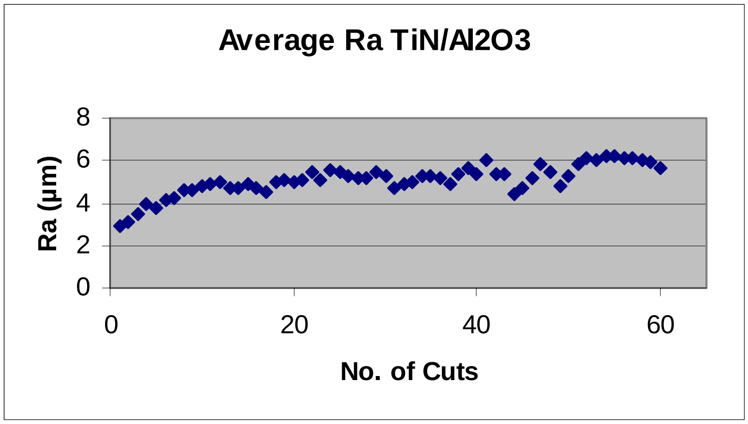


Figure 4- 8 Surface roughness vs. number of cuts for TiN/Al_2O_3 coated tool

Table 4-11 shows the SAS output for the regression of surface roughness on the number of cuts for the TiN/Al_2O_3 coated tool. A null hypothesis (Ho) that the number of cuts has no effect on the surface roughness and an alternative hypothesis (Ha) that the number of cuts has an effect on surface roughness were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis in this case since the P value for this regression is <0.0001. And so it can be concluded that the number of cuts has a significant effect on surface roughness for the TiN/Al_2O_3 coated tool.

Table 4- 11 Regression of surface roughness on number of cuts for TiN/Al_2O_3 coated tool.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: roughness

                             Analysis of Variance

                                    Sum of           Mean
Source                   DF        Squares         Square    F Value    Pr > F

Model                     1       19.13646       19.13646      98.91    <.0001
Error                    58       11.22174        0.19348
Corrected Total          59       30.35820


Root MSE              0.43986    R-Square     0.6304
Dependent Mean        5.09108    Adj R-Sq     0.6240
Coeff Var             8.63984
```

4.3.4 Roughness of TiN/Al_2O_3 Coated vs. Uncoated Tool

To compare the performance of the TiN/Al_2O_3 coating, the machined part surface roughness obtained from the TiN/Al_2O_3 coated tool was compared with the surface roughness obtained from the uncoated tool. Table 4-12 shows the SAS output for the regression of surface roughness on the number of cuts for both TiN/Al_2O_3 coated and the uncoated tools.

Table 4- 12 Regression of surface roughness on type of tool for TiN/Al_2O_3 and uncoated.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: roughness

                             Analysis of Variance

                                    Sum of           Mean
Source                   DF        Squares         Square    F Value    Pr > F

Model                     2       50.27134       25.13567     138.51    <.0001
Error                   117       21.23200        0.18147
Corrected Total         119       71.50334


Root MSE              0.42599    R-Square     0.7031
Dependent Mean        4.64775    Adj R-Sq     0.6980
Coeff Var             9.16558
```

A null hypothesis (Ho) that the TiN/Al_2O_3 coating has no effect on the surface roughness and an alternative hypothesis (Ha) that the TiN/Al_2O_3 coating has an effect on surface roughness were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis since the P value for this regression is <0.0001. And so it can be concluded that the TiN/Al_2O_3 coating has a significant effect on machined surface roughness for the TiN/Al_2O_3 coated tool.

The average surface roughness for the TiN/Al_2O_3 coated tool during the 60 cuts, from Table 4-11, is 5.09 μm whereas the average surface roughness for the uncoated tool is 4.20 μm as shown in Table 4-2. And so the surface roughness increased with the addition of TiN/Al_2O_3 coating. The addition of coating materials is shown to decrease surface roughness in many previous experiments. And some other factor connected with chip formation should be the reason for it, since this tool tended to produce long chips that curled around the machined part during machining. The reason for this was the different chip breaking geometry that this tool had compared to the others.

4.3.5 Roughness Vs. Wear

The machined part surface roughness as a function of tool flank wear is shown in Figure 4-9. This figure shows the increase of machined surface roughness with increasing tool flank wear.

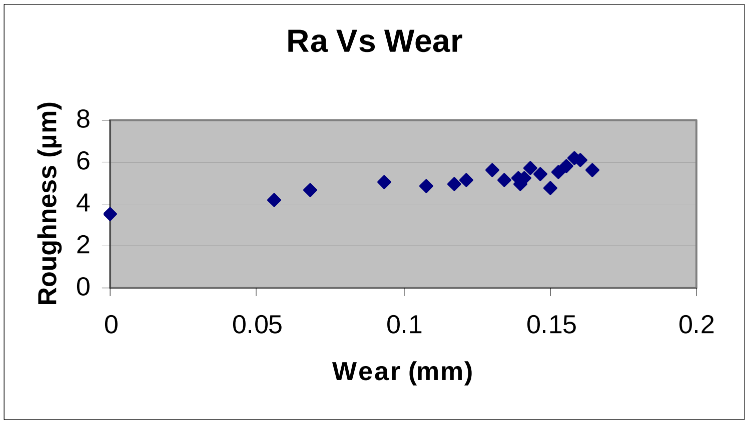


Figure 4- 9 Roughness vs. wear for TiN/Al_2O_3 coated tool.

Table 4-13 shows the SAS output for the regression of surface roughness on the tool flank-wear for the TiN/Al_2O_3 coated tool. A null hypothesis (Ho) that the tool flank-wear has no effect on the surface roughness and an alternative hypothesis (Ha) that the tool flank wear has an effect on surface roughness were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis since the P value for this regression is <0.0001. And so it can be concluded that the flank wear has a significant effect on surface roughness for the TiN/Al_2O_3 coated tool.

Table 4- 13 Regression of surface roughness on flank wear for TiN/Al_2O_3 coated tool.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: roughness

                             Analysis of Variance

                                    Sum of           Mean
Source                   DF        Squares         Square    F Value    Pr > F

Model                     1        5.96597        5.96597      60.63    <.0001
Error                    18        1.77121        0.09840
Corrected Total          19        7.73717


