2008-01-03

Tool Life and Flank Wear Modeling of Physical Vapour Deposited TiAlN/TiN Multilayer Coated Carbide End Mill Inserts when Machining 4340 Steel Under Dry and Semi-Dry Cutting Conditions

Pinaki Chakraborty
University of Miami, p.chakraborty@mycanes.miami.edu

UNIVERSITY OF MIAMI

TOOL LIFE AND FLANK WEAR MODELING OF PHYSICAL VAPOUR DEPOSITED TiAlN/TiN MULTILAYER COATED CARBIDE INSERTS WHEN END MILLING 4340 STEEL UNDER DRY AND SEMI-DRY CUTTING CONDITIONS

By

Pinaki Chakraborty

A DISSERTATION

Submitted to the Faculty
of the University of Miami
in partial fulfillment of the requirements for
the degree of Doctor of Philosophy

Coral Gables, Florida

December 2007

UNIVERSITY OF MIAMI

A dissertation submitted in partial fulfillment of
the requirements for the degree of
Doctor of Philosophy

TOOL LIFE AND FLANK WEAR MODELING OF PHYSICAL VAPOUR DEPOSITED TiAlN/TiN MULTILAYER COATED CARBIDE INSERTS WHEN END MILLING 4340 STEEL UNDER DRY AND SEMI-DRY CUTTING CONDITIONS

Pinaki Chakraborty

Approved:

Dr. Shihab Asfour Professor and Chairman of Industrial Engineering	Dr. Terri A. Scandura Dean of the Graduate School
Dr. Sohyung Cho Assistant Professor of Industrial Engineering	Dr. Murat Erkoc Assistant Professor of Industrial Engineering
Dr. Arzu Onar Assistant Member Department of Biostatistics St. Jude Children's Research Hospital Memphis, TN	Dr. Matthew J. Lynn Assistant Scientist Center for Advanced Microscopy Department of Chemistry

CHAKRABORTY, PINAKI (Ph.D., Industrial Engineering)

Tool Life and Flank Wear Modeling of Physical Vapour Deposited TiAlN/TiN Multilayer Coated Carbide End Mill Inserts when Machining 4340 Steel Under Dry and Semi-Dry Cutting Conditions (December 2007)

Abstract of a dissertation at the University of Miami.

Dissertation supervised by Professor Shihab Asfour.
No. of pages in text. (287)

This study investigates the tool wear of advanced PVD TiALN/TiN multilayer coated end mill inserts when dry and semi-dry machining 4340 low alloy medium carbon steel. A factorial design of experiment setup consisting of two levels of speed, three levels of feed, two levels of depth of cut, and two levels of cutting conditions (semi-dry and dry) was used for the study. The combination of cutting conditions that gave the best response for different components of cutting force, cutting power, surface roughness and tool life were determined using MANOVA & ANOVA analysis and Tukey comparison of means test using MINITAB statistical software package. From a study of the Energy Dispersive X ray (EDX) analysis and primary back scatter images obtained from the worn out crater surface of the insert, it was observed that diffusion wear prevailed under both dry and semi-dry machining conditions. A tool life model was developed using multiple regression analysis within the range of cutting conditions selected. A model for flank wear progression was also developed using mixed effects modeling technique using S Plus statistical software package. This technique takes into account between and within work piece variations during end milling and produces a very accurate model for tool wear progression. This is the first time application of the mixed effects modeling technique in metal cutting literature.

Acknowledgements

I would like to express my sincere gratitude to my advisor, Professor and Chairman of Industrial Engineering Department, Dr. Shihab Asfour for his financial support, guidance and mentorship for this study and through the course of study for the Masters and Ph.D. program at the University of Miami Industrial Engineering Department. I would like to thank Dr. Sohyung Cho for his valuable guidance and help during the experimental setup and critical assessment of the manuscript. A special thank goes out to external committee member Dr. Arzu Onar for her help with the statistical analysis part of this study, especially the mixed effects modeling technique.

I would like to thank Dr. Matthew Lynn and Dr. Pratik Joshi from the University of Miami Center for Advanced Microscopy (CASM) for their help with EDX analysis. Also, thanks to Dr. Murat Erkoc for his input and help in refining the document.

I would also thank Charles Erghott, Moataz Eltoukhy, Ravi Namani and Andres Barreto for their help with the experimental setup. Also, thanks to Dr. Shihab Asfour and Dr. Nourredine Boubekri for their encouragement in pursuing a Ph.D. program and the management at Boston Scientific Corporation for their encouragement and support in completing the program.

I would like to thank my wife Nila and her parents for her support throughout the course of running the experiment and subsequent data analysis. A special thanks to my parents and sisters for their support in pursing higher studies at the University of Miami.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Background

AISI 4340 is a widely used medium carbon low alloy steel containing nickel, chromium and molybdenum that is known for its toughness and high strength properties at heat treated conditions while retaining good fatigue strength. 4340 steel is primarily used for constructing machine tool structural parts, aircraft landing gears, power transmission gears, shafts, and other structural parts. It is an alloy of iron and carbon containing 0.38 - 0.43 % carbon, 0.7 - 0.9 % chromium, 0.6 - 0.8 % manganese, 0.2 - 0.3 % molybdenum, 1.65 - 6 % nickel, 0.15 - 0.3 % silicon, and maximum sulphur and phosphorus concentrations of 0.035 % and 0.04 % respectively. 4340 steel has good machinability in annealed, normalized and tempered ("4340 Alloy steel," 2006).

Cutting fluids are used in the metal cutting industry for cooling the tool-work piece interface, providing lubrication, chip evacuation, increasing tool life, and protecting surface finish by preventing adhesion and galling while machining. However, increasing coolant costs, maintenance, disposal costs and emission concerns are making dry and semi-dry machining increasingly attractive to the metal cutting industry world wide. The U.S. National Institute for Occupational Safety and Health (NIOSH) recommended exposure limit (REL) for metal working fluids (MWF) is 0.5 mg/m^3. This corresponds to 0.4 mg/m^3 of thoracic particulate mass over a time weighted average (TWA) of 10 hrs of exposure time over a 40 hr work period ("What you need to know", 1998).

The Occupational Safety and Health Administration (OSHA) recommended permissible exposure level (PEL) for mineral oil mist in air is 5 mg/m^3 and 15 mg/m^3 for particulate not classified otherwise (PNOC) for an 8 hr ("Metal working fluids," 1999). The mineral oil mist concentration associated with the use of flood cooling using metal working fluids in the U.S. automotive parts industry is in the range of 20 – 90 mg/m^3 indicating a significant potential for improvement (Autret and Liang, 2003). ISO 14001 has also set standards for environmental management systems in order to help the metal cutting industry reduce their impact on the environment. Of special focus is the automotive and aerospace industry where metal cutting is widely used. Special attention is being directed towards the role of cutting fluid and their environmental impact (Dudzinski et al., 2004). Semi-dry and dry machining can significantly reduce waste and reduce the burden on the environment (Aizawaa et al, 2005).

Globally, cutting tool usage consists of 49 % carbide tools. In the U.S., 60 % of all cutting tools used are carbide tools ("Using Cermets,"1998). The late sixties saw the development of coated titanium carbide (TiC) tools that enabled machining at higher speeds and feeds. The seventies saw the development of chemical vapor deposited (CVD) multi-layered coated carbide tools that provided a combination of greater wear resistance and lower friction (Smith, 1989). The last decade has been dominated by physical vapor deposited (PVD) coated carbide tools. Nowadays, thin advanced multilayer coatings deposited by physical vapor deposition (PVD) technique on tungsten carbide substrate material are used in order to increase wear resistance and reduce insert chipping.

Tool wear, cutting force, surface roughness and cutting power are relative responses. Tool wear results in changes in tool geometry that affect cutting forces, cutting power, and surface finish. It is the main factor that determines the economics in metal cutting. A lower rate of tool wear means increased tool life, better surface finish, reduced tooling cost and lower cost of production.

The global tooling market is worth $ 10 to $ 12 Billion out of which 49 % share in dollar value is held by carbide and high speed steel tools. High speed steel consists of the next 44 % in market share. The remaining 7 % market share is occupied by diamond, cubic boron nitride, and cermet tools ("Using Cermets,"1998). It is important to use the right tool for the right cutting condition in order to reduce tool wear and fracture, increase machining accuracy, and increase tool life and productivity.

Flank and crater wear are the two main wear mechanisms that limit a tools performance. Flank wear is caused when the relief face of the tool rubs against the machined surface. It has an adverse impact on the finish and dimensional accuracy of products that are machined (Bukkapatnam et al., 2000). Crater wear on the other hand occurs on the rake face of the tool and affects the geometry at the chip tool interface, which in turn affects the cutting force.

A majority of the tool wear models developed in metal cutting literature have been developed for orthogonal machining conditions where constant cutting conditions, constant chip thickness and constant cutting force during machining exist. However during milling, interrupted tool engagement, varying cutting forces and varying chip thickness cause variations in machining conditions. Difference in material composition, variation in surface hardness and machine rigidity can create even more variations during the milling process. As a result, very few models for tool wear prediction exist because of the complexity of the milling process as mentioned above.

In the last decade, the mixed effects modeling technique has received a lot of attention in reliability literature. It is particularly useful when there are subject specific variations or variations in environments and operating parameters that affect the measure of interest. Briefly, the model captures longitudinal subject specific effects by repeated measurements in the first step. In the second stage, subject specific regression coefficients are related to know covariates using regression equations. The combination of the random effects in step 1 and fixed effects in step 2 yields the mixed effects model that takes into account subject specific variations while estimating the covariate effects common across subjects. This model will be well suited for tool degradation modeling in milling conditions where there exist subject specific variations due to significant variations in machining conditions.

1.2 Research objectives

The primary objective of this research is to develop a tool wear model for end milling 4340 steel with physical vapor deposited (PVD) TiAlN/TiN multi-layer coated carbide inserts under dry and semi-dry cutting conditions that takes into account unobserved heterogeneity like variations between and within blocks. This is also the first time in metal cutting literature that a comprehensive study involving tool wear, cutting force, cutting power, surface roughness measurements, scanning electron microscope (SEM) analysis and X ray energy dispersive spectrum (EDX) analysis has been conducted under dry and semi-dry cutting conditions.

The following points will be specifically addressed in this study:

1. Investigate effect of cutting conditions like speed, feed, depth of cut and semi-dry/dry cutting conditions on one, two and three dimensional average and maximum cutting force components acting on the work piece when end milling 4340 steel with physical vapor deposited (PVD) titanium aluminum nitride/ titanium nitride (TiAlN/TiN) multi-layer coated carbide inserts.
2. Investigate surface finish of work piece measured by average surface roughness (R_a) when end milling 4340 steel with PVD TiAlN/TiN coated carbide inserts under dry and semi-dry machining conditions.
3. Investigate cutting power (in Watts) when end milling 4340 steel alloy steel using PVD TiAlN/TiN coated carbide inserts under dry and semi-dry machining conditions.
4. Investigate tool life of PVD TiAlN/TiN multilayer coated carbide inserts under dry and semi-dry cutting conditions when end milling 4340 steel.
5. Degradation modeling of tool wear in end milling using mixed effects model.
6. Analysis of energy dispersive X ray (EDX) in order to explain the wear process (abrasive, adhesive or diffusion wear) that occurs on the crater face of the end milling insert during semi-dry and dry machining.
7. Analysis of backscattered electron images obtained from the crater surface of PVD TiAlN/TiN coated carbide inserts when end milling 4340 steel under semi-dry and dry cutting conditions.

Chapter 2

Literature Review

Cutting tool is one of the critical elements in the machining process. End milling is cutting processes where varying cutting forces, cutter run out, chip thickness and variation in material composition cause non-uniform wear. Dry and semi-dry end milling is increasingly being adopted in the U.S and worldwide due to environmental concerns and cost associated with purchasing, handling and disposing off coolants. There are very few tool wear models in end milling because of the variations in wear progression introduced by the above mentioned factors. Mixed effects modeling technique has been used for degradation modeling in reliability literature. This modeling technique offers substantially higher power in detecting significant factor effects by absorbing unobserved heterogeneity in random effects instead of random error. This modeling technique has not been used in the metal cutting literature and will be perfectly suitable for wear modeling in end milling under semi-dry and dry conditions. This chapter is organized in the following order; in the following section, the developments in recent coated carbide tools since its inception in the 1960's have been discussed. Sections 2.3 and 2.4 talks about physical and chemical vapor deposition techniques used for coating carbide tools used for semi-dry and dry machining. Sections 2.5 and 2.6 discuss cutting fluid used in machining and associated hazards. Section 2.9 lists tool wear studies in end milling and introduces the mixed effects modeling technique. Section 2.15 discusses the multiple analysis of variance (MANOVA) analysis technique that can be used to determine effect of independent variables on response (dependant) variables.

2.1 Cutting inserts

Cutting inserts can be broadly classified into uncoated and coated carbides, ceramic inserts, cermets, and poly crystalline grade inserts. Inserts of different grades are used in cutting tools. Insert selection is usually based on work piece material, surface finish, machine capability and rigidity, cutting speed and feed, and productivity goals.

Uncoated carbides are still used to machine ferrous and non-ferrous material at low speeds, where diffusion of coating material into the work piece is of concern, or for very short runs. They can be further classified into the alloyed and un-alloyed type. The alloyed type is mostly used for machining ferrous material where crater wear is of concern. The un-alloyed type is used for machining non-ferrous material where abrasive wear is prevalent. The binder content determines toughness and the grain size determines the wear resistance of un-coated carbides.

In the present carbide tool market, more than 85% of all cemented carbide tools utilize coatings (Ng and Aspinwall, 2002). The outer coating layer consists of single or multiple layers of physical or chemical vapor deposited coating material like titanium carbide (TiC), titanium nitride (TiN) or aluminum oxide (Al_2O_3). The inert nature of TiC and Al_2O_3 reduce cratering whereas the lubricious TiN layer reduces friction during machining thus generating less heat at the tool work piece interface (Smith, 1989).

Ceramic grade of inserts can be subdivided into two types: alumina (Al_2O_3 based and silicon nitride (SiN_4) based. These inserts can be used for machining cast iron, hardened steel and stainless steel, iron, ductile irons and high temperature alloys. Ceramic inserts can be extremely productive when it is possible to machine at high speeds.

Cermets usually consist of a titanium carbonitride (TiCN) core dispersed in a nickel, cobalt and molybdenum binder (D'Errico et al., 1999). They have excellent thermal and chemical resistance and are used for high-speed semi finishing and finishing machining of steels and stainless steel (most types). However, cermets have low toughness compared to cemented carbides (Liu et al, 2005). Therefore, they are not suited for roughing cuts when compared to carbide insert. Surface finish obtained with cermets is very good as they are able to hold their sharpness at elevated temperatures ("Kennametal Milling Tooling," 2005).