Root MSE              0.31369    R-Square     0.7711
Dependent Mean        5.18025    Adj R-Sq     0.7584
Coeff Var             6.05547
```

4.4 Al_2O_3 Coated Carbide Insert

4.4.1 Wear

The flank-wear as a function of the number of cuts for the Al_2O_3 coated tool is shown in Figure 4-10. From the figure, the flank wear did not appear until cut number 42. However, the flank wear appears to increase after that with the number of cuts as expected. For 60 cuts, only the initial stage of rapid wear growth can be observed. This delay in wear is due to the superior wear resistance of the Al_2O_3 coating at high speeds, and is in accordance with previous studies performed on this type of coated tool.

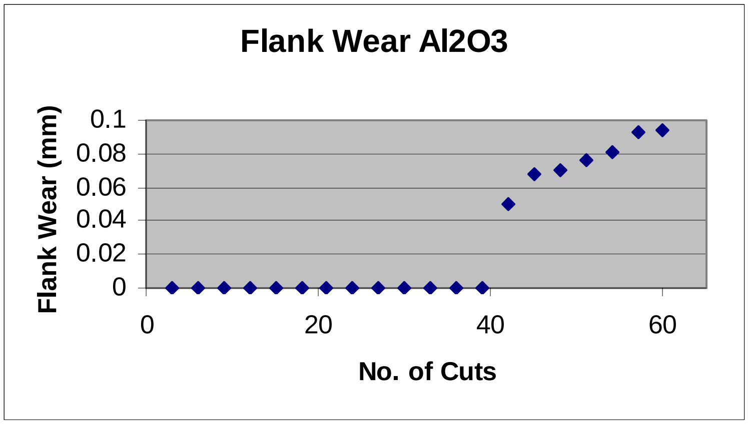


Figure 4- 10 Flank wear vs. number of cuts for Al_2O_3 coated tool.

Table 4-14 shows the SAS output for the regression of flank-wear on the number of cuts for the Al_2O_3 coated tool.

Table 4- 14 Regression of flank wear on number of cuts for Al_2O_3 coated tool.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: wear

                             Analysis of Variance

                                    Sum of           Mean
Source                   DF        Squares         Square    F Value    Pr > F

Model                     1        0.02007        0.02007      47.22    <.0001
Error                    18        0.00765     0.00042508
Corrected Total          19        0.02772


Root MSE            0.02062    R-Square     0.7240
Dependent Mean      0.02661    Adj R-Sq     0.7087
Coeff Var          77.47997
```

A null hypothesis (Ho) that the number of cuts has no effect on the flank wear and an alternative hypothesis (Ha) that the number of cuts has an effect on flank wear were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis since the P value for this regression is <0.0001. And so it can be concluded that the number of cuts has a significant effect on tool flank wear for the Al_2O_3 coated tool.

4.4.2 Wear Al_2O_3 vs. Uncoated

To compare the performance of the Al_2O_3 coating, the flank wear of the Al_2O_3 coated tool was compared with the flank wear of the uncoated tool. Table 4-15 shows the SAS output for the regression of flank-wear on the number of cuts for both Al_2O_3 coated and the uncoated tools.

Table 4- 15 Regression of flank wear on type of tool for Al_2O_3 and uncoated.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: wear

                             Analysis of Variance

                                    Sum of           Mean
Source                   DF        Squares         Square    F Value    Pr > F

Model                     2        1.20563        0.60282     405.60    <.0001
Error                    37        0.05499        0.00149
Corrected Total          39        1.26062


Root MSE              0.03855    R-Square     0.9564
Dependent Mean        0.18919    Adj R-Sq     0.9540
Coeff Var            20.37718
```

A null hypothesis (Ho) that the Al_2O_3 coating has no effect on the flank wear and an alternative hypothesis (Ha) that the Al_2O_3 coating has an effect on flank-wear were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis since the P value for this regression is <0.0001. And so it can be concluded that the Al_2O_3 coating has a significant effect on tool flank wear for the Al_2O_3 coated tool.

The average wear for the Al_2O_3 coated tool during the 60 cuts, from Table 4-14, is 0.0266 mm whereas the average wear for the uncoated tool is 0.3518 mm as shown in Table 4-1. And so the tool flank wear decreased with the addition of Al_2O_3 coating.

4.4.3 Roughness

The machined part surface roughness as a function of number of cuts is shown in Figure 4-11. This figure shows that the surface roughness oscillates while increasing. An initial steady growth of surface roughness is not observed when machining using this type of tool, as was observed for the previous three tools. This could be due to the higher wear-resistance and the delay of wear formation on the flank face of the Al_2O_3 coated tool.

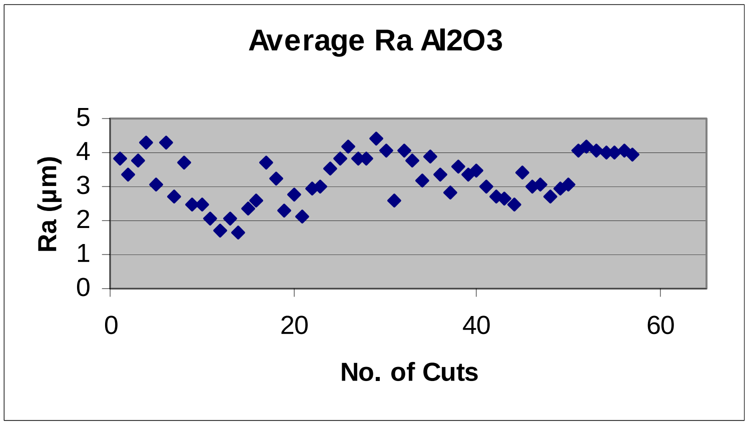


Figure 4- 11 Surface roughness vs. number of cuts for Al_2O_3 coated tool.

Table 4-16 shows the SAS output for the regression of surface roughness on the number of cuts for the Al_2O_3 coated tool. A null hypothesis (Ho) that the number of cuts has no effect on the surface roughness and an alternative hypothesis (Ha) that the number of cuts has an effect on surface roughness were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis in this case since the P value for this regression is 0.0499. And so it can be concluded that the number of cuts has a significant effect on surface roughness for the Al_2O_3 coated tool.

Table 4- 16 Regression of surface roughness on number of cuts for Al_2O_3 coated tool

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: roughness

                             Analysis of Variance

                                    Sum of           Mean
Source                   DF        Squares         Square    F Value    Pr > F

Model                     1        1.95857        1.95857       4.02    0.0499
Error                    55       26.79148        0.48712
Corrected Total          56       28.75006


Root MSE              0.69794    R-Square     0.0681
Dependent Mean        3.25237    Adj R-Sq     0.0512
Coeff Var            21.45939
```

4.4.4 Roughness Al_2O_3 vs. Uncoated

To compare the performance of the Al_2O_3 coating, the machined part surface roughness obtained from the Al_2O_3 coated tool was compared with the surface roughness obtained from the uncoated tool. Table 4-17 shows the SAS output for the regression of surface roughness on the number of cuts for both Al_2O_3 coated and the uncoated tools. A null hypothesis (Ho) that the Al_2O_3 coating has no effect on the surface roughness and an alternative hypothesis (Ha) that the Al_2O_3 coating has an effect on surface roughness were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis since the P value for this regression is <0.0001. And so it can be concluded that the Al_2O_3 coating has a significant effect on machined surface roughness for the Al_2O_3 coated tool.

The average surface roughness for the Al_2O_3 coated tool during the 60 cuts, from Table 4-16, is 3.25 μm whereas the average surface roughness for the uncoated tool is 4.20 μm as shown in Figure 4-2. And so the surface roughness decreased with the addition of Al_2O_3 coating.

Table 4- 17 Regression of surface roughness on type of tool for Al_2O_3 and uncoated.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: roughness

                             Analysis of Variance

                                    Sum of           Mean
Source                   DF        Squares         Square    F Value    Pr > F

Model                     2       36.11421       18.05710      56.11    <.0001
Error                   114       36.69030        0.32184
Corrected Total         116       72.80451


Root MSE              0.56731    R-Square     0.4960
Dependent Mean        3.74060    Adj R-Sq     0.4872
Coeff Var            15.16639
```

4.4.5 Roughness vs. Wear

The machined part surface roughness as a function of tool flank wear is shown in Figure 4-12. This figure does not show a clear pattern for the surface roughness against flank-wear since the flank-wear was delayed in machining. However, the surface roughness appears to oscillate while increasing after the appearance of flank-wear.

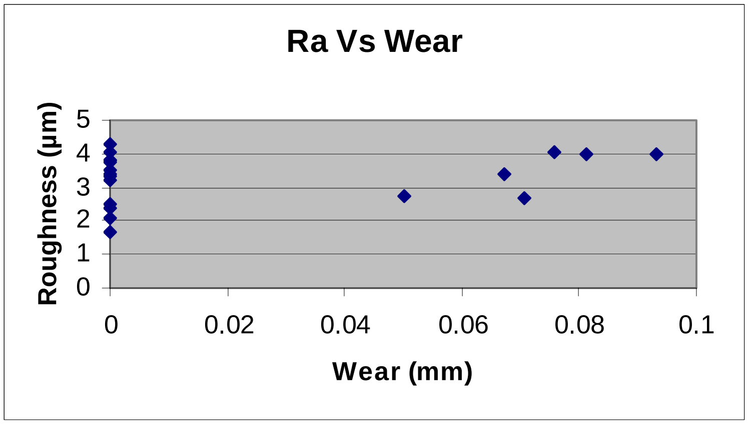


Figure 4- 12 Surface roughness vs. flank wear for Al_2O_3 coated tool.

Table 4-18 shows the SAS output for the regression of surface roughness on the tool flank-wear for the Al_2O_3 coated tool.

Table 4- 18 Regression of surface roughness on flank wear for Al_2O_3 coated tool.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: roughness

                             Analysis of Variance

                                     Sum of           Mean
Source                   DF         Squares         Square    F Value    Pr > F

Model                     1         0.56098        0.56098       1.01    0.3300
Error                    17         9.48138        0.55773
Corrected Total          18        10.04237


Root MSE                0.74681    R-Square     0.0559
Dependent Mean          3.29289    Adj R-Sq     0.0003
Coeff Var              22.67950
```

A null hypothesis (Ho) that the tool flank-wear has no effect on the surface roughness and an alternative hypothesis (Ha) that the tool flank wear has an effect on surface roughness were used. Again using a α-value of 0.05, the null hypothesis is not rejected in favor of the alternative hypothesis in this case since the P value for this regression is 0.3300. And so it can be concluded that the flank wear has no significant effect on surface roughness for the Al_2O_3 coated tool. This is due to the high wear resistance of the Al_2O_3 and the delay of the appearance of the flank wear.

4.5 TiC/Al_2O_3/TiN Coated Carbide Insert

4.5.1 Wear

The flank-wear as a function of the number of cuts for the TiC/Al_2O_3/TiN coated tool is shown in Figure 4-13. From the figure, the flank wear did not appear until cut number 49. However, the flank wear appears to increase after that with the number of cuts as expected. For 60 cuts, only the initial stage of rapid wear growth can be observed. This delay in wear is again due to the superior wear resistance of the TiC/Al_2O_3/TiN coating at high speeds, and is in accordance with previous studies performed.

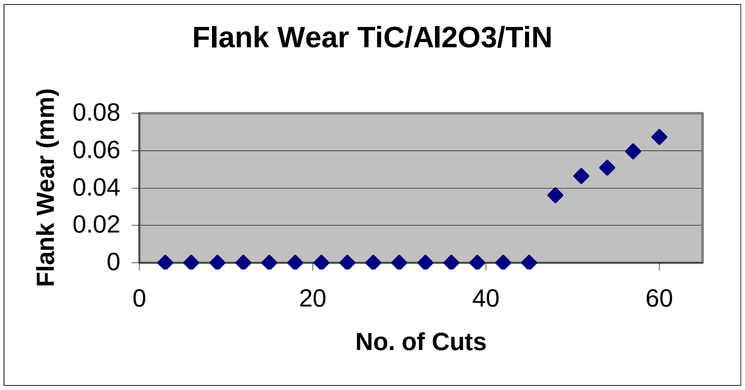


Figure 4- 13 Flank wear vs. number of cuts for TiC/Al_2O_3/TiN coated tool.

Table 4-19 shows the SAS output for the regression of flank-wear on the number of cuts for the TiC/Al_2O_3/TiN coated tool. A null hypothesis (Ho) that the number of cuts has no effect on the flank wear and an alternative hypothesis (Ha) that the number of cuts has an effect on flank wear were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis since the P value for this regression is 0.0001. And so it can be concluded that the number of cuts has a significant effect on tool flank wear for the TiC/Al_2O_3/TiN coated tool.

Table 4- 19 Regression of flank wear on number of cuts for TiC/Al_2O_3/TiN coated tool.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: wear

                             Analysis of Variance

                                    Sum of           Mean
Source                    DF       Squares         Square    F Value    Pr > F

Model                      1       0.00619        0.00619      24.43    0.0001
Error                     18       0.00456     0.00025330
Corrected Total           19       0.01075


Root MSE              0.01592    R-Square     0.5758
Dependent Mean        0.01302    Adj R-Sq     0.5522
Coeff Var           122.23709
```

4.5.2 Wear TiC/Al_2O_3/TiN vs. Uncoated

To compare the performance of the TiC/Al_2O_3/TiN coating, the flank wear of the TiC/Al_2O_3/TiN coated tool was compared with the flank wear of the uncoated tool. Table4-20 shows the SAS output for the regression of flank-wear on the number of cuts for both TiC/Al_2O_3/TiN coated and the uncoated tools. A null hypothesis (Ho) that the TiC/Al_2O_3/TiN coating has no effect on the flank wear and an alternative hypothesis (Ha) that the TiC/Al_2O_3/TiN coating has an effect on flank-wear were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis since the P value for this regression is <0.0001. And so it can be concluded that the $TiC/Al_2O_3/TiN$ coating has a significant effect on tool flank wear for the $TiC/Al_2O_3/TiN$ coated tool.

The average wear for the $TiC/Al_2O_3/TiN$ coated tool during the 60 cuts, from Table 4-19, is 0.0130 mm whereas the average wear for the uncoated tool is 0.3518 mm as shown in Table 4-1. And so the tool flank wear decreased with the addition of $TiC/Al_2O_3/TiN$ coating.

Table 4- 20 Regression of flank wear on tool type for $TiC/Al_2O_3/TiN$ and uncoated.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: wear

                             Analysis of Variance

                                    Sum of           Mean
Source                   DF        Squares         Square    F Value    Pr > F

Model                     2        1.26352        0.63176     332.26    <.0001
Error                    37        0.07035        0.00190
Corrected Total          39        1.33387


Root MSE              0.04361    R-Square     0.9473
Dependent Mean        0.18240    Adj R-Sq     0.9444
Coeff Var            23.90691
```

4.5.3 Roughness

The machined part surface roughness as a function of number of cuts is shown in Figure 4-14. This figure shows that the surface roughness oscillates while increasing slowly. This could be due to the higher wear-resistance and the delay of wear formation on the flank face of the TiC/Al_2O_3/TiN coated tool, where the flank wear was very small during the 60 cuts machined, in order for the surface roughness to increase significantly.