The poly crystalline (PCD) grade of inserts can be classified into two types: diamond and cubic boron nitride. These inserts need extremely rigid machine and fixture setup. Although diamond and cubic boron nitride (CBN) inserts are expensive compared to carbide, ceramics and cermet inserts, the cost of the insert can be recovered by a longer tool life and higher productivity. Diamond inserts are the hardest cutting tool material available and are abrasion resistant. They are used to machine non-ferrous materials at high speeds and have high thermal conductivity. Cubic boron nitride inserts on the other hand are of two types; high and low CBN content grades. Low CBN content grades have low thermal conductivity but higher compressive strength, which makes them conducive to machine hot at higher speeds. Thus low content CBN grades are best suited for finish machining of hardened steel. High CBN content inserts on the other hand have higher thermal conductivity and are comparatively tougher than low content CBN inserts. This makes it more suitable for rough cutting hardened steel and pearlitic gray cast iron where severe edge loading occurs.

From the discussion above, it can be see that coated carbide inserts are one of the most widely used in metal cutting. It is nine times cheaper than CBN coated tools and can be used for both dry and semi-dry machining purposes ("Kennametal Milling Tooling," 2005). This research will focus on advanced physical vapor deposited (PVD) TiAlN/TiN multi-layer coated carbide inserts (4 μm total coating thickness) that can be used in both dry machining and semi-dry machining applications in order to reduce the harmful effects of coolants. In the following section, coated carbide inserts and associated coatings will be discussed.

2.2 Coated carbide inserts

The developments of coated carbide inserts followed the evolution of cutting tools. Initially, carbide tools had poor wear resistance. Additives like titanium carbide (TiC), Niobium carbide (NbC) and Tantalum carbide (TaC) were added to the tungsten carbide substrate to improve the wear resistance. However, the additives mentioned above caused increased sensitivity to cracks. The developments of coatings came in the end of 1960's when tungsten carbide tools that had good toughness needed a wear resistant top coat. Ever since, cutting tool material and coating technology has seen a rapid development. Nowadays, with the advent of dry machining, high speed machining and dry high speed machining, coatings need good insulation properties. Due to high hardness, chemical stability and inertness, carbide and nitride coatings make good candidates for cutting tool coating material (Bull et al., 2003).

TiN is the most widely used coating and is suited for machining a wide variety of work piece materials. The tooling industry and vendors have been working on improved formulations of TiN coatings that are being spurred by the improvement in performance of cutting tools. TiCN coatings have developed over the past few years due to need for tools with improved flank wear resistance. These tools on the other are more suited for machining steels with high toughness, specifically in milling and thread cutting operations (Bull et al., 2003).

TiCN and TiN tools are widely used in traditional PVD coatings in order to make the tools perform better (Harris et al., 2001). Titanium aluminum nitride (TiAlN) coating on the other hand is known for its high wear resistance properties while machining abrasive material at high temperatures like cast iron (Dey and Deevi, 2003). It can be produced by using cathodic arc evaporation technique or by magnetron sputter deposition. Aluminum can substitute titanium at different levels based on various factors like target material composition, evaporation rate and parameters of the plasma process.

Tungsten carbide/carbide (WC/C) and molybdenum sulphide (MoS_2) are two other coatings that are being used in the metal cutting industry. Tungsten carbide/carbide (WC/C) is a lubricious material that is deposited on top of TiAlN in order to reduce friction during semi-dry or dry machining (Derflinger et al, 1999). MoS_2 coatings increase tool life and reduce friction while machining. However, MoS_2 has affinity for moisture and the coating does not perform well when exposed to air. The coating can be improved by depositing a small amount of titanium with it. The resulting coating called MoST™ is much harder and is much less sensitive to atmospheric moisture. It is produced by a technique called field unbalanced magnetron sputtering and is used in applications involving cutting and forming (Renevier et al., 2000; Fox et al., 2000).

Multi-layered coatings are formed by depositing two layers of coating alternatively to form the overall coating thickness like in the case of TiN/TiAlN coatings.

In summary, different types of coating materials have been used on carbide tools. This research will focus on study of tool life and flank wear progression of advanced physical vapor deposited (PVD) TiAlN/TiN multi-layer coated carbide cutting inserts under dry and semi-dry cutting conditions. Additionally, the effect of cutting conditions on surface finish, cutting power and cutting forces will also be studied when end milling AISI 4340 medium carbon low alloy steel with coated carbide inserts under different cutting conditions.

2.3 PVD and CVD Coatings

Chemical vapor deposition (CVD) and Physical vapor deposition (PVD) are two coating techniques that are used in a majority of carbide cutting tools. In the chemical vapor deposition technique, a substrate is exposed to reactant gases that are often diluted with a carrier gas at room temperature in a reaction chamber. The reactant gas is heated by an external media and impinges on a heated substrate material. The reactant gases may undergo homogeneous chemical reactions in the gaseous phase based on operating conditions and the process before striking the surface of the substrate material. Volatile by-products produced are taken out of the reaction chamber by gas flow. There are different types of chemical vapor deposition techniques. Some examples are atmospheric pressure chemical vapor deposition (APCVD), low-pressure chemical vapor deposition (LPCVD) and plasma assisted (enhanced) chemical vapor deposition (PACVD, PECVD)

("Corrosion-doctors," n.d.). CVD technique has a wide range of application from semi-conductor device industry to deposition of coatings for cutting tools.

The initial coating on carbide tools at the end of the sixties was chemical vapor deposited. Since then, chemical vapor deposition techniques have significantly developed and have been used to deposit single to multiple layers of TiC, TiN, TiCN and Al_2O_3. Today's CVD processes produce wear resistant coatings with combination of high and medium temperature processes and complex cycles with coating thickness in the range of 4 to 20 μm.

Physical vapor deposition technique (PVD) on the other hand is a vaporization coating process in which a solid get vaporized and the vapor gets re-solidified on another surface thus building a layer of coating over another. In the reactive vapor deposition technique, the material to be deposited reacts with surrounding gas to deposit a thin film of compound material like carbo-nitride, nitride, oxide and carbide on the substrate material. The PVD process can be classified into three basic types, namely sputtering, ion plating and evaporation. High-ionization magnetron sputtering and new cathodic arc processes have improved the performance of PVD coated tools several fold (Prengel et al., 2001).

The PVD process occurs in three steps, namely

a) Vapor formation by techniques like sputtering, arc vaporization, or evaporation
b) Vapor transfer from the source to the substrate material, and
c) Film growth and deposition on surface

The steps can occur independently or can be repeated in a particular order depending on coating characteristics ("Surface Coating," n.d.). Coating thickness usually varies from 1 to 10 μm (Hedenqvist, 1997). A thicker coating thickness means more thermal compressive stress in the insert that reduces crack propagation risk. Also, the substrate cemented carbide is better protected against thermal load and abrasive wear. However, the coating mechanical strength decreases with higher coating thickness (Bouzakis et al., 2003).

Majority of today's coated carbide tools use physical vapor deposition (PVD) technique. PVD coated cemented carbides have advantages over their CVD coated version. In the case of PVD coated carbides, the combination of moderate cobalt content with finer tungsten carbide grain size gives a wear resistant insert with good transverse rupture strength, and high hardness. PVD coatings have been shown to perform well during interrupted cutting when a sharp tool edge is required and during finishing operations (Prengel et al., 2001).

The first generation PVD coating on carbide used TiN hard coatings and was used in the milling operation of steel (interrupted cutting condition). Following their success in milling applications, their use was extended to other machining operations like threading, grooving, boring, turning and parting. The second and third generation of PVD coatings utilized is TiCN and TiAlN that have further boosted productivity (Jindal et al, 1999). Instead of single homogeneous coatings of TiN, TiCN and TiAlN, a new class of coating that have multiple layers of coating material deposited on a carbide substrate have shown better tribological and mechanical properties. The thin films of material are alternatively deposited on a micro or nano-thickness scale and have the same total thickness as a single layer (Ducros et al, 2003).

It is possible to achieve higher productivity with PVD coated carbides as they consume less power and give a better surface finish when compared to uncoated tools. The PVD coating can increase tool life up to three times when compared to uncoated tools (Ezugwu and Okeke, 2001). Diamond like carbon (DLC) coating is a new PVD deposited coating with low coefficient of friction that is also being used for high speed machining (Navinsek et al., 2002).

In summary, PVD coated carbide tools have shown better performance than their CVD counterparts and have been extensively used in the metal cutting industry for the past decade. Our research will focus on advanced multi-layered PVD TiAlN/TiN coated carbide end mill inserts that have good wear resistance, higher hardness, and higher transverse rupture strength and are suited for dry and semi-dry machining applications. End mill inserts were chosen as they are widely used in the automotive, die and mold, and machine tool manufacturing industry. They are subjected to high stress and cutting forces during interrupted milling conditions.

2.4 Coated Carbide Tools used in Semi-dry and Dry Machining

Cutting tools suited for dry machining can be manufactured in three different ways; changing cutting tool material, changing tool geometry or by applying coating on the tool (hard or soft). The most widely used and practical solution is the third option i.e. applying coating on the tool. Coatings have low thermal conductivity and thus prevent heat transfer from the cutting zone to the tool material and also cause less temperature fluctuation in the substrate material. Thus, coated inserts can work under high cutting temperatures, which mean that they can be used under aggressive conditions in turning and milling without compromising tool life. The coating thickness can vary from 2 to 18 microns. Thinner coatings are more suited for interrupted cutting conditions like milling because they undergo more stress when compared to thick coatings during rapid cooling and heating cycles. Thinly coated inserts have shown a tool life improvement of up to 40 %. PVD coating techniques are being used to deposit thinner layers of coatings that adhere better to contours of round tools and sharp edges on milling and turning tools ("Dry up," n.d.).

TiAlN based coatings are widely used in the tooling industry to improve the life and performance of the cutting tool. At elevated temperatures, this coating has high hardness and good wear resistance (Jindal et al., 1999; Kathrein et al, 2005). TiN is a traditional PVD coated tool that can be used for both wet and dry machining conditions. However under dry machining conditions, TiN deteriorates significantly. At about 550°C, TiN forms an oxide layer TiO_2 (titanium dioxide) that reduces the wear resistance of the tool compared to that of an uncoated tool. On the other hands, TiAlN resists oxidation up to a temperature of 925˚C at which point, an oxide layer forms on the surface that prevents oxygen from diffusing into the underlying coating (Harris et al., 2000). There is also an inward diffusion of oxygen that forms a titanium rich oxide layer at the interface of the coating and the substrate. Thus, there is a passive double oxide layer formation that inhibits further oxygen diffusion into the coating (Harris et al., 2003a). TiAlN coated carbides are suited for machining dry and also at high speeds because of the properties mentioned above (Zelinski, 2003).

The automotive industry has taken particular interest in the development of PVD TiAlN tools as they can machine gray cast iron and aluminum silicon alloy components at higher speeds and feeds. These materials account for the majority of material used in the car and truck industry today. This success has prompted more research in the developments of quaternary nitride coatings like titanium aluminum vanadium nitride (TiAlVN), titanium aluminum zirconium nitride (TiAlZrN), titanium aluminum carbo-nitride (TiAlCN) and titanium aluminum chromium nitride (TiAlCrN). Of the above mentioned coatings, addition of up to 3 % chromium in TiAlN coatings has considerably improved the oxidation resistance of the coating (Harris et al.,2003b).

From the above discussion, it can be seen that TiAlN coated carbide inserts are preferred when high hardness and wear resistance is needed at elevated temperatures. This kind of a condition prevails at the tool work piece interface during dry and semi-dry machining. This research will study the wear behavior of PVD TiAlN/TiN multi layer coated carbide inserts during semi-dry and dry machining conditions.

2.5 Cutting Fluids used in Machining

The traditional method of cooling in metal cutting is to use copious amounts of fluids at a low pressure in order to flush out chips, increase tool life, carry away the heat generated during metal cutting, improve surface finish and lower cutting tool force (Rahman et al., 2002).

Workers can be exposed to cutting fluids by inhalation of the mist from the cutting fluid or by skin contact. Skin contact for workers can happen by touching workspaces inside the machine that is cover with cutting fluid, or by dipping their hand in the fluid, by fluid splashes or by handling coolant coated work pieces. The aerosol or mist generation and exposure during use of metal working fluids (MWF) depends on the type of ventilation system, the temperature of the MWF, and the presence of splash guards or machining enclosures ("What you need to know", 1998).

The four major classifications of cutting fluids are straight, oil, soluble oil, semi-synthetic and synthetic. Other then the straight oils, cutting fluids that fall in the three other categories are mixed with water before use. Each type of cutting fluid also contain extreme pressure agents, biocides, surfactants, corrosion inhibitors and anti-oxidants that improve the fluid performance and increase the life of the coolant ("Metal Working," 1998)

Straight oil

Straight oils are made of vegetable or mineral oil. Straight oil made from crude oil is severely hydro treated to reduce presence of cancer causing poly-nuclear aromatic hydrocarbons (PAH's). They have an oily appearance, have a viscous feel and may contain sulphur and chlorinated additives. Straight oil is generally used as a lubricant and not so much as a coolant, and may need fire protection. The best performance of straight oils are obtained during machining conditions that cause high metal to metal contact, in older machines that are designed to use straight oils and at slow cutting speeds.

Soluble oil

Soluble oils contain 30 % to 85 % of severely refined lubricant base oil and emulsifiers that aid in its dissolution in water. It is usually supplied as a concentrate to which water needs to be added. Soluble oils may contain colorants and contain other additives that increase cutting fluid life and improve performance while machining. These oils are better at cooling when compared to straight oils. However, the disadvantage of soluble oils is reduced sump life, poor mix stability, smoking tendencies and less corrosion resistance.

Semi-synthetic oil

These oils contain 5 % to 30 % of severely refined base oil. They have better cooling properties, offer good lubrication, cause less rusting on machines and have better sump life. The constituents are more or less the same as soluble oils excepting the fact that semi-synthetics have more complex emulsifier package.

Synthetic oil

Synthetic oils are mixed with water and do not contains any petroleum products. Detergent like components and other additives that are added for performance improvement cause the cooling action. Synthetic oils are clear, offering easy visibility of the component while machining, has the most corrosion resistance and has the most sump life (“Metal Working,” 1998).

In summary, straight oil, soluble oil, semi-synthetic oil and synthetic oils are used as cutting fluids in the metal cutting industry. Cutting fluids are a health hazard for machine operators as they can cause respiratory ailments and skin disease. Also, their procurement cost, use and disposal account for 7 % to 17 % of the total cost of manufacture of products (Makiyama, 2000). The goal of the metal cutting industry is to move towards environmental friendly dry and semi-dry machining techniques that eliminate or reduce the amount of cutting fluid exposure to the industrial operator.

This research will study tool wear behavior of PVD TiAlN/TiN coated carbide end mill inserts while machining 4340 steel under dry and semi-dry cutting conditions. Recommendations will also be given on cutting speed, feed, and depth of cut levels that will yield the longest tool life and the best surface finish under dry and semi-dry cutting conditions.