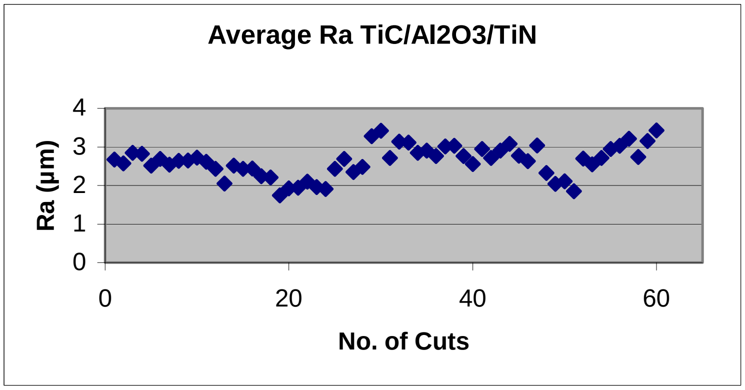


Figure 4- 14 Surface roughness vs. number of cuts for TiC/Al_2O_3/TiN coated tool.

Table 4-21 shows the SAS output for the regression of surface roughness on the number of cuts for the TiC/Al_2O_3/TiN coated tool.

Table 4- 21 Regression of surface roughness on number of cuts for TiC/Al_2O_3/TiN coated tool.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: roughness

                             Analysis of Variance

                                    Sum of           Mean
Source                   DF        Squares         Square    F Value    Pr > F

Model                     1        0.92569        0.92569       6.26    0.0152
Error                    58        8.57220        0.14780
Corrected Total          59        9.49789


Root MSE              0.38444    R-Square     0.0975
Dependent Mean        2.62550    Adj R-Sq     0.0819
Coeff Var            14.64266
```

A null hypothesis (Ho) that the number of cuts has no effect on the surface roughness and an alternative hypothesis (Ha) that the number of cuts has an effect on surface roughness were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis in this case since the P value for this regression is 0.0152. And so it can be concluded that the number of cuts has a significant effect on surface roughness for the TiC/Al_2O_3/TiN coated tool.

4.5.4 Roughness TiC/Al_2O_3/TiN Coated vs. Uncoated Tool

To compare the performance of the TiC/Al_2O_3/TiN coating, the machined part surface roughness obtained from the TiC/Al_2O_3/TiN coated tool was compared with the surface roughness obtained from the uncoated tool. Table 4-22 shows the SAS output for the regression of surface roughness on the number of cuts for both TiC/Al_2O_3/TiN coated and the uncoated tools.

Table 4- 22 Regression of surface roughness on type of tool for TiC/Al_2O_3/TiN and uncoated.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: roughness

                             Analysis of Variance

                                    Sum of           Mean
Source                   DF        Squares         Square    F Value    Pr > F

Model                     2       82.36791       41.18395     247.37    <.0001
Error                   117       19.47912        0.16649
Corrected Total         119      101.84702


Root MSE            0.40803    R-Square     0.8087
Dependent Mean      3.41496    Adj R-Sq     0.8055
Coeff Var          11.94830
```

A null hypothesis (Ho) that the TiC/Al_2O_3/TiN coating has no effect on the surface roughness and an alternative hypothesis (Ha) that the TiC/Al_2O_3/TiN coating has an effect on surface roughness were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis since the P value for this regression is <0.0001. And so it can be concluded that the TiC/Al_2O_3/TiN coating has a significant effect on machined surface roughness for the TiC/Al_2O_3/TiN coated tool.

The average surface roughness for the TiC/Al_2O_3/TiN coated tool during the 60 cuts, from Table 4-21, is 2.63 µm whereas the average surface roughness for the uncoated tool is 4.20 µm as shown in Table 4-1. And so the surface roughness decreased with the addition of TiC/Al_2O_3/TiN coating.

4.5.5 Roughness vs. Wear

The machined part surface roughness as a function of tool flank wear is shown in Figure 4-15. Again, the figure does not show a clear pattern for the surface roughness against flank-wear since the flank wear was delayed in machining. The surface roughness oscillated before the appearance of flank-wear. However, there appears an increase in surface roughness with increase in wear once the wear developed.

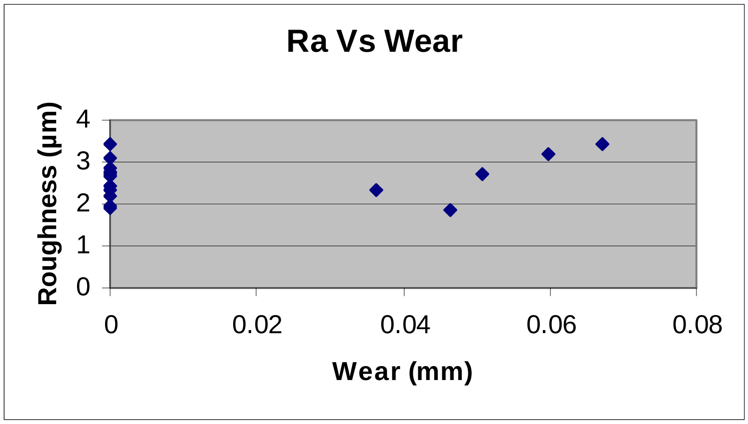


Figure 4- 15 Surface roughness vs. flank wear for TiC/Al_2O_3/TiN coated tool.

Table 4-23 shows the SAS output for the regression of surface roughness on the tool flank-wear for the TiC/Al_2O_3/TiN coated tool.

Table 4- 23 Regression of surface roughness on flank wear for TiC/Al_2O_3/TiN coated tool

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: roughness

                             Analysis of Variance

                                    Sum of           Mean
Source                   DF        Squares         Square    F Value    Pr > F

Model                     1        0.19531        0.19531       0.93    0.3479
Error                    18        3.78501        0.21028
Corrected Total          19        3.98032


Root MSE              0.45856    R-Square     0.0491
Dependent Mean        2.62700    Adj R-Sq    -0.0038
Coeff Var            17.45570
```

A null hypothesis (Ho) that the tool flank-wear has no effect on the surface roughness and an alternative hypothesis (Ha) that the tool flank wear has an effect on surface roughness were used. Again using a α-value of 0.05, the null hypothesis is not rejected in favor of the alternative hypothesis in this case since the P value for this regression is 0.3479. And so it can be concluded that the flank wear has no significant effect on surface roughness for the TiC/Al_2O_3/TiN coated tool. This is due to the high wear resistance of the TiC/Al_2O_3/TiN and the delay of the appearance of the flank wear.

4.6 Comparison of the Coated Carbide Inserts

4.6.1 TiN and TiN/Al_2O_3

Table 4-24 shows the SAS output for the regression of flank-wear on the number of cuts for both TiN and TiN/Al_2O_3 coated tools. A null hypothesis (Ho) that the difference in coating has no effect on the flank wear and an alternative hypothesis (Ha) that the difference in coating has an effect on flank-wear were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis since the P value for this regression is <0.0001. And so it can be concluded that the difference in coating has a significant effect on tool flank wear.

The average wear for the TiN/Al_2O_3 coated tool during the 60 cuts, from Table 4-9, is 0.1241 mm whereas the average wear for the TiN coated tool is 0.3096 mm as shown in Table 4-4. And so the tool flank-wear decreased when using TiN/Al_2O_3 coating compared to TiN coating.

Table 4- 24 Regression of flank wear on tool type for TiN and TiN/Al_2O_3.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: wear

                             Analysis of Variance

                                    Sum of           Mean
Source                    DF       Squares         Square    F Value    Pr > F

Model                      2       0.41722        0.20861     630.72    <.0001
Error                     37       0.01224     0.00033075
Corrected Total           39       0.42946


Root MSE             0.01819    R-Square     0.9715
Dependent Mean       0.21685    Adj R-Sq     0.9700
Coeff Var            8.38659
```

Table 4-25 shows the SAS output for the regression of surface roughness on the number of cuts for both TiN/Al_2O_3 and TiN coated tools. A null hypothesis (Ho) that the change in coating has no effect on the surface roughness and an alternative hypothesis (Ha) that the change in coating has an effect on surface roughness were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis since the P value for this regression is <0.0001. And so it can be concluded that the change in coating has a significant effect on machined surface roughness.

The average surface roughness for the TiN/Al_2O_3 coated tool during the 60 cuts, from Table 4-11, is 5.09 μm whereas the average surface roughness for the TiN coated tool is 3.93 μm as shown in Table 4-6. And so the surface roughness increased when using TiN/Al_2O_3 coating compared to TiN coating.

Table 4- 25 Regression of surface roughness on tool type for TiN and TiC/Al_2O_3/TiN.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: roughness

                             Analysis of Variance

                                       Sum of           Mean
Source                   DF           Squares         Square    F Value    Pr > F

Model                     2          47.97662       23.98831      89.53    <.0001
Error                   115          30.81122        0.26792
Corrected Total         117          78.78784


Root MSE              0.51761    R-Square     0.6089
Dependent Mean        4.52025    Adj R-Sq     0.6021
Coeff Var            11.45098
```

4.6.2 TiN and Al_2O_3

Table 4-26 shows the SAS output for the regression of flank-wear on the number of cuts for both TiN and Al_2O_3 coated tools. A null hypothesis (Ho) that the difference in coating has no effect on the flank wear and an alternative hypothesis (Ha) that the difference in coating has an effect on flank-wear were used. Again using a α-value of

0.05, the null hypothesis is rejected in favor of the alternative hypothesis since the P value for this regression is <0.0001. And so it can be concluded that the difference in coating has a significant effect on tool flank wear.

The average wear for the Al_2O_3 coated tool during the 60 cuts, from Table 4-14, is 0.02661 mm whereas the average wear for the TiN coated tool is 0.30960 mm as shown in Table 4-4. And so the tool flank-wear decreased when using Al_2O_3 coating compared to TiN coating.

Table 4- 26 Regression of flank wear on tool type for TiN and Al_2O_3.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: wear

                             Analysis of Variance

                                    Sum of           Mean
Source                  DF         Squares         Square    F Value    Pr > F

Model                    2         0.86805        0.43403    1233.84    <.0001
Error                   37         0.01302     0.00035177
Corrected Total         39         0.88107


Root MSE              0.01876    R-Square     0.9852
Dependent Mean        0.16811    Adj R-Sq     0.9844
Coeff Var            11.15702
```

Table 4-27 shows the SAS output for the regression of surface roughness on the number of cuts for both Al_2O_3 and TiN coated tools. A null hypothesis (Ho) that the change in coating has no effect on the surface roughness and an alternative hypothesis (Ha) that the change in coating has an effect on surface roughness were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis since the P value for this regression is <0.0001. And so it can be concluded that the change in coating has a significant effect on machined surface roughness.

The average surface roughness for the Al_2O_3 coated tool during the 60 cuts, from Table 4-16, is 3.25 µm whereas the average surface roughness for the TiN coated tool is 3.93 µm as shown in Table 4-6. And so the surface roughness decreased when using Al_2O_3 coating compared to TiN coating.

Table 4- 27 Regression of surface roughness on tool type for TiN and Al_2O_3.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: roughness

                             Analysis of Variance

                                    Sum of           Mean
Source                   DF        Squares         Square    F Value    Pr > F

Model                     2       13.63419        6.81710      20.66    <.0001
Error                   112       36.96032        0.33000
Corrected Total         114       50.59451


Root MSE              0.57446    R-Square     0.2695
Dependent Mean        3.59400    Adj R-Sq     0.2564
Coeff Var            15.98383
```

4.6.3 TiN and TiC/Al_2O_3/TiN

Table 4-28 shows the SAS output for the regression of flank-wear on the number of cuts for both TiN and TiC/Al_2O_3/TiN coated tools. A null hypothesis (Ho) that the difference in coating has no effect on the flank wear and an alternative hypothesis (Ha) that the difference in coating has an effect on flank-wear were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis since the P value for this regression is <0.0001. And so it can be concluded that the difference in coating has a significant effect on tool flank wear.

The average wear for the TiC/Al_2O_3/TiN coated tool during the 60 cuts, from Table 4-19, is 0.01302 mm whereas the average wear for the TiN coated tool is 0.30960 mm as shown in Table 4-4. And so the tool flank wear decreased when using TiC/Al_2O_3/TiN coating compared to TiN coating.

Table 4- 28 Regression of flank wear on tool type for TiN and TiC/Al_2O_3/TiN.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: wear

                             Analysis of Variance

                                    Sum of           Mean
Source                   DF        Squares         Square    F Value    Pr > F

Model                     2        0.92570        0.46285     998.06    <.0001
Error                    37        0.01716     0.00046375
Corrected Total          39        0.94286


Root MSE              0.02153    R-Square     0.9818
Dependent Mean        0.16131    Adj R-Sq     0.9808
Coeff Var            13.34995
```

Table 4-29 shows the SAS output for the regression of surface roughness on the number of cuts for both TiC/Al_2O_3/TiN and TiN coated tools. A null hypothesis (Ho) that the change in coating has no effect on the surface roughness and an alternative hypothesis (Ha) that the change in coating has an effect on surface roughness were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis since the P value for this regression is <0.0001. And so it can be concluded that the change in coating has a significant effect on machined surface roughness.