2.6 Hazards Associated with Cutting Fluids

Sometimes, cutting fluids may contain polynuclear aromatic hydrocarbons (PAH's), formaldehyde based biocides, chlorinated paraffin's and nitrites that may be potentially carcinogenic. Excessive amount of formaldehyde based biocide used in water miscible cutting oils may cause employee skin irritation and sensitization or respiratory irritation. Straight oils may also be flammable and may pose a fire hazard. Metal working fluids (MWF's) have been associated with irritation of the eyes, lungs, nose, throat and skin. Skin diseases like dermatitis and acne can be caused by exposure to MWF's. Respiratory diseases that can be caused by metal working fluids include asthma, upper respiratory track infection and hypersensitivity pneumonitis. A variety of cancers have also been associated with MWF's ("Metal Working," 1998). In the U.S., the Environmental Protection Agency (EPA) has instituted the Clean Air Act, the Resources Conservation and Recovery Act and the Clean Water Act to regulate the disposal of substances and control emissions. State and local publicly owned treatment works (PTOW's) however can have stricter disposal norms for substances like used metal working fluids, which can considerably increase disposal costs.

The National Institute for Occupational Safety and Health (NIOSH) in 1998 published a document that sets an upper limit of 0.4 mg/m^3 for thoracic particulate mass for a time weighted average (TWA) of up to 10 hrs a day for a 40 hr work week. Since it is difficult to measure thoracic particulate mass, total particulate mass was recognized as a suitable substitute. The recommended exposure limit (REL) for thoracic particulate mass by NIOSH is set at 0.5 mg/m^3 for a TWA of up to 10 hrs/day for a 40 hr work week. Reduction of respiratory disorders related to exposure to metal working fluids is the main focus of this guideline. The expectation to reduce consumption of metal working fluids can be best summed up from the following quote from the OSHA Metal Working: Safety and Health Best Practices Manual, 1998;

> It is NIOSH's belief, that in most metal removal operations, it is technologically feasible to limit MWF aerosol exposures to 0.4 mg/m^3 or less ("Metal Working," 1998).

Problems associated with cutting fluids use are discussed by Heidenreich (1985) and mitigation steps are discussed by Deodhar (1995). An European consortium of six countries (LEPOCUT) specializing in tooling, roller bearing, lubricant manufacture and physical vapor deposition (PVD) coating techniques in collaboration with research institutes and final end users have already taken lead in developing semi-dry and dry machining techniques that are less polluting. These techniques have drastically reduced the amount of coolant used in certain metal cutting processes.

New PVD coating material suitable for dry machining, environmentally friendly coolants, tools and cutting techniques, and hard coating for machine tools have been developed by the consortium. The new technologies developed are cost effective and have already been put to use in European manufacturing industry. The dry machining techniques developed have a big potential of cost savings throughout Europe's manufacturing industry and would reduce hazards and pollution at the work place associated with harmful lubricants ("European Commission," 2005).

2.7 Semi-dry Machining

Cutting fluids have their advantages but also pose a health hazard in the shop floor environment. However, stricter OSHA and NIOSH guidelines associated with Permissible exposure limits (PEL) and Recommended Exposure limits (REL) associated with cutting fluids, disposal and handling costs and rising cost of coolants used in flood cooling has lead to increasing interest in semi-dry or dry machining techniques.

Semi-dry machining

In semi dry machining, a small amount of cutting fluid is broken into extremely small particles with the help of air, which then impinge on the tool work piece. The process is also called minimum quantity lubrication (MQL) as minimal amounts of cutting fluid are used in the process (Rahman et al., 2002). The intention is to reduce the cost of coolant use that can be 3 to 5 times the cost of tooling (Makiyama, 2000).

Very few published research articles are available on MQL. Machado and Wallbank (1997) conducted preliminary tests using quantities of cutting fluid in the 200 – 300 milliliter/hour (ml/hr) range (low quantity) when compared to traditional flood cooling coolant fluid flow rates of 5, 200 milliliter/min (ml/min). The experiments were conducted using turning operation with medium carbon steel (AISI 1040) cylindrical bars using five different lubricant conditions; namely, dry, air, air and water mist, air and soluble oil mist and flood cooling using soluble oil at full flooding conditions (5 liter/min). The air pressure was set at 0.2 Mpa. The results showed that during machining medium carbon steels, flood cooling under low cutting speed and high feed rate conditions cause a cutting and feed force reduction. In all other instances, air and soluble oil and water mist showed better performance. Problems associated with odor, bacterial and fungi growth during flood cooling can be eliminated by mist cooling. Soluble oil mist however necessitates the use of a ventilation system for mist removal. Use of water and soluble oil coolant combinations were shown to reduce the amplitude of oscillation of the force components indicating that during attrition wear conditions, mist cooling is the best option. A water mist however can cause the machine surfaces that come in contact to corrode.

Wakabayashi et al.(1998) used a low concentration cutting oil mist (concentration 0.01 to 0.16 ml/min) for semi dry machining during turning on the rake and flank face of a cutting tool using a pressure of 0.6 Mpa and showed that minimum quantity lubrication was still effective when compared to flood cooling at 4,270 ml/min.

Tests using minimum quantity lubrication were conducted during drilling by Klocke and Eisenblatter (1997). The conclusion of the test was that minimum quantity lubrication provides a suitable alternative to dry machining in dry drilling.

Rahman et al. (2002) studied the effect of minimum quantity lubricant (MQL) while machining ASSAB 718 HH steel (35 HRc hardness) using uncoated carbide inserts. The levels of MQL and flood cooling were 8.5 ml/hr at a mist pressure of 0.68 MPa and 42,000 ml/hr flood cooling rate at a pressure head of 0.14 Mpa. It was observed that at low speed, feed rate and depth of cut during full immersion milling of the ASSAB 718 HH steel blocks, uncoated carbide inserts subjected to MQL could still be used for machining in spite of high flank wear. On the other hand, inserts used under dry machining conditions and flood cooling conditions failed catastrophically under similar machining conditions. An analysis of cutting forces, surface finish, chip configuration and EDX spectrum of the crater surface of the insert during MQL machining yielded favorable results. This study shows that MQL can be considered environmentally friendly and an economically beneficial lubrication technique that can be used in the metal cutting industry at low range of the cutting conditions (speed, feed and depth of cut).

Hassan and Yao (2004) studied the effect of MQL using soluble oil mist when face milling Ti-6Al-4V titanium alloys. Titanium alloys usually have low thermal conductivity and high hardness and density making it a difficult material to machine. The optimum flow rate determined as per their study was 125 ml/hr of lubricant in a MQL mix that gave equivalent results when compared to full flood cooling.

Kelly and Cotterell (2002) studied the various lubrication methods including semi-dry machining during drilling aluminum alloy (ACP 5080) having a Brinell hardness (BHN) of 85. The results showed that semi dry machining was suited for high cutting speed and feed rates.

Su et al.(2006) studied the effect of lubricants on high speed end milling of Ti-6Al-4V alloy at a cutting speed of 400 m/min, feed of 0.1 mm/rev, axial depth of cut of 5 mm and a radial depth of cut of 1 mm using (TiN/TiC/TiN) coated carbide end mill. The results showed that compressed cold nitrogen gas and oil mist (CCNGOM) had the optimal cooling/lubrication properties. The tool life obtained using CCNGOM as a coolant was 2.69 times higher than dry machining conditions and 1.93 times higher than nitrogen-oil mist cooling. Tool life also increased when using compressed cold nitrogen gas at -10˚C was used as a coolant. No chipping or fracture of the end mill was observed while using cold nitrogen gas.

Le and Hwang (2006) conducted finish-turning experiments using SM45C structural steel under different speeds and feeds and under varying levels of cutting oil quantity using MQL. An ANOVA analysis was done and it was determined that surface roughness improved when using less oil for mist cooling and for lower feed rates.

From the above discussion, it can be seen that some research advances have been made in the field of semi-dry machining. Semi-dry machining is a good alternative to flood cooling. It can be used to reduce amount of coolants used during metal cutting and can provide some of the beneficial effects of flood cooling. In this research, semi-dry and dry machining of 4340 medium carbon low alloy steel with PVD TiAlN/TiN coated carbide tools will be studied. Cutting parameters like speed, feed, depth of cut and condition that yield low cutting forces, low cutting power, high surface finish and tool life will be suggested for this work piece cutting tool material combination selected.

2.8 Dry Machining Using Coated Carbides

Like semi-dry machining, the motivation for moving towards dry machining is the same; namely, ecological, economic consideration and lower health risk to operators. During dry machining, the cutting edge of the cutting tool undergoes a high degree of thermal loading and mechanical stress. In order to perform dry machining, cutting tool material of high hot hardness and toughness need to be developed. In addition, cutting tool geometry needs to be improved and better coatings need to be developed (Rech, 2006).

In the last three decades, coatings have been used on cemented carbide tools in order to shield the substrate material from high temperature zones in the insert, improve the hot hardness of the insert bulk material, reduce friction force between the rake face and the metal chip and reduce the friction force between the flank face and the work piece (Grzesik, 1998).

Coated carbide tools have been used in dry machining research of advanced aeronautical material like Inconel 718, a difficult to machine material. Inconel 718 is a nickel based super alloy that is used extensively in fabricating gas turbine parts. It has high hot hardness at temperature ranges of 600˚C, low thermal conductivity, and a tendency to work harden during machining (Sharman et al., 2001). Cutting tools used to machine super alloys like Inconel 718 are PVD coated tungsten carbide tools with K type carbide substrate that does not have carbide inclusions (composition WC – Co 5.5 % alloy that is designated K10-20). This material has better toughness than P type of carbide substrate and has a lesser risk of cutting edge chipping (Ducros et al., 2003).

Itakura et al. (1999) conducted experiments for turning Inconel 718 under continuous and interrupted cutting conditions with square tipped inserts made of P20 coated cemented (TiN/TiC multilayer coating). The range of cutting speed selected was 30, 100 and 150 m/min with a feed rate of 0.2 mm/rev and a depth of cut of 2.5 mm. At 30 m/min, a built up edge protected the rake face of the insert from further deterioration. However, abrasive wear was noticed on the flank face due to hard particles contained in Inconel 718. The average temperature at the tool work piece interface was measured by a thermocouple to be 717˚C (990˚K) at 30 m/min cutting speed and 1047˚C (1320˚K) at 100 m/min cutting speed respectively. At higher cutting speeds, because of elevated temperatures and oxidation of the surface, diffusion wear prevailed which ultimately caused the tool to degrade on both the rake and flank faces.

Sharman et al.(2001) used TiAlN and CrN PVD coated tungsten K10 grade carbide end mills to machine rectangular blocks of Inconel 718 (43 ±1 HRc). A full factorial experiment was conducted using two levels of speed (90 and 150 m/min), two different coatings (TiAlN and CrN) on a carbide substrate, and two different work piece angles. When machining at cuttings speeds of 90 m/min, the TiAlN coated carbide tool performed better then CrN because of its resistance to oxidation and high hardness. The main wear mechanism was adhesive wear for both the coating material. However, extensive built up edge (BUE) was seen for the CrN coated carbide tool suggesting that CrN has a higher chemical affinity for Inconel 718 when compared to TiAlN.

Nouari et al. (2003) conducted research on the effect of drill geometry and coatings on machining quality (surface roughness, burr height and dimensional accuracy) during drilling of aluminum–copper alloy AA2024 T351. In dry drilling, the tool is subjected to an extreme environment that includes high frictional forces and high temperatures. To withstand these conditions, drills need to have high hot hardness, low coefficient of friction and low thermal conductivity (Kalidas et al., 2001). Tungsten carbide drills from different manufacturers and with different coatings were used in the experiment; namely TiAlN coating (Kennametal insert), Hardlube® TiAlN + WC/C coating (Kennametal insert), Diamond coating (Kennametal insert – Type TF KCD), TiN + Ag (silver) coating (Jabro tool –Type Step Drill), TiN coating (HAM France – Type Super Drill) and with no coating (MMC Metal France – Type MAE). 500 holes (6 mm dia.) were produced with each tool using an axial depth of cut of 25 mm. Although the ANOVA experiment did not show that coatings had any significant effects on machining quality when machining at a low feed rate (0.04 mm/rev), it was shown that the quality of holes produced by diamond and TiAlN+WC/C coated tools are very close to that of the uncoated tools (Nouari et al., 2003).

Santhanam et al. (1996) compared the performance of CVD and PVD coated TiCN inserts in milling AISI 4140 steel with Kennametal SEHW 1204 AFTN style inserts. The results showed that both PVD and CVD coated TiCN inserts showed dramatically longer tool life (triple) when machining under dry conditions. PVD coated TiCN coated inserts however performed better in dry condition under intermittent cutting conditions like milling.

The mean tool life of CVD coated TiCN coated tools shows more variation then corresponding PVD coated tools. PVD coated inserts have residual compressive stresses in the coating that suppresses insert edge chipping in dry cutting conditions where cyclic mechanical stress is more prevalent compared to thermal stress. The tensile stress in CVD coated inserts make it more susceptible to fatigue due to mechanical cycling thus causing the variation in tool life.

Sometime, dry machining is also associated with high speed machining. High speed machining is a relative term. A speed of 500 m/min can be considered as high speed for machining alloy steel, but is a conventional machining speed for machining aluminum (Fallboehmer, 2000). Figure 1 shows the conventional and high speed machining ranges for different materials that are machined.

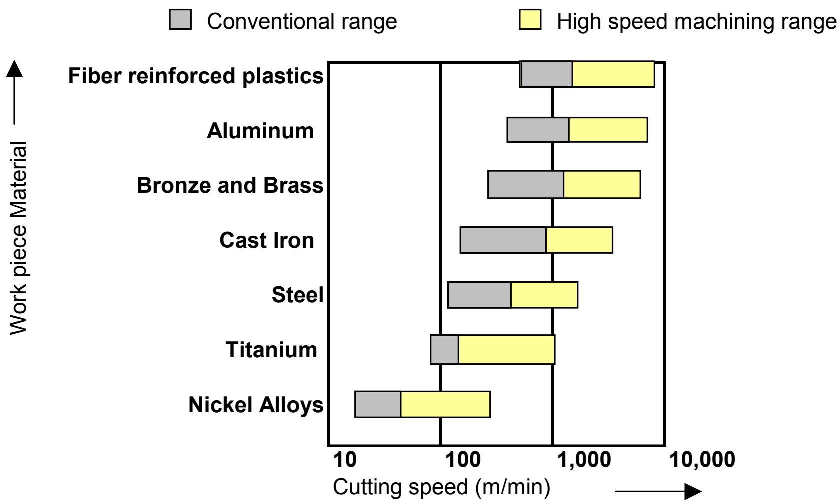


Figure 2-1 Conventional Versus High Speed Machining Speeds for Different Materials (Schulz and Moriwaki, 1992)

High speed machining (HSM) technology has been applied to a variety of industries including aviation and aerospace, the die and mold making industry, and the automotive industry. HSM of tool steels with hardness greater than 30 Hrc has been possible with the development of new dry cutting tools (Ozel and Altan, 2000). It has been used to cut different alloys of steel, cast iron, alloys of aluminum and magnesium and nickel/cobalt/titanium based super alloys and composite materials (Liu et al., 2002). In the stamping die industry, high speed machining can reduce manufacturing times from 7 % to 10 % and also improve machined part quality (Lacalle, 2002).