The average surface roughness for the TiC/Al_2O_3/TiN coated tool during the 60 cuts, from Table 4-21, is 2.63 µm whereas the average surface roughness for the TiN coated tool is 3.93 µm as shown in Table 4-6. And so the surface roughness decreased when using TiC/Al_2O_3/TiN coating compared to TiN coating.

Table 4- 29 Regression of surface roughness on tool type for TiN and TiC/Al_2O_3/TiN.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: roughness

                             Analysis of Variance

                                    Sum of           Mean
Source                   DF        Squares         Square    F Value    Pr > F

Model                     2       50.32637       25.16319     160.84    <.0001
Error                   115       17.99191        0.15645
Corrected Total         117       68.31828


Root MSE              0.39554    R-Square     0.7366
Dependent Mean        3.26657    Adj R-Sq     0.7321
Coeff Var            12.10872
```

4.6.4 TiN/Al_2O_3 and Al_2O_3

Table 4-30 shows the SAS output for the regression of flank-wear on the number of cuts for both TiN/Al_2O_3 and Al_2O_3 coated tools. A null hypothesis (Ho) that the difference in coating has no effect on the flank wear and an alternative hypothesis (Ha) that the difference in coating has an effect on flank-wear were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis since the P value for this regression is <0.0001. And so it can be concluded that the difference in coating has a significant effect on tool flank wear.

The average wear for the TiN/Al_2O_3 coated tool during the 60 cuts, from Table 4-9, is 0.1241 mm whereas the average wear for the Al_2O_3 coated tool is 0.0266 mm as shown in Table 4-14. And so the tool flank wear decreased when using Al_2O_3 coating compared to TiN/Al_2O_3 coating.

Table 4- 30 Regression of flank wear on tool type for TiN/Al_2O_3 and Al_2O_3.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: wear

                             Analysis of Variance

                                    Sum of           Mean
Source                   DF        Squares         Square    F Value    Pr > F

Model                     2        0.13979        0.06990     163.27    <.0001
Error                    37        0.01584     0.00042811
Corrected Total          39        0.15563


Root MSE            0.02069    R-Square     0.8982
Dependent Mean      0.07536    Adj R-Sq     0.8927
Coeff Var          27.45693
```

Table 4-31 shows the SAS output for the regression of surface roughness on the number of cuts for both TiN/Al_2O_3 and Al_2O_3 coated tools. A null hypothesis (Ho) that the change in coating has no effect on the surface roughness and an alternative hypothesis (Ha) that the change in coating has an effect on surface roughness were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis since the P value for this regression is <0.0001. And so it can be concluded that the change in coating has a significant effect on machined surface roughness.

The average surface roughness for the TiN/Al_2O_3 coated tool during the 60 cuts, from Table 4-11, is 5.09 µm whereas the average surface roughness for the Al_2O_3 coated tool is 3.25 μm as shown in Table 4-16. And so the surface roughness decreased when using Al_2O_3 coating compared to TiN/Al_2O_3 coating.

Table 4- 31 Regression of surface roughness on tool type for TiN/Al_2O_3 and Al_2O_3.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: roughness

                             Analysis of Variance

                                    Sum of           Mean
Source                   DF        Squares         Square    F Value    Pr > F

Model                     2      116.13670       58.06835     158.38    <.0001
Error                   114       41.79706        0.36664
Corrected Total         116      157.93376


Root MSE              0.60551    R-Square     0.7354
Dependent Mean        4.19530    Adj R-Sq     0.7307
Coeff Var            14.43303
```

4.6.5 TiN/Al_2O_3 and $TiC/Al_2O_3/TiN$

Table 4-32 shows the SAS output for the regression of flank-wear on the number of cuts for both TiN/Al_2O_3 and $TiC/Al_2O_3/TiN$ coated tools. A null hypothesis (Ho) that the difference in coating has no effect on the flank wear and an alternative hypothesis (Ha) that the difference in coating has an effect on flank-wear were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis since the P value for this regression is <0.0001. And so it can be concluded that the difference in coating has a significant effect on tool flank wear.

The average wear for the TiN/Al_2O_3 coated tool during the 60 cuts, from Table 4-9, is 0.1241 mm whereas the average wear for the $TiC/Al_2O_3/TiN$ coated tool is 0.0130 mm as shown in Table 4-19. And so the tool flank wear decreased when using TiC/Al_2O_3/TiN coating compared to TiN/Al_2O_3 coating.

Table 4- 32 Regression of flank wear on tool type for TiN/Al_2O_3 and TiC/Al2O3/TiN.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: wear

                             Analysis of Variance

                                    Sum of           Mean
Source                    DF       Squares         Square    F Value    Pr > F

Model                      2       0.15128        0.07564     177.94    <.0001
Error                     37       0.01573     0.00042509
Corrected Total           39       0.16700


Root MSE              0.02062    R-Square     0.9058
Dependent Mean        0.06856    Adj R-Sq     0.9007
Coeff Var            30.07124
```

Table 4-33 shows the SAS output for the regression of surface roughness on the number of cuts for both TiN/Al_2O_3 and TiC/Al_2O_3/TiN coated tools. A null hypothesis (Ho) that the change in coating has no effect on the surface roughness and an alternative hypothesis (Ha) that the change in coating has an effect on surface roughness were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis since the P value for this regression is <0.0001. And so it can be concluded that the change in coating has a significant effect on machined surface roughness.

The average surface roughness for the TiN/Al_2O_3 coated tool during the 60 cuts, from Table 4-11, is 5.09 μm whereas the average surface roughness for the

TiC/Al_2O_3/TiN coated tool is 2.63 μm as shown in Table 4-21. And so the surface roughness decreased when using TiC/Al_2O_3/TiN coating compared to TiN/Al_2O_3 coating.

Table 4- 33 Regression of surface roughness on tool type for TiN/Al_2O_3 and TiC/Al2O3/TiN.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: roughness

                             Analysis of Variance

                                    Sum of           Mean
Source                  DF         Squares         Square    F Value    Pr > F

Model                    2       196.61296       98.30648     449.01    <.0001
Error                  117        25.61616        0.21894
Corrected Total        119       222.22912


Root MSE              0.46791    R-Square     0.8847
Dependent Mean        3.85829    Adj R-Sq     0.8828
Coeff Var            12.12744
```

4.6.6 Al_2O_3 and TiC/Al2O3/TiN

Table 4-34 shows the SAS output for the regression of flank-wear on the number of cuts for both Al_2O_3 and TiC/Al_2O_3/TiN coated tools. A null hypothesis (Ho) that the difference in coating has no effect on the flank wear and an alternative hypothesis (Ha) that the difference in coating has an effect on flank-wear were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis since the P value for this regression is 0.0346. And so it can be concluded that the difference in coating has a significant effect on tool flank wear.

The average wear for the Al_2O_3 coated tool during the 60 cuts, from Table 4-14, is 0.0266 mm whereas the average wear for the TiC/Al_2O_3/TiN coated tool is 0.0130 mm as shown in Table 4-19. And so the tool flank wear decreased when using TiC/Al_2O_3/TiN coating compared to Al_2O_3 coating.

Table 4- 34 Regression of flank wear on tool type for Al_2O_3 and TiC/Al_2O_3/TiN.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: wear

                             Analysis of Variance

                                    Sum of           Mean
Source                   DF        Squares         Square    F Value    Pr > F

Model                     2        0.02612        0.01306      34.04    <.0001
Error                    37        0.01420     0.00038368
Corrected Total          39        0.04032


Root MSE              0.01959    R-Square     0.6479
Dependent Mean        0.01982    Adj R-Sq     0.6289
Coeff Var            98.85315
```

Table 4-35 shows the SAS output for the regression of surface roughness on the number of cuts for both Al_2O_3 and TiC/Al_2O_3/TiN coated tools. A null hypothesis (Ho) that the change in coating has no effect on the surface roughness and an alternative hypothesis (Ha) that the change in coating has an effect on surface roughness were used. Again using a α-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis since the P value for this regression is <0.0001. And so it can be concluded that the change in coating has a significant effect on machined surface roughness.

The average surface roughness for the Al_2O_3 coated tool during the 60 cuts, from Table 4-16, is 3.25 μm whereas the average surface roughness for the TiC/Al_2O_3/TiN coated tool is 2.63 μm as shown in Table 4-21. And so the surface roughness decreased when using TiC/Al_2O_3/TiN coating compared to Al_2O_3 coating.

Table 4- 35 Regression of surface roughness on tool type for Al_2O_3 and $TiC/Al_2O_3/TiN$.

```
The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: roughness

                             Analysis of Variance

                                    Sum of           Mean
Source                   DF        Squares         Square    F Value    Pr > F

Model                     2       14.23162        7.11581      22.85    <.0001
Error                   114       35.50296        0.31143
Corrected Total         116       49.73458


Root MSE              0.55806    R-Square     0.2862
Dependent Mean        2.93090    Adj R-Sq     0.2736
Coeff Var            19.04054
```

4.7 Discussion

The flank wear for the five different types of cutting tools tested are shown in Figure 4-16. The uncoated tool exhibited the largest wear within the 60 cuts machined in the test. All the coated tools were observed to have better wear resistance than the uncoated tool as expected.

The TiN coated tool showed a slight improvement compared to the uncoated tool. This is because of the added wear resistance of the TiN coating. The TiN/Al_2O_3 had the third highest flank wear. The improvement of the wear resistance compared to the TiN coating was due to the addition of the Al_2O_3 layer. This layer protected the TiN coating by preventing diffusion of oxygen and by dissipation of heat via chip removal due to its low thermal conductivity.

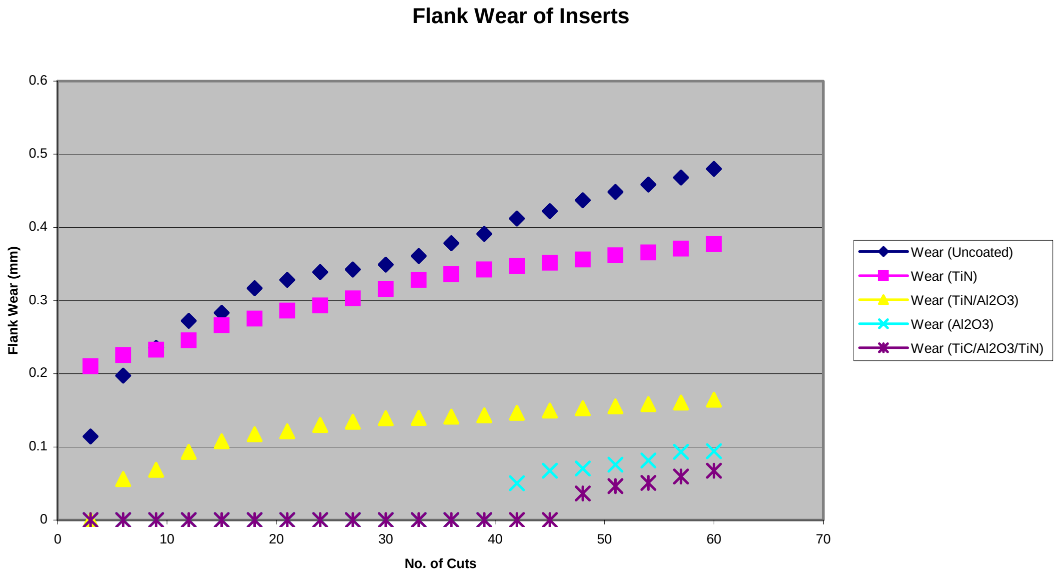


Figure 4- 16 Flank wear vs. number of cuts for different cutting tools.

However, the Al_2O_3 coating had the second highest flank wear resistance and showed an improvement in wear resistance as compared to TiN/Al_2O_3. Hence, using one layer of Al_2O_3 appears to have better wear resistance to flank wear as compared to using 2 layers of coating with TiN interlayer and Al_2O_3 outer layer. Some studies have claimed that at high temperatures, the TiO_2 formed by the TiN layer may affect the performance of the protective Al_2O_3 layer.

The TiC/Al_2O_3/TiN coated tool appeared to have the best wear resistance under the testing conditions used. This was as expected since the combination of TiC with high abrasive resistance, chemically stable Al_2O_3 with low thermal conductivity and the added wear resistance of the TiN coating improved the overall wear resistance of the cutting tool. Statistical tests in previous sections were conducted to confirm the wear performance difference between the different tools.

The photographs of the flank face for each of the machined tools are shown in Figure 4-17. The flank-wear on the uncoated and TiN coated tool can be easily seen. The lower flank-wear on the TiN/Al_2O_3, Al_2O_3 and TiC/Al_2O_3/TiN coated tools displays their higher wear resistance performance.