The use of coolant in high speed machining is not very effective. High speed dry machining also leads to low cutting forces, higher material removal rates and lower energy consumed during cutting (Dudzinski, 2004). D'Errico et al. (1999) conducted experiments on high speed dry machining of normalized steel AISI-SAE 1045 (HB~190) using coated carbide ends mills. Under dry machining conditions and at a cutting speed of 200 m/min, feed rate of 0.04 mm/rev, axial depth of cut of 0.5 mm, and a radial depth of cut of 10 mm, there was a dramatic improvement in tool life for coated carbide inserts when compared to the un-coated tungsten carbide end mill.

Kim et al.(2001) conducted experiments using ball end milling on machining Inconel 718 (HRc 43) and a die steel (STF4, HRc 42) with TiAlN coated carbide tools under different cutting conditions. They showed that the for the die steel, tool life obtained with TiAlN coated carbide ball mill using compressed chilly air at -12˚C as a coolant was 2 times more than dry cutting and 3.5 times more than flood cooling respectively. However at 210 m/min (high cutting speed), there was no significant improvement in tool life by using compressed chilly air system and dry cutting. Since Inconel 718 alloy has high hot strength and toughness, severe thermal friction makes the coolant ineffective.

Ghani (2004) used Taguchi optimization methodology to optimize cutting parameters while end milling AISI H13 steel with TiN coated P10 carbide insert under dry cutting condition. The milling parameters to be optimization were cutting speed, feed rate and depth of cut. The results of the study showed that low resultant forces and a good surface finish can be obtained when using a high speed, a low feed and a low depth of cut.

Ning et al. (2001) studied the chip formation process in dry high speed milling of AISI H13 mold steel (HRc 55) using TiAlN coated solid carbide high speed ball-nose end mills at spindle speeds in the 10,000 to 30,000 RPM range. They established that tool chatter could be recognized from the chip analysis thus establishing a link between stability of the process and the formation of chips. It was also shown that the classical adiabatic shear process during chip formation does not occur in high speed ball-nose end milling of AISI H13 mold steel.

Koshy et al. (2002) conducted a study to identify appropriate cutting parameters and type of wear when machining AISI D2 tool steel (58 Hrc) with PVD coated carbide ball nose end mills under dry high speed milling conditions. Their study revealed no significant difference in tool life amongst the various PVD coated carbide inserts despite difference in coating material combination and geometry. Flank wear analysis revealed that the main mode of wear was chipping, attrition and adhesion.

The above section discusses research advances made in dry machining using coated carbide inserts. Coated carbides do not cost as much as CBN inserts (about 9 times cheaper) and can be used for semi-dry and dry machining of a wide variety of ferrous material (“Kennametal Milling Tooling,”2005). This research will focus on evaluating tool wear and recommending cutting conditions that will reduce cutting forces, cutting power, increase surface finish and tool life during semi-dry and dry machining AISI 4340 medium carbon low alloy steel with PVD TiAlN/TiN coated carbide inserts. Models for tool wear progression and tool life will also be developed under these conditions.

2.9 Tool Wear Studies in Milling

Most tool life and tool wear models in the metal cutting literature have been developed for the turning process. On the contrary, such models for milling are very few due to the complexity of modeling the intermittent cutting process (Alauddin and El Baradie, 1997).

Dos Santos et al. (1999) developed an optimization technique to determine the coefficients of the extended Taylor tool life equation in milling. The best set of cutting conditions that yield the fastest convergence for the coefficients of the extended Taylor tool life equation and associated confidence intervals for the coefficients was determined. This was done by obtaining the minimum ratio (NC) between maximum and minimum singular values of the sensitivity matrix of tool life related to variation of machine parameters. They compared their technique to the commonly used fractional factorial technique used to determine the coefficients of the Taylor tool life equation during dry face milling of AISI 1045 rolled steel (mean hardness of 197 HB) with triple TiN/TiC/TiN coated carbide inserts (ISO P45-M35 class). The mean percentage error and standard deviation between tool life values was higher for the fractional factorial technique compared to the optimization procedure. The same study was repeated for AISI 304 stainless. However, it was found that mean percentage error between tool life estimates obtained for AISI 304 stainless steel was 46 % compared to 10 % for AISI 1045 steel. It was found that irregular flank wear patterns and variations in work piece material composition in the case of AISI 304 stainless steel caused more variation in tool life estimates compared to AISI 1045 steel.

Vieira et al.(2001) developed expanded Taylor tool life models for predicting tool life when face milling AISI 8640 steel bars (mean hardness 299 HV) with triple coated (TiN/TiC/TiN) P45 carbide inserts under different lubricant/cooling conditions during face milling. A standard deviation of 20 % between wear progression curves under different lubricant/cooling conditions was reported for experiments conducted under the same cutting condition. This was considered acceptable for intermittent cutting conditions that exist during end milling.

Alauddin and El Baradie (1997) developed tool life models for slot milling AISI 1020 cold rolled steel (190 BHN hardness) during dry cutting conditions using uncoated cobalt alloyed high speed steel (HSS) slot drills (S11 per ISO 4957). They developed a first order and a second order tool life prediction model based on cutting speed, feed, and depth of cut (DOC) using design of experiments and response surface methodology technique. They used the central composite design of experiment technique with three factors to run different treatment combinations in order to estimate model terms. Twenty four experiments were conducted in four blocks (6 experiments per block) and each experiment repeated twice to increase model accuracy. Contours of material removal rate on tool life output curves in two dimensional space for different speed and feed levels were also constructed.

Sharman et al. (2001) studied tool life when high speed ball nose end milling Inconel 718 alloy (Hardness 43 ± 1 HRc) using TiAlN and CrN coated K10 grade carbide inserts. They varied the angle of the work piece, cutting speed and coating in a 2^3 full factorial design of experiment. Increased chipping was observed when machining the Inconel 718 super alloy due to vibrations caused by tool deflection. This caused a large residual error terms in the ANOVA table for main effects. Each trial was replicated twice to increase model statistical accuracy. It was reported that tool coating was the main factor that affected tool life, followed by cutting speed and work piece angle.

Alauddin et al. (1995) studied the wear progression of carbide end mill inserts when dry machining hot forged and annealed Inconel 718 alloy (260 BHN hardness).

Inconel 718 alloy was machined using full and half immersion milling techniques during up and down milling. Maximum and localized flank wear were found to be the main wear criterion. Test runs were repeated five times under identical cutting conditions and the corresponding arithmetic mean used to plot the tool wear progression. There were variations observed in the flank wear progression curves over time even if the same cutting conditions were used.

In general, tool wear prediction models in milling suffer from a drawback. The variation in work piece composition and characteristics or variation caused due to environmental or other operating parameters appear as a large error term in the mathematical model for tool wear. The mixed effects model is a powerful statistical technique that is used both in reliability and survival analysis literature. The model was first introduced by Laird and Ware in 1982 in a survival setting. This model can be used to capture the variability within and across test blocks under random effect terms in the model and can output a much more accurate model of tool wear progression. More recently, it has gained popularity in the reliability literature as degradation measurements over time provide more valuable information then single life time values (Meeker and Escobar, 1998). To the best of our knowledge, this model has not been used in metal cutting literature for tool wear prediction.

2.9.1 Mixed Effects Model

The mixed effects model is known for its versatility and can be used in the case when measures are unequally spaced or when unequal sample sizes are selected. A two stage approach is used for mixed effects modeling. Longitudinal subject specific patterns are modeled using regression techniques (linear or non-linear) in Stage 1. Patterns in repeated measurements are captured using subject specific regression coefficients. Subject specific parameters are related to known covariates in the second stage of the analysis using multiple regression models (Onar et al., 2005). A few studies utilizing mixed effects modeling in statistical and reliability literature are Carey and Konig (1991), Doksum and Hoyland (1992), Lawless et al. (1990), Hu and Cao (1995), and Kwam and Bae (1991).

The first stage of the model is $\mathbf{Y}_i = Z_i\boldsymbol{\theta}_i + \boldsymbol{\varepsilon}_i$, where longitudinal measurements specific to the specimen are modeled using a linear regression model. In the second stage, the subject specific parameter vector $\boldsymbol{\theta}_i$ related to know covariates via equation $\boldsymbol{\theta}_i = K_i\boldsymbol{\beta} + \mathbf{b}_i$. Combing the two stages yields the general mixed effects model

$$\begin{aligned}\mathbf{Y}_i &= Z_i(K_i\boldsymbol{\beta} + \mathbf{b}_i) + \boldsymbol{\varepsilon}_i \\ &= (Z_iK_i)\boldsymbol{\beta} + Z_i\mathbf{b}_i + \boldsymbol{\varepsilon}_i \\ &= X_i\boldsymbol{\beta} + Z_i\mathbf{b}_i + \boldsymbol{\varepsilon}_i \qquad \textbf{\textit{(2-1)}}\end{aligned}$$

where

$\mathbf{b}_i \sim N(0, D)$,

$\boldsymbol{\varepsilon}_i \sim N(0, \Sigma_i)$,

$b_1, b_2, \ldots b_n, \varepsilon_1, \varepsilon_2, \ldots, \varepsilon_N$ are independent of each other

Where,

$\mathbf{Y}_i = n_i$ dimensional response vector for subject i, $1 \le i \le N$,

N = Number of subjects,

$Z_i : n_i \times q$ and $K_i : q \times p$ are matrices of known covariates

$\boldsymbol{\theta}_i$ = specimen-specific parameter vector,

$\boldsymbol{\beta}$ = p dimensional vector containing fixed effects,

$\mathbf{b}_i$ = q dimensional vector containing the random effect

$\boldsymbol{\varepsilon}_i$ = n_i dimensional vector of residual components

D = (q x q) covariance matrix

Σ_i = (n_i x n_i) covariance matrix which depend on i only through its dimension n_i i.e. the set of unknown parameters in Σ_i will not depend on i. In some cases, this assumption is relaxed (Verbeke and Molenberghs, 1999).

2.10 Classification of End Milling

End milling can be classified by the immersion ratio (a_r/D), where a_r is the radial depth of cut (mm), and D = diameter of cutter (mm). The most commonly used types of end milling process are a) Full immersion end milling or slot milling, b) Half immersion end milling, and, c) Quarter immersion end milling (Alauddin et al., 1995). Figure 2-2 shows an example of full and half immersion milling.

In this study, 2/3 immersion ratio was used (i.e. a_r = 2 D /3). This was based on recommendation from the insert supplier (Kennametal) as there is a risk of insert breakage in full immersion milling conditions when end milling of AISI 4340 low alloy steel blocks (average hardness - 26 HRc) with multi-layer PVD TiAlN/TiN coated carbide end mill inserts. A half immersion milling on the other hand may not create enough chip - load for the insert to reach its flank wear criterion within the confines of a test block.

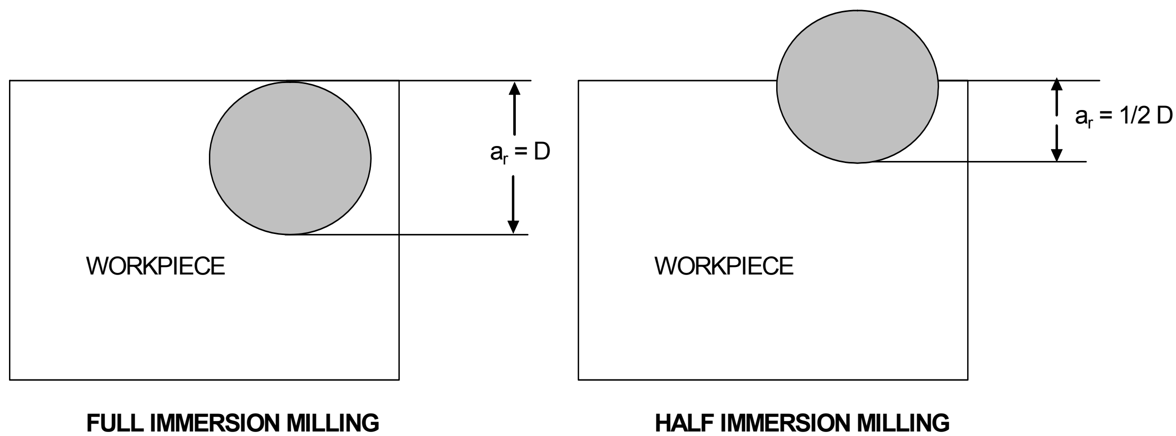


Figure 2-2 Full Immersion versus Half Immersion Milling (Alauddin et al., 1995)

2.11 Tool Geometry for Dry and Semi-dry Machining

Tool geometry needs to be optimized in order to use the tool for semi-dry and dry machining. In this regard, three types of tool geometries are usually considered:

a) Macro geometry - This includes dimensions of tool, important cutting angles, presence of chip breakers etc. that have an order of magnitude greater than 100 μm.

b) Meso geometry – This includes cutting edge radius with an order of magnitude of 1–100 μm, and

c) Micro geometry – This includes surface texture with an order of magnitude of less than 1 μm

The meso and micro tool geometry has not been properly considered by tool manufacturers due to lack of poor manufacturing control over the same (Rech, 2006).

Chamfer on the cutting edge geometry reduces stress concentration and strengthens the cutting edge for milling conditions. Edge honing also creates a similar effect, but to a lesser extent. Santhanam et al. (1996) showed that increase in tool life by edge honing of the T Land and wiper face for CVD coated tools is more prominent when compared to that of PVD coated tools at lower cutting speeds (152 m/min). At higher cutting speeds (213 m/min), edge honing had a detrimental effect on PVD coated tools but was shown to improve tool life for CVD coated tools.

Smith et al. (1997) showed that surface finish of TiAlN coating could affect the tool life. The life of a TiAlN coated high speed steel (HSS) drill was shown to double by reducing the surface roughness of the coating while machining cast iron (GG25).

Kountanya and Endres (2004) conducted research on the interaction of corner radius and edge radius on flank wear. The research showed that a corner radius on a sharp cornered tool does decrease flank wear. For honed tools, it is advantageous to use a large corner radius with a large edge radius.

The PVD TiAlN/TiN coated carbide inserts used in this study for dry and semi-dry machining of AISI 4340 low alloy steel (26 HRc) have a rake angle of 5°, an end relief angle of 5°, a hone and a T- Land of 20° ± 0.005 inch (0.127 mm).End milling inserts with this geometry are suited for semi-dry and dry machining operations and were selected from the Kennametal milling catalog 3050 (“Kennametal Milling Catalog,” 2005).

2.12 Wear Mechanisms

Wear mechanisms during machining can be categorized into three main types: abrasion wear, adhesion wear and attrition wear. Abrasion wear prevails at low cutting speeds and at low chip tool interface temperature when sliding conditions prevail. It is caused by hard particles or asperities at the tool work piece interface during the relative motion between the tool surface and the work piece surface (Huang and Liang, 2004). A built up edge can appear at this stage. Further increase in speed causes a built up layer at the contact zone.

Adhesion wear occurs when tool material is removed from the tool surface when the adhesive junction in the tool material or coating breaks. The tool rake surface can deteriorate fast during adhesive wear. If the cutting speed is further increased, the adhesion wear effect can be reduced as a thin adhesive layer reduces chip tool surface friction.

Chemical wear occurs at a high temperature which causes diffusion of material from tool surface to chip and vice versa. The contact conditions can change fast because of chemical diffusion that can lead to tool failure (Nouari et al., 2005).

In this study, dry and semi-dry machining of AISI 4340 steel (26 HRc) with PVD TiAlN/TiN coated carbide inserts will be conducted. The type of wear will be analyzed using optical microscopy images and Energy dispersive spectral (EDS) analysis.

2.13 Cutter Run Out

Cutter run out is a problem that particularly affects face-milling operations that causes variations in forces, undeformed chip thickness and surface finish. The two kinds of cutter run outs are a) Cutter axis run out (eccentricity), and b) cutting point positioning offset run out. For milling cutters that use inserts, run out can be caused by variation in insert size, error in insert seating in the tool holder and also the misalignment of the spindle axis and the holder axis. The run outs affect the positioning of the cutting point to be offset in the axial and radial direction and also cause eccentricity errors (Zheng et al., 1999).

In this study, a Kennametal KISR-KSSM 10 mm IC single insert tool holder (CV40 shank) that has a taper accuracy of AT3 or better per IS0-1947 was selected. The short shank length of 2.687 inch (68.25 mm) provides this tool holder with high rigidity during end milling and reduces cutter run out problems to a minimum.

2.14 Cutting Forces Acting on a Single Insert End Mill

Please refer to Figure 2-3 for forces acting on the cutting tool insert and cutting table during end milling with a single insert (Alauddin et al., 1998).

The following is the nomenclature of the forces:

1. F_x = Force in X direction on work piece
2. F_y = Force in Y direction on work piece
3. F_z = Force in Z direction of work piece
4. F_t = Instantaneous tangential force on insert
5. F_r = Instantaneous radial force on insert
6. F_a = Axial force on insert
7. f_m = feed
8. F'_R = Resultant of cutting forces acting on insert
9. F_R = Resultant of cutting forces acting on table
10. ψ = Instantaneous angle of contact of insert with work piece
11. F_{ta} = Average tangential force per tooth = F_t x Z_c
12. F_{ra} = Average radial force per tooth = F_r x Z_c

13. Z_c = Number of tooth of cutter

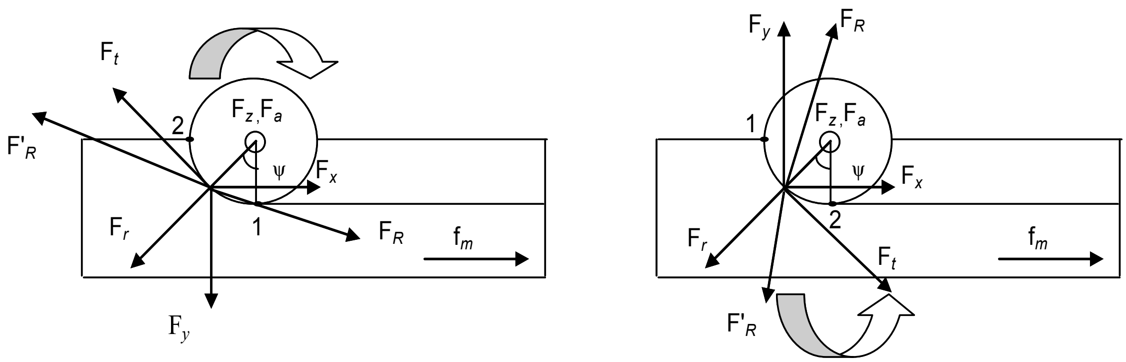


Figure 2-3 Cutting Force Components on a Single End Mill Tooth (Alauddin et al., 1998)

The following is the relationship between forces acting on the table and the forces acting on the cuter in up and down milling mode:

$$\left.\begin{aligned} F_{ta} &= F_x \cos(\psi) + F_y \sin(\psi) \\ F_{ra} &= F_x \sin(\psi) + F_y \cos(\psi) \end{aligned}\right\} \text{up milling} \qquad (2\text{-}2)$$

$$\left.\begin{aligned} F_{ta} &= F_y \sin(\psi) - F_x \cos(\psi) \\ F_{ra} &= F_x \cos(\psi) + F_x \sin(\psi) \end{aligned}\right\} \text{down milling} \qquad (2\text{-}3)$$

Alauddin et al. (1998) studied the cutting forces during half immersion end milling of Inconel 718 alloy using uncoated carbide inserts in up and down milling modes. They found that the cutting forces decreased as the cutting speed increased for this particular tool material combination between speeds of 11 to 25 m/min. The cutting forces also increased with feed rate and axial depth of cut for both up and down milling conditions. Also, the F_x forces (force acting in the X direction on the table) were the highest in up milling and F_y forces (force acting in the Y direction of the table) were the highest in the down milling mode.

In this study, the effect of cutting parameters like cutting speed, feed, depth of cut and cutting condition will be studied on various cutting force components acting on the work piece during end milling AISI 4340 low alloy steel (HRc 26) with PVD TiAlN/TiN coated inserts under dry and semi-dry conditions.

2.15 Multiple Analysis of Variance (MANOVA)

Multiple analyses of variance (MANOVA) is a powerful statistical tool that can be used to study the effect of one or more independent variables on more than one dependant variables. The following are assumptions that must be met for a MANOVA analysis to be valid (Bray and Maxwell, 1986):

1) Data should be randomly sampled from the population of interest
2) Observations should be independent of each other
3) Multivariate normality assumptions should be met for the dependant variables. A method of verifying multivariate normality is by plotting the Chi squared plot of Mahalanobis distance (MD) of the dependant variables. The test plot is a straight line with points lying on it or uniformly scattered across it. The dependant variables should also meet univariate normality assumptions.
4) Equality of covariance matrices of all groups of dependant variables. For a particular "m" group of dependant variables, homogeneity of variance assumption must be met for all dependant variables in each group. In addition, the correlation between any two variables within a subgroup should be the same for all other groups.

In practice, it is unlikely that all assumptions for MANOVA will be met perfectly (Bray and Maxwell, 1986). MANOVA is relatively robust to assumption violations in a lot of cases. Four different tests may be employed in MANOVA analyses which are a) Hotelling's T-squared test, b) Wilk's Lambda, c) Pillai-Bartlett and d) Roy's greatest character root (GCR). Hotelling's T-squared test is a common traditional test used to compare mean vectors of two groups formed by the independent variables. The Wilk's Lamda test is conducted when there are more than two groups formed by the independent variables. It is one of the most common and widely used traditional tests. The sum of explained variances of the discriminant variables are given by the Pillai Bartlett Trace. Olson (1976) reported that this test statistic is the most robust to multivariate normality violations and is sometimes preferred for this reason. Roy's GCR (Greatest character root) is the most powerful test when the first root is larger compared to the other roots.

MANOVA analysis is also robust enough to modest violations in normality caused by skewness in the data (French and Poulsen, 2000). Olson (1976) reported that the Pillai-Bartlett test was the most robust to inflations in the Type I error due to non-normality as compared to the other three test statistic discussed above. All the test statistics are quite robust to Type I errors as long as sample sizes are equal and the difference in covariance matrices is not large. In terms of power, the Pillai Bartlett Trace (V) has the highest power followed by Wilk's likelihood ratio (W), Hotelling-Lawley trace (T), followed by Roy's largest root (R) in the case of diffused non-centrality structure of multiple response measures.

2.15.1 Test for Data Independence

When the outcome of one observation is not dependant on the outcome of another, the observations are said to be independent. It has been shown in research that in the case of correlated observations, actual alpha levels could be up to ten times the nominal alpha level. This is one of the instances where the effect worsens with sample size (Sharma, 1996).

Independence of data assumption is verified using residual versus fitted values, residual versus time or some other sequence, and residuals versus predictor variables. All plots should ideally display a random pattern (Neter et al, 1996). Transformations may be utilized where needed to obtain random data patterns.

2.15.2 Test for Multivariate Normality

A necessary but not sufficient condition for MANOVA is that univariate normality assumption for each separate variable should be met. The first step is to obtain the fitted model and the residuals. The second step is to conduct a normality test on the residuals obtained. For this purpose, the normal probability plots of the residuals can be used. The p-value from the Anderson Darling test for normality in Minitab can be used as an additional check for normality. If the residuals obtained do not meet the normality assumption, data transformations can be carried out in the third step. Once the data has been transformed, the fitted model is obtained again and steps one and two repeated in the fourth step (Sunkhapong, 2000). If the data passes the normality test, the Chi square plot of Mahalanobis distance for multivariate normality can be plotted.

The Box Cox is a powerful family of transform that can be used in Minitab for this purpose. It is a response transformation that can be used to transform non-normal data to fit a regression model. This particular transform is used for a positive variable X when the variable has heteroscedasticity problems and when the distribution of the variable is not exactly know ("Box Cox Transformation," n.d.).

The Box Cox transform utilizes the following equation:

$$X_i^{(\lambda)} = (X_i^{(\lambda)} - 1) / \lambda \text{ when } \lambda \neq 0$$

$$= \log(X_i) \text{ when } \lambda = 0 \qquad \textbf{2-4}$$

Where, X_i = Response variable,

λ = Transformation parameter

The parameter λ is calculated using the maximum likelihood (ML) technique ("Robust Box Cox Response Transformations," n.d.). The Box Cox normality plot shows the optimal value for λ for which the normality probability plot has the best linearity.

2.15.3 Equivalence of Covariance Matrices

One of the important MANOVA assumptions is the equivalence of covariance matrices or homogeneity of dispersion matrices. Two matrices are said to be equal if all their corresponding elements are equal to each other. For example, if three different variables are studied, there will be six elements in the covariance matrix; namely variance components σ_1^2, σ_2^2 and σ_3^2 and covariance components, σ_{12} , σ_{13} and σ_{23}. All of these six elements will have to be equal to each other in order to satisfy the equivalency of covariance matrices assumption. There is a good chance that this MANOVA assumption will be violated. This kind of a violation affects Type I and Type

II errors. However, as per simulation studies, Type I error is affected more compared to Type II error. For equal sample size and cell sizes, the significance level is not much affected for unequal covariance matrix (Sharma, 1996). Olson (1976) reported that the Pillai-Bartlett trace test gives the best result amongst the four test statistics studied here with respect to Type I error as it is most robust to violation of assumptions across a wide variety of population.

2.16 Summary

In this chapter, new coatings used on cutting tools used for semi-dry and dry machining have been discussed. Of special mention is multilayer TiAlN/TiN coated carbide inserts, a new generation of physical vapor deposited (PVD) cutting inserts that can withstand high temperatures associated with semi-dry and dry machining. The increasing use of semi-dry and dry machining in the U.S. and worldwide has been highlighted. The hazards associated with traditional metal working cutting fluids have been discussed. A widely used machining process (end milling) has been elaborated upon. Research conducted in semi-dry using minimum quality lubrication machining has been detailed in turning, drilling and milling. Dry machining research and high speed machining using coated carbide inserts has also been detailed. Tool wear studies in milling have been discussed and the variations associated due to material composition, hardness and other machining variations in these models have been pointed out. Mixed effects modeling technique that is widely used in reliability literature is been proposed as a solution for modeling tool wear progression in end milling. This model takes into account between and within block variations and accounts for it in as random effect instead of random error. The multiple analysis of variance (MANOVA) technique and associated assumptions have been discussed in detail and will be used in Chapter 3 to determine effects of independent variables and their combination on response variable cutting forces, cutting power, surface finish and tool life.

Chapter 3

Methods and Procedures

The experimental setup to measure tool wear has been described in detail in this chapter. This includes the proposed design of experiment study, cutting parameters and cutting condition used, cutting tools, test block, machining center and data collection devices like power sensor, force dynamometer and amplifier, optimal microscope and environmental scanning electron microscope (ESEM) setup. Also, the pilot study used to select cutting levels based on the objective of the experiment has been detailed. The sections in the chapter are laid out as follows; Section 3.1 discusses the design of experiment setup, cutting parameters, cutting tool, and tool life criterion used for the study. In Section 3.2, equipment and material used for the experiment has been elaborated upon; namely the work piece material, machining center, optical microscope, surface profilometer, power sensor, misting device, hardness tester (bench type and portable type), force dynamometer, Allen Bradley PLC and the environmental scanning microscope. Section 3.3 discusses work piece preparation for experiment, setup of the power sensor, and cutting tool preparation before end milling. The process of taking the end milling cuts, measuring surface finish, flank wear, cutting forces and cutting power has also been detailed in this section. Section 3.4 elaborates on the MANOVA technique used to analyze the data. Section 3.5 reports the finding of the pilot study conducted as a part of this study.

3.1 Design of Experiment

A full-factorial design with 2 replications was utilized in order to effectively investigate the main effects as well as the interactions among the independent variables selected for the experiment. Table 3-1 shows the factorial design.

The four independent variables used for the design of experiment are cutting speed, feed, depth of cut and cutting condition. The fourteen dependent variables selected for the design of experiment are cutting forces $F_{x\ max}$ (maximum force in X direction), $F_{y\ max}$ (maximum force in Y direction) and $F_{z\ max}$ (maximum force in Z direction), $F_{xy\ max}$ (maximum 2D force), $F_{xyz\ max}$ (maximum 3D force), $F_{x\ avg}$ (average force in X direction), $F_{y\ avg}$ (average force in Y direction), $F_{z\ avg}$ (average force in Z direction), $F_{xy\ avg}$ (average 2D forces) and F_{xyz} (average 3D forces), Maximum power (P_{max}), Total power (P_{total}), Average surface roughness (R_a), and tool life (T_{life}).

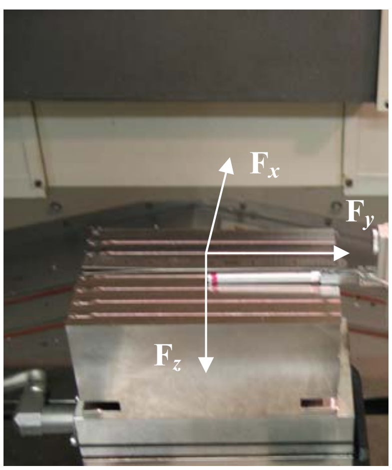


Figure 3-1 Force in X, Y and Z Directions acting on the Work piece

The variables being kept constant are work piece material (material composition and size), tool geometry (rake angle, hone, T land and finish), machine and operator.

3.1.1 Cutting Speed

Cutting speed is defined as the linear speed at the tool/work piece contact area. This speed is measured in meter per minute (m/min). Two levels of cutting speed were selected.

The two levels selected cover the upper 2/3 range of the machining speed recommended by the insert supplier (Kennametal). Higher levels of speed were selected in order for the insert to reach its flank wear criterion within the confines of the AISI 4340 test blocks used for the experiment. The two levels are as follows:

- 183 m/min
- 229 m/min

3.1.2 Feed Rate

The tool feed is the relative motion of the cutting tool with respect to the work piece. It is measured in millimeter per revolution (mm/rev). Three levels of feed were selected. The three feed levels covering the range of feeds suggested for the KC725M end milling insert supplied by the tooling supplier (Kennametal) are as follows:

- 0.10 mm/rev
- 0.15 mm/rev
- 0.20 mm/rev

Table 3-1 Factorial Experiment

Cutting condition	Depth of cut (mm)	Cutting speed (m/min)	Feed rate (mm/rev)					
			0.1		0.15		0.2	
			Replicate 1	Replicate 2	Replicate 1	Replicate 2	Replicate 1	Replicate 2
Semi -dry (Condition 1)	2.54	183	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i
		229	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i
	3.81	183	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i
		229	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i
Dry (Condition 2)	2.54	183	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i
		229	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i
	3.81	183	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i
		229	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i	Cut # 1 Cut # 2 ….. Cut # n_i

Independent variables:

1. Cutting speed (2 levels) : 183 m/min (600 sfpm), 229 m/min (750 sfpm)
2. Feed (3 levels) : 0.10 mm/rev (0.004 ipr), 0.15 mm/rev (0.006 ipr), 0.20 mm/rev (0.008 ipr)
3. Depth of cut (2 levels) : 2.54 mm (0.1 inch), 3.81 mm (0.15 inch)
4. Cutting condition : Semi-dry, Dry

3.1.3 Depth of Cut

The depth of cut (DOC) is the distance between the bottom of the cut and the uncut surface of the work measured in a direction at right angles to the machined surface. Two levels of DOC were selected. The end mill inserts used in the study can be used for a maximum depth of cut of 5.08 mm. However, insert supplier (Kennametal) recommended against use of such a high value of depth of cut as one of the DOC levels as it can damage the inserts. Depth of cut levels 0.1 and 0.15 inch (2.54 and 3.81 mm) were selected well within the maximum allowable depth of cut range in order to obtain a difference in response variables (cutting force, cutting power, surface finish and tool life). Also, a low depth of cut was not selected as flank wear criterion for tool wear has to be reached within the confines the AISI 4340 low alloy steel test block.

- 2.54 mm
- 3.81 mm

3.1.4 Cutting Condition

One of the objectives of this research is to study the effect of semi-dry and dry end milling AISI 4340 medium carbon low alloy steel with PVD TiAlN/TiN multilayer coated carbide inserts. The two cutting conditions selected were as follows:

- Dry machining
- Semi-dry machining (mist cooling)

3.1.5 Cutting Tools

The cutting inserts used in this experiment were Kennametal SPET3125PPER8GB2 (ISO designation of SPET10T3PPERGB) ground physical vapor deposited (PVD) titanium aluminum nitride/titanium nitride (TiAlN/TiN) multilayer coated carbide inserts (KC725M grade). The overall coating thickness is 3 to 5 µm. The substrate material of the insert consists of tungsten carbide with 11.5 % cobalt binder.

The following are the details of the tool geometry square end mill inserts selected:

a) Square shape

b) Rake angle: 5°

c) End relief angle: 5°

d) Length of cutting edge: 10 mm

e) Insert thickness: 3.96 mm

f) Edge radius: 0.79 mm

A Kennametal KISR-KSSM 10 mm IC indexable single insert end mill (19 mm dia.) was used for this experiment. The insert was mounted on a CV40 shank tool holder.

3.1.6 Tool Life Measurement

Tool life (T_{life}) was measured by the number of cuts taken by the insert to reach a maximum flank wear criterion of 400 µm or 0.4 mm (T_{life}). There is no specific ISO standard for flank wear criterion when machining AISI 4340 steel with PVD TiAlN/TiN multi-layer coated carbide inserts during dry and semi-dry machining conditions.

ISO 8688-2:1989 (E) sets a recommended uniform wear criterion of 0.3 mm and a maximum wear criterion of 0.5 mm when machining steel during end milling. However, the recommended tool material to be used for this criterion is: (1) Non-cobalt alloyed uncoated high speed steel, S2 or S4, or (2) Cobalt alloyed high speed steel, S8 or S11. As per the ISO standard, the reference tool should not have any coating or surface treatment. The recommended work piece material is C45 steel prepared per ISO/R 683-3 or cast iron grade 25 prepared per ISO/R 185 ("Tool Life Testing," 1989).

The insert manufacturer "Kennametal" recommended a maximum flank wear criterion of 0.4 mm (400 µm) for flank wear for the cutting insert work piece combination selected. This lies within the maximum flank wear criterion of 0.5 mm or 500 µm recommended per ISO standard for tool life testing during ending milling (ISO 8688-2: 1989 E).

3.2 Physical Equipment and Material

3.2.1 4340 Steel Blocks

AISI 4340 steel blocks supplied by Ryerson Tull, a division of J.M. Tull Metals was used for the experiment. The blocks were normalized, quenched, and tempered to a hardness range of 26 HRc. Each block was 6 inch (152.4 mm) long, 4 inch (101.6 mm) wide and 3 inch (76.2 mm high). The block had a positive tolerance of +3/16 inch (4.76 mm) for machining allowance. The chemical composition of the Grade 4340 stress relieved alloy steel is as follows (%):

C	MN	S	P	SI	CR	NI	MO	AL	V	CU	NB
0.40	0.77	0.011	0.011	0.30	0.80	1.77	0.21	0.034	0.007	0.24	0.0020

3.2.2 CNC Vertical Machining Center

An Okuma vertical machining center (VMC) Model ES-V3016 was used for conducting the experiment. Figure 3-2 shows the Okuma ES-V3016 vertical machining center.

Figure 3-2 Okuma Vertical Machining Center (ES-V3016) used for the Experiment

The following are the specification of the Okuma ES-V3016 vertical machining center:

a) Table size: 762 mm (length) x 410 mm (width)
b) Travels: Spindle end to table surface: 160 to 610 mm
c) Table (maximum load capacity): 680 kg
d) Spindle speed: 80 to 8,000 RPM
e) Spindle Motor (10 min/30 min/ continuous): 10.5/7.5/5.5 KW (14/11/7.4 HP) VAC spindle drive
f) Tool magazine capacity: 20

g) Tool shank V flange type: CAT40

h) Feed rate (rapid traverse): 25 m/min

i) Maximum cutting feed rate (X, Y and Z axis): 1 – 8,000 mm/min

j) Positioning accuracy: ± 0.005 mm

k) Repeatable positioning accuracy: ± 0.0020 mm

l) CNC control: OSP-U10M CNC System

3.2.3 Optical Microscope

A Carl Zeiss microscope (Axioskop 2 Mat) was used to measure the flank wear of the insert. This kind of microscope is mainly used in micro system technology, in the automotive industry and for metallographic analysis. The microscope works with transmitted light and has a HAL 100 halogen illuminator for incident light. It has four objective lenses of magnification 5X, 10X, 20X and 50X. The highest magnification achieved with this microscope is 500X. The microscope has an Axiocam MRC™ high resolution digital camera that captures vivid color images of the surface being studied. A standard Axiovision Release 4.4 software module with two extra licensed modules, Panorama™ (for stitching images) and Extended Focus™ (for focusing on different Z heights) were used in conjunction with the microscope to acquire, edit and store images. Figure 3-3 shows the Zeiss Axioskop 2 Mat microscope.

Figure 3-3 The Carl Zeiss Axioskop 2 Mat Microscope

The microscope was mounted on a high performance active air suspension vibration isolation table manufactured by Kinetic Systems (Model - 1200 Series Labmate). This table has an isolation efficiency of 99 % with automated leveling and height control. The table is connected to a Thomas make Model T-35HD portable air compressor for 40 psi compressed air supply. Figure 3-4 shows the vibration isolation table.

Figure 3-4 Kinetic Systems make Vibration Isolation Table - Model 1200 Series Labmate (Courtesy- Kinetic Systems)

A Dollan and Jenner make fiber optic illuminator (Model – Fiber Lite MI-150) was used to provide extra light to the insert surface when necessary during use of the CCD camera on the microscope (Figure 3-5). It uses a 150 Watt quartz halogen illuminator that can deliver 400,000 foot candles of high intensity cold illumination light. The gooseneck attachment to the illuminator houses the fiber optic cable for illumination.

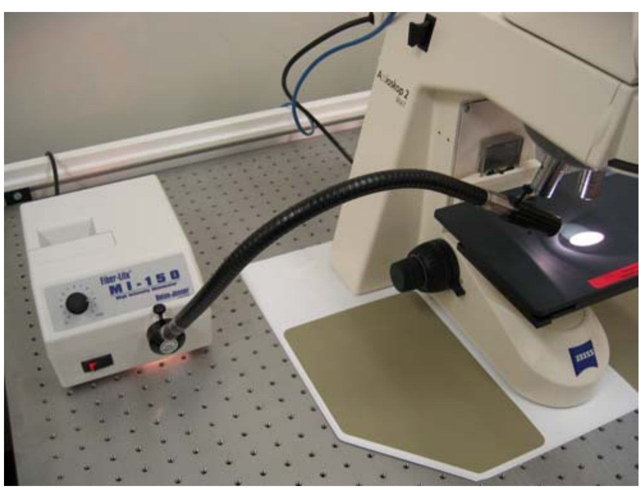


Figure 3-5 Fiber Optic Illuminator Manufactured by Dollan and Jenner used with the Zeiss Optical Microscope

3.2.4 Surface Profilometer

Surface roughness was measured using the "Surtronic 3+" surface profilometer manufactured by Rank Taylor Hobson Inc., as shown in Figure 3-6. The arithmetic average roughness values (R_a) was measured by this instrument. The surface finish of the machined 4340 steel block was measured after every four cuts using the profilometer.

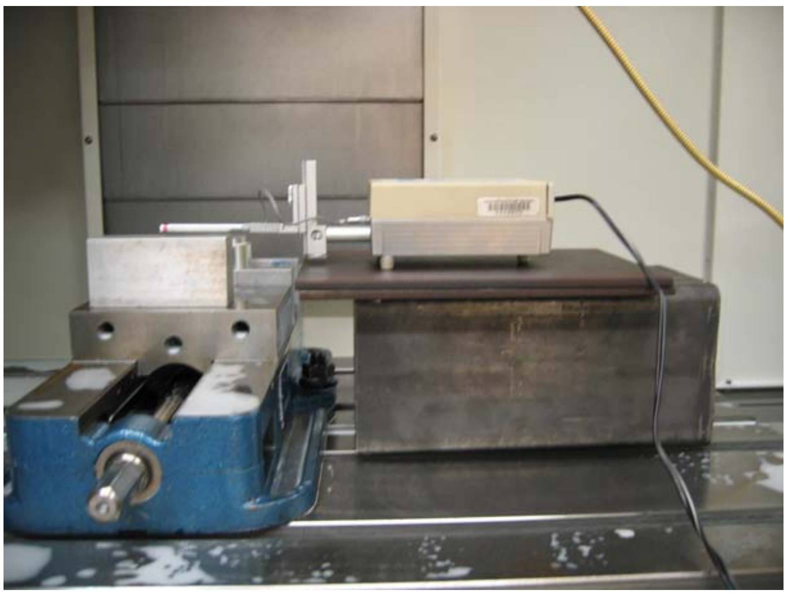


Figure 3-6 The Setup of the Surtronic 3 + Surface Profilometer to Measure Average Surface Roughness (Ra in μm)

3.2.5 Power Sensor

A power sensor instrument made by Artis System Inc. (model MTC-W 1-2) measured the power consumed during the machining process. This is an on-line measuring method. The power sensor set up is shown in Figure 3-7. The MTC-W model is a part of the MTC product line. This system was designed for measuring and analyzing true power signals. It measures the true power of the spindle drive motor.

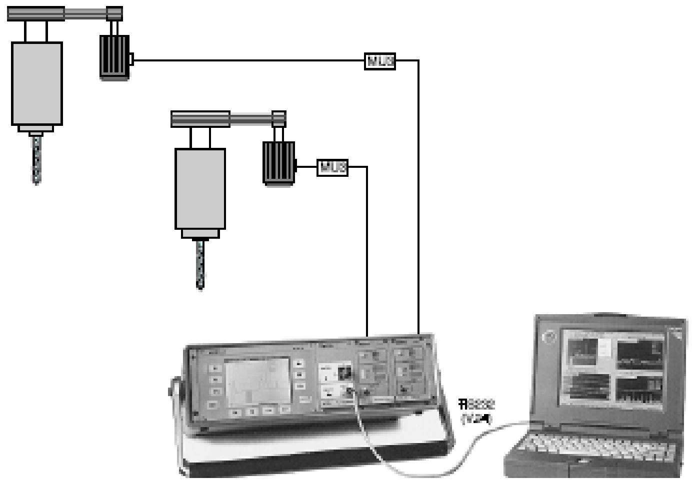


Figure 3-7 The Power Sensor Setup, Artis Systems Co. ("Artis GmBH," 1997)

The power sensor measures cutting power consumed during a cut above a baseline power consumption level (P_o) shown in Figure 3-8. Cutting power higher than the baseline is used to calculate the total power consumed during a cut. The energy consumed is calculated from the measurement of power consumed during cutting which is the area under the curve as shown in Figure 3-8.

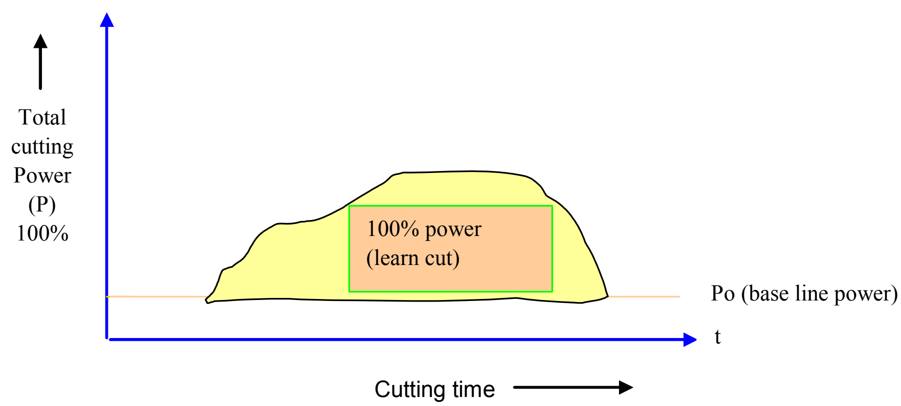


Figure 3-8 Area under the Power-Time Curve (Work done). The Learn Curve showing 100 % Power Consumption for the Base line Level ("Artis GmBH," 1997)

In the beginning of the cutting process, a cut is designated as a learn cut (Figure 3-9). The learned signal for the process remains in memory until a new learned process starts. All subsequent cuts are compared to the learn cut in order to obtain relative maximum and total power readings out put by the Vidi© software in conjunction with the power sensor. As the tool starts to wear, the energy consumed in subsequent cuts increase as shown in Figure 3-9 (“Visualization & Diagnostic System,” 1997).

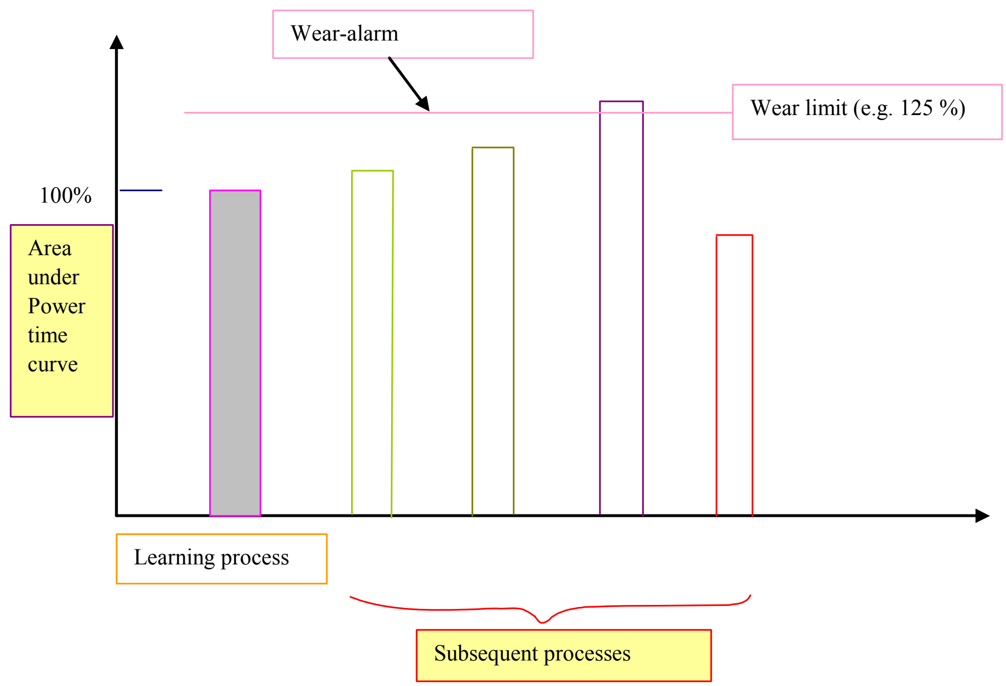


Figure 3-9 The Comparative Percentage of Learned and Following Processes, (“Artis GmBH,” 1997)

According to Shao et al. (2004), the cutting power during end milling is given by equation ($P = S \times F_{ta}$), where P = cutting power in Watts, S = Cutting speed, F_{ta} = Average tangential force acting on work piece. Degarmo et al. (1997) reported that power consumed during machining process is converted to heat, which increase the temperature of the work piece, the tool and the cutting chip. The increase in temperature affects the rate of wear of the tool. Therefore, it can be inferred that an increase in cutting power results in an increases of tool wear and vice versa. Thus, power consumed during cutting can be taken as a measure of tool wear.

Keeping machining speed constant, cutting power is directly proportional to tangential cutting force, $F_{ta.}$ Therefore, it can be inferred that higher tangential force acting on the work piece leads to higher rate of tool wear.

Figure 3-9 shows the power consumption during the base line process compared to power consumption during subsequent processes. A wear limit can be set on the power sensor; so whenever the wear limit is exceeded, the Vidi© software gives a breakage alarm. In general, wear limits depend on the combination of tool material, work piece material and cutting condition.

3.2.6 Misting Device

A Trico Spraymaster II misting device was used to spray mist on the work piece tool interface during semi-dry machining conditions (Figure 3-10). The device has a solenoid valve control that was used to trigger the spray on and off mechanism from a remote switch. The Spraymaster II works on 80 psi compressed air pressure. It has a 1-gallon reservoir for the coolant. The reservoir comes with two flexible segmented hoses that are used to convey the high pressure mist to the tool/work piece interface. Two valves at the distal end of the segmented hose control the ratio of coolant to air. As per information obtained from the manufacturer, by turning both the valves one complete turn, 757 ml/hr (0.2 gallons/hr) of coolant is dispensed as a mist at 0.65 Mpa pressure (80 psi) pressure obtained from shop flow compressed air supply. Figure 3-8 shows the Trico Spraymaster^{TM} II device. The mist is contained within the machine enclosure while machining. Therefore, the machinist is not exposed to the mist.

Water soluble 100 % synthetic and bio-degradable mist coolant (Kool MIST™ Formula #78) was used for semi-dry machining. The mix ratio is 4 ounce (113 grams) of coolant concentrate in 1 gallon (3.8 liters) of water. The Koolmist™ Formula#78 mist spray coolant is specifically developed for mist spray. The coolant provides high lubricity during machining does not produce any mist fog fumes and meets OSHA and EPA requirements.

Figure 3-10 The Trico SpraymasterTM Misting Device

3.2.7 Rockwell Hardness Tester

The hardness of each block was measured using a Wilson bench top hardness tester (Model – 3JR, Tester # 10072) before start of machining and at the final machined surface after the insert reached its wear criterion. An average of 15 readings on the surface of the block was taken. Figure 3-11 shows the portable hardness tester.

Figure 3-11 The Wilson Bench Top Hardness Tester (Model – 3JR, Tester # 10072)

3.2.8 Portable Hardness Tester

Hardness of every fourth tool path created during end milling was measured using a Mitutoyo rebound type portable hardness tester (Model - Hardmatic HH-401) that uses a carbide ball for indentation. This is an ultra light portable device that can be carried to the work piece for hardness measurements. The tester has an inbuilt conversion function between the following hardness scales: Rockwell C scale - HRC, Rockwell B scale-HRB, Leeb scale - HL, Vickers hardness - HV, Brinell hardness – HB and Shore Scleroscope hardness - HS scale. The battery powered tester with 900 data point memory storage function conforms to ASTMA956, has high and low limit settings and outputs to a RS-232C port. The device is shown in Figure 3-12.

Figure 3-12 The Mitutoyo Hardmatic HH-401 Rebound Type Portable Hardness Tester

3.2.9 Kistler Dynamometer, A/D Card and Dual Mode Amplifier

A 3-component dynamometer (Make Kistler, Type 9257B) was used to measure the three orthogonal components of force. This dynamometer has great rigidity and natural high frequency. It has a high resolution, which makes it detect dynamic changes in large forces. An A/D card (Model - PCIM-DASI1602/16) was used to convert signal obtained from the charge amplifier from Voltage to Newton. A Kistler make dual mode amplifier (Type 5010B) was used to convert the dynamometer charges signals into voltage proportional to the force. Figure 3-13 shows the Kistler dynamometer, and Figure 3-14 shows the dual mode amplifier.

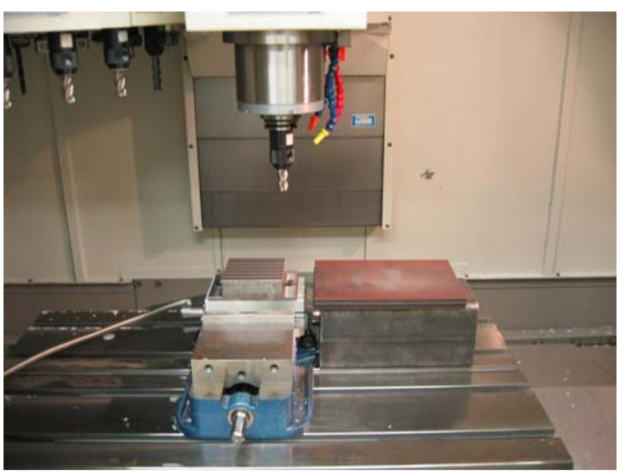


Figure 3-13 The Kistler Dynamometer (Type- 9257B) Clamped in a Vice on the Okuma Vertical Machining Center (VMC) Worktable

Figure 3-14 The Kistler Dual Mode Amplifier

3.2.10 Allen Bradley PLC

An Allen Bradley PLC (SLC 500) was used to send a signal to the power sensor to start and stop data acquisition. Also, it was used to reset the CNC after the power sensor received the stop signal. For this purpose, Rockwell software (RsLogix 500) was used to program the PLC. Figure 3-15 shows the Allen Bradley PLC 7 slot rack mounted on a stand.

Figure 3-15 The Allen Bradley PLC (SLC 500) used in the Experiment

3.2.11 Environmental Scanning Electron Microscope (ESEM)

A Philips/FEI XL30 ESEM-FEG instrument was used for qualitative analysis of back scatter images of the worn out crater surface of each insert after it reached its wear criterion (Figure 3-16). Elemental analysis of the crater surfaces of inserts using X ray energy dispersive spectral (EDS) analysis was also conducted using this instrument. The ESEM instrument combines the enhanced resolution and low-kV capabilities of a field emission gun with the ease and utility of an environmental SEM. Additional accessories include a solid-state backscattered electron detector and a Link/Oxford X-ray analysis system for energy dispersive spectroscopy. The system is built around an Oxford/Link Pentafet detector with super atmospheric thin window for light-element detection.

Figure 3-16 The Philips/FEI XL30 ESEM-FEG Instrument Setup (Image Courtesy of The Center for Advanced Microscopy at the University of Miami)

3.3 Methods of Data Collection

The experiment was conducted using two levels of speeds, three levels of feed, two levels of depth of cut and two cutting conditions. Therefore, twenty four treatments were run, each with two replications to give 48 runs. Each treatment was repeated till a maximum flank wear criterion of 0.4 mm or 400 μm was obtained. For each run, a single AISI 4340 block was used to prevent any confounding effect amongst blocks.

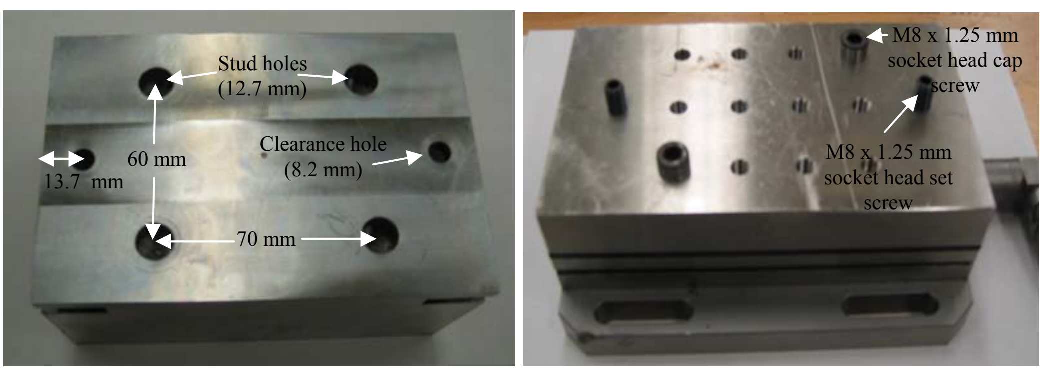
The selection of block for each run was completely randomized. During the end milling operation, eight cuts were taken on the surface of the work piece. A 2/3 immersion rato was used for the end milling operation, meaning a_r (radial depth of cut) / D (diameter of cutter) = 2/3. It was not recommended by the supplier to conduct full immersion end milling with the KC725M insert – AISI 4340 steel (26 HRc) tool - work piece combination for the cutting conditions selected to avoid tool breakage.

For every block, the second cut was taken as the learn cut for the power sensor. After that, cutting forces, tool flank wear, surface roughness and cutting power consumed was measured every four cuts. Towards the end of the tool wear criterion, readings were taken more frequently as deemed appropriate.

The power consumed during each cut was recorded as a percentage of the power consumed during the learn curve by the power sensor. The learned process was assigned a value of 100% and the subsequent cuts were compared to the learn cut and assigned a percentage. The consumed power can be calculated for cuts by multiplying this number by the nominal power consumption of the VMC motor. The spindle motor of the Okuma CNC was rated at 14/11/7.4 HP based on 10 min's, 30 min's or continuous operation time.

3.3.1 Work Piece Preparation

Each block of AISI 4340 steel had a flame cut tolerance of + 4.76 mm. The normalized and tempered 4340 steel blocks were first cleaned with sand paper and then a moist cloth to remove any dust or rust particles sticking to it. The top surface of the block was then skimmed with a 45˚ lead angle high shear angle face mill (Kennametal Vintage cutter – 80 mm effective cutting diameter) using Kennametal KC935M grade face milling inserts. The block was then turned over and finish machined to the dimension of the height i.e. 76.2 mm. The sides of the block were then finish machined the same way. The next step was to drill four blind holes at the bottom of the block and two pilot holes on opposite ends. The location of the holes is shown in Figure 3-17 (a). Two socket head screws (M8 x 1.25 mm) were then fastened onto the dynamometer base plate at two diagonally opposite blind holes at the bottom of the block, as shown in Figure 3-17 (b). This prevented the block from moving in the XY plane.



(a) (b)

Figure 3-17 (a) Clearance and blind holes drilled in the bottom of the block, and (b) Socket head set screws and cap screw on dynamometer plate

The block was then clamped to the dynamometer by bolting it down using the pilot holes drilled in the slots on the sides as shown in Figure 3-18. This prevented the block in moving in the Z direction. This setup minimized vibrations during machining that can introduce errors in the tool wear progression model.

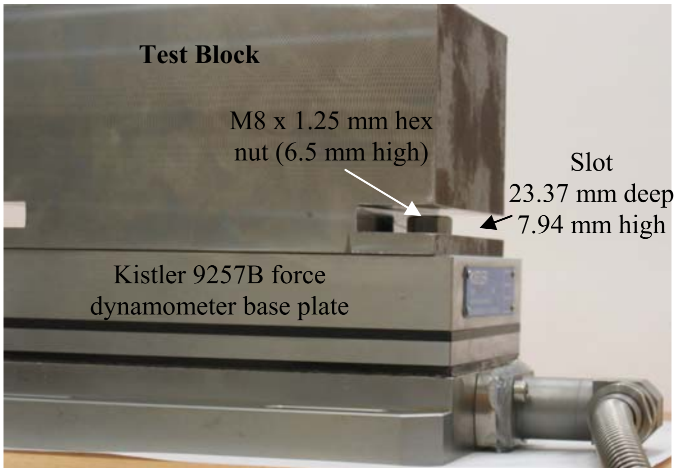


Figure 3-18 Test block clamped down to the Kistler dynamometer plate using M8 x 1.25 mm hex nut and socket head cap screw

3.3.2 Setting up the Power Sensing Instrument

The power sensor includes:

1. A measurement converter, MU3;
2. A hall sensor, LT 100-S; and
3. A modular tool control system for tool and process monitoring (MCON module W1-2).

The power sensor was connected to the computer. The ViDi software was installed on the PC to visualize and save the actual cutting process parameter readings.

3.3.3 Preparing the Cutting Tools

The following cutting insert was used for the experiment.

1. Kennametal SPET3125PPER8GB2 ground PVD coated TiAlN/TiN coated carbide inserts.

Prior to running the experiment, each cutting insert was wiped down with alcohol and the rake face and flank face observed for defects. A digital picture of the rake and flank face was taken with the Zeiss microscope.

3.3.4 Milling the Work Piece

After the block along with the dynamometer had been clamped on the vice in the CNC mill, a CNC program was used to take cuts on the block along its length (152.4 mm). The program stopped the machine every four cuts in order to measure the surface finish and flank wear on the insert. Cutting power was recorded by the Artis power sensor and cutting forces were recorded by the Kistler dynamometer every four subsequent cuts after the 2^{nd} cut.

3.3.5 Measuring Surface Finish

Surface finish values (R_a - arithmetic average) was measured using a stylus profilometer (Surtronic 3+). Calibration of the instrument requires the setting of the roughness width cut off based on the roughness values expected. The width cut off was selected as 0.25 mm. A total of 6 readings were taken to determine the average surface roughness of cut i.e. 3 readings in the center of the block and 3 readings at a distance of 1 inch from the right hand side edge of the block.

3.3.6 Measuring Flank Wear

Flank wear on the end mill insert was measured after every four cuts on the work piece. ISO 8688-2: 1989 (E) sets a recommended uniform wear criterion of 0.3 mm and a maximum wear criterion of 0.5 mm when machining steel during end milling operation. However in this case, uniform flank wear is hardly seen during dry and semi-dry end milling with KC725M inserts at the speed and feed levels selected. A maximum wear criterion of 0.5 mm may damage the tool holder and cause catastrophic failure of the insert. The tool life criterion was set at 0.4 mm after obtaining recommendations from Kennametal, the manufacturer of the KC725 M end milling insert. Maximum flank wear was selected as the preferred mode of failure because of its predictable nature. It was recorded every four cuts till the insert reached its wear criterion. After recording the flank wear, the insert was fastened back to the end mill using a Torx screwdriver that clamps the insert in the tool holder at a present tightening torque. All data recorded were used in subsequent MANOVA analyses.

3.3.7 Measuring Cutting Forces

The three orthogonal machining components, F_x, F_y and F_z were recorded with a frequency of 1,000 Hz using the Kistler force dynamometer in conjunction with the Dynoware™ software. Force measurements were taken every four cuts after the second cut till the insert reached its tool life criterion. A signal was sent by the click of a mouse to the Dynoware software to start acquiring data. The stop point for signal acquisition by the dynamometer was determined by the duration of data recording that was set in the software. The cutting force data was then exported to an excel spread sheet and used for subsequent analysis. All data recorded were used in the subsequent MANOVA analyses.

3.3.8 Measuring Cutting Power

The second cut on each block was recorded as a learn curve. The value for Breakage or maximum power and Wear or total power was recorded by the Vidi© software for every fourth cut after the learn curve till the insert reached its wear criterion. All data recorded were used in the subsequent MANOVA analyses.

3.4 Method of Data Analysis for MANOVA

Data obtained from the DOE factorial design shown in Table 3-1 was used to conduct a MANOVA analysis and fourteen subsequent ANOVA analyses. The MONOVA analysis was conducted to investigate all main and interaction effects of the independent variables (speed, feed, depth of cut and cutting condition) on all dependant variables, namely cutting force, cutting power, surface finish and tool life. MINITAB statistical software package was used for the data analysis.

The following were the steps taken for the MANOVA analysis:

1. Determination of the fitted MANOVA model.
2. Analyze residuals versus fits and normal plots of residuals to verify the assumptions for MANOVA.
3. Verify equality of covariance matrix assumption for model.
4. Verify multivariate normality assumption for model (Chi-square plot of Mahalanobis distance).
5. If appropriate, conduct data transformation.
6. Determine significance level of independent variables using Pillai-Bartlett trace test at the 95 % confidence level.

Fourteen univariate analyses of variance (ANOVA) were conducted for the fourteen dependent variables, namely: cutting forces ($F_{x\ max}$, $F_{x\ avg}$, $F_{y\ max}$, $F_{y\ avg}$, $F_{z\ max}$, $F_{z\ avg}$, $F_{xy\ max}$, $F_{xy\ avg}$, $F_{xyz\ max}$, $F_{xyz\ avg}$), cutting power (P_{max} and P_{total}), surface roughness (R_a), and tool life (T_{life} - Nos. of cuts till wear criterion). The fourteen independent ANOVA tests followed the MANOVA analysis in order to identify main and interaction effects (2 way and 3 way) for each dependant variable separately.

The steps implemented for the ANOVA analysis are as follows:

1) Perform test of significance of all main and interaction effects (two way and three way interaction terms) for all independent variables that were significant in the MANOVA analysis.
2) Perform Tukey test of means to determine if there is any statistically significant difference between dependant variable means at 95 % confidence level.
3) Interpret main and interaction effect plots (2 way and 3 way interactions). If any independent variable is involved in any interaction effect, then the highest interaction effect was studied in detail.

3.5 Pilot Study

The section of the report pertains to instrument and equipment setup for the experiment, namely, CNC mill, power sensor, dynamometer, optical microscope and profilometer, preparing work samples, testing procedures and drawing inferences.

The pilot study was conducted for four cutting conditions using KC725M coated carbide inserts in order to verify that a certain rate of tool wear was obtained to finish each experimental run within the confines of a test block.

Kennametal, the supplier of the KC725M insert states the recommended speed range of the insert to be in the range of 300 to 650 sfpm (or 91.4 to 198.1 m/min) when machining alloy steel. However as per information obtained from Kennametal, the insert can be used for cutting speeds up to 750 sfpm (229 m/min). Similarly, recommended feed rates were 0.004 to 0.010 inches per tooth (0.10 to 0.25 mm/tooth) respectively. Three levels of feed were thus selected that covered the range of recommended feed, i.e. 0.004 ipt (0.10 mm/tooth), 0.006 ipt (0.15 mm/tooth) and 0.008 ipt (0.20 mm/tooth). The highest feed level 0.010 ipt (0.25 mm/tooth) was not recommended by the supplier as it could cause machine vibration problems. The maximum depth of cut that the insert can take is 0.20 inch (5 mm). At the same time, too little of a depth of cut may not yield significant wear. Therefore, depths of cut levels were selected at 0.10 inch (2.54 mm) and 0.15 inch (3.81 mm). As per recommendation from Kennametal, going towards the maximum end of the spectrum for DOC could cause catastrophic tool failure and damage the tool.

Since this is a tool wear modeling experiment, it is absolutely necessary that the tool reach its wear criterion before the entire block is machined off to prevent any block confounding effects. Preliminary tests were conducted at low end of the speed spectrum, i.e. a cutting speed of 450 sfpm (137 m/min), a high level of federate (0.008 ipt or 0.20 mm/tooth) and a high DOC level of 0.15 inch (3.81 mm). The results were however not favorable as shown in Figure 3-19.

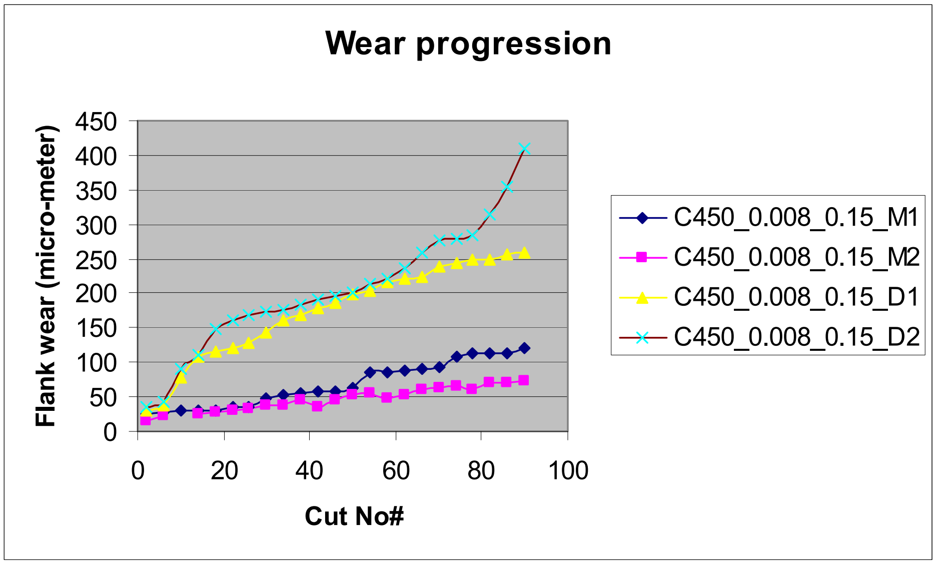


Figure 3-19 Tool Wear Progression when Machining at 450 sfpm (137 m/min), 0.008 ipt (0.20 mm per tooth) Feed and 0.15 inch (3.18 mm) Depth of Cut under Semi-dry (Condition 1) and Dry Cutting Conditions (Condition 2)

The results showed that flank wear criterion of 0.4 mm or 400 μm was reached under only one dry machining condition. Under mist conditions, maximum flank wear of only 121 μm and 90 μm were reached respectively for the two repetitions. Therefore, this speed was not acceptable as wear criterion was not being reached for most of the cutting parameter combinations with the low cutting speed level of 450 sfpm (137.2 m/min).

Therefore, cutting speed was increased to 600 sfpm (183 m/min). It was observed that even at the low levels of 0.004 ipt (0.10 mm/tooth) feed, 0.1 inch (2.54 mm) DOC and mist cooling, tool wear criterion of 400 μm was reached, as shown in Figure 3-20.

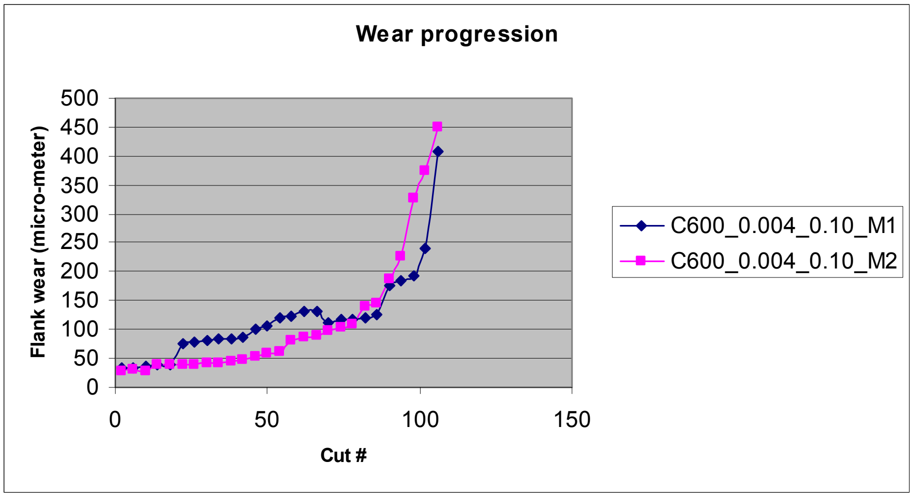


Figure 3-20 Tool Wear Progression when Machining at 600 sfpm, 0.004 ipr and 0.10 inch Depth of Cut under Mist Conditions

Based on suggestion from the tool supplier, a high cutting speed of 750 sfpm (229 m/min) was set as a high level of speed. It was observed that flank wear criterion of 400 µm was reached within the confines of a test block under the speed, feed and DOC conditions shown in Figure 3-21. Therefore, 750 sfpm (229 m/min) was selected as the upper level of cutting speed.

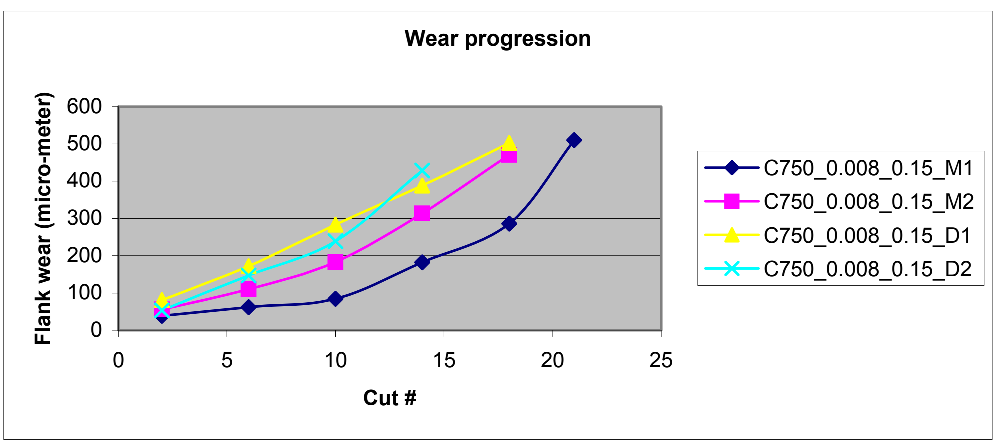


Figure 3-21 Tool Wear Progression when Machining at 750 sfpm (229 m/min), 0.008 ipt (0.20 mm/ tooth) and 0.15 inch (3.81 mm) DOC under Semi-dry and Dry Cutting Conditions

3.6 Summary

In this chapter, the experimental setup, method of data collection and analysis is discussed. A full factorial experiment with two replicates has been used for the wear experiment in order to include the experimental error in the tool wear model. Four independent (predictor) variables and fourteen dependant (response) variables have been used for the design of experiment setup. Two levels of cutting parameters were used for independent variables speed, depth of cut and cutting condition was selected for this study. Independent variable feed was selected at three levels. One of the objectives of this study is to find optimal cutting parameters when end milling AISI 4340 steel with advanced PVD coated TiAlN/TiN multilayered coated carbide inserts under semi-dry and dry cutting conditions. Tool wear modeling during end milling for this tool-work piece combination is also another important objective of this study. The criterion for maximum flank wear was established by analyzing ISO standards for milling, recommendations from insert manufacturer (Kennametal) and from results of the pilot study.

For this tool wear experiment, a pilot study was conducted to determine if cutting conditions levels used would cause the insert to reach its flank wear criterion under semi-dry and dry cutting conditions within the confines of the test block. The pilot study indicated that cutting speed levels of 600 and 750 sfpm, feed levels of 0.004, 0.006, and 0.008 inches per tooth, and depth of cut levels of 2.54 and 3.81 mm would cover supplier recommended safe cutting parameter ranges while ensuring the above mentioned objective.

Chapter 4

Analysis of Results

This chapter includes the following: i) Results of the MANOVA analysis, ii) Results of the fourteen independent ANOVA analysis, iii) Study of main and interaction effects, iv) Tukey analysis of means, v) Regression models for tool life prediction, vi) Energy dispersive spectral (EDS) analysis/ back scatter electron image analysis of tool crater surface and vii) Flank wear prediction model using mixed effects modeling technique. Section 4.0 discusses the effect of cutting parameters on the fourteen dependant variables, namely one, two and three dimensional cutting force components, cutting power, flank wear and surface roughness. Section 4.2 presents the findings of the independent ANOVA analyses conducted to study the effects of predictor variables and their interactions on the fourteen response variables selected for this study. Section 4.3 proposes a multiple regression model for predicting tool life for the range of cutting conditions discussed in this study. In Section 4.4, an analysis of flank face of the insert after it reached its wear criterion is conducted. Energy dispersive X ray (EDX) analysis results are also detailed upon in this section. Section 5 presents the mixed effects model for predicting flank wear progression. This modeling technique has been used extensively in the reliability literature for tool wear modeling and has been used for the first time in the metal cutting literature.

4.1 MANOVA Analysis

The data used in this study was checked for MANOVA assumptions. The assumptions are data independence, univariate normality, multivariate normality and equality of covariance matrices. Minitab and SPSS statistical software package were used for the analysis.

Maximum cutting force acting