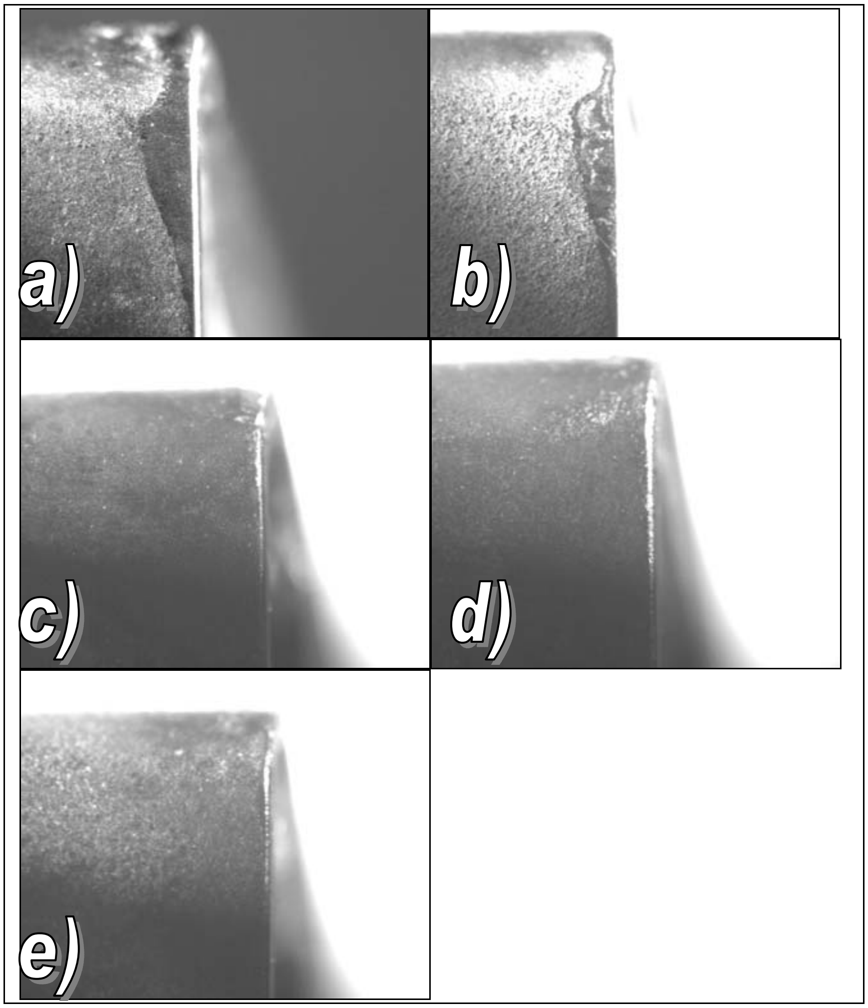


Figure 4- 17 Photographs of the final flank wear for a) uncoated tool, b) TiN coated tool, c) TiN/Al_2O_3 coated tool, d) Al_2O_3 coated tool and e) TiC/Al_2O_3/TiN coated tool.

The machined part surface roughness appeared to decrease with the addition of a coating layer for all cases except the TiN/Al_2O_3, in which the addition of this coating tended to increase the value of the surface roughness compared to that obtained using the uncoated tool. This however is not a direct result of the coating material, since individually used, the TiN and Al_2O_3 coatings tended to decrease the surface roughness. Hence, this can be a result of the formation of longer chips during the turning process using the TiN/Al_2O_3 coated tool that caused the chips to curl around the machined part and affected its surface roughness.

The TiC/Al_2O_3/TiN coated tool exhibited the lowest surface finish followed by Al_2O_3 coated tool, TiN coated tool, uncoated tool and the TiN/Al_2O_3 coated tool respectively. The statistical tests conducted in the previous sections confirm these results.

Chapter 5 Summary and Conclusions

This study evaluates the machining performance of five commercially available cutting tool inserts in turning AISI 1018 steel. Uncoated, TiN coated, TiN/Al_2O_3 coated, Al_2O_3 coated and TiC/Al_2O_3/TiN coated tools were examined and their flank wear and the resultant machined work piece surface finish were analyzed.

The tool coatings were found to improve upon the wear resistance of the cutting tool. This was shown by the decrease in wear on the flank face of the coated tools compared to that of the uncoated tool. The wear of the TiN coated tool was around 12% lower than the wear observed on the uncoated tool. TiN/Al_2O_3 coated tool showed a decrease of around 65% compared to the uncoated tool. The decrease in wear was due to the wear resistance properties of the TiN and Al_2O_3 materials and the high chemical stability of the Al_2O_3 layer.

The Al_2O_3 coated tool showed a decrease of around 92% compared to the uncoated tool. The increased wear resistance of the Al_2O_3 coated tool compared to the TiN/Al_2O_3 coated tool was believed to be due to the oxidation of the TiN material and the appearance of TiO2 under the Al_2O_3 layer which deteriorated the performance of the Al_2O_3 layer. The TiC/Al_2O_3/TiN coated tool appeared to have the lowest wear of all the tools tested, and showed a decrease of around 96% in wear compared to the uncoated tool.

In the case of the machined surface roughness, all the coated tools produced lower surface roughness than that produced by the uncoated tool except for the TiN/Al_2O_3 coated tool. This was believed to be due to factors other than the coating material and mainly the different chip breaker geometry on the tool which produced longer chips that got in contact with the work piece material and increased its surface roughness.

The TiC/Al_2O_3/TiN coated tool produced the lowest average surface roughness during the 60 cuts with a decrease of around 38% compared to the uncoated tool. The Al_2O_3 coated tool produced the second lowest average surface roughness with a decrease of around 23% compared to the uncoated tool. The TiN coated tool produced the third lowest average surface roughness with a decrease of around 7%. While on the other hand, the TiN/Al_2O_3 coated tool produced the highest average surface roughness with an increase of around 21%.

The surface roughness increased while oscillating for all the cutting tools used except for the TiN coated tool in which surface roughness oscillated around a constant value and produced more consistent surface roughness that was not affected by the flank wear of the tool.

Reliable quantitative models for predicting machining performance of cutting tools do not exist due to the large number of parameters involved and the complex interactions between these parameters. Machining performance of cutting tools are made by conducting actual machining tests. This study contributes to the large data bank of cutting tools performance, adding on to the data collected from previous machining studies.

This research addresses the effect of different coating materials on the tool flank wear and the work piece surface roughness. The tools considered were single layer, two layer, and three layer coated tools.

This research may be extended to study the effects of multi-layer coatings on cutting tool performance. Multi layers are composed of alternating layers of two different materials that can vary in number from few up to tens of thousands. Multi layers are believed to offer very high strength, hardness, heat resistance, and many new properties that could greatly enhance the performance of the cutting tools. And so it would be interesting to examine the machining performance of multi layer coated tools and how the number and thickness of the alternating layers affect the wear resistance of the cutting tool and the surface roughness of the work piece.

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Vita

Mohamad Nouilati was born on May 1st, 1979, in Damascus, capital of Syria. He obtained his Bachelor of Science in Mechanical Engineering degree in 2002 from Louisiana State University, United States. Currently he is a candidate for the degree of Master in Science in Industrial Engineering, to be awarded during the Louisiana State University commencement ceremonies in the spring of 2004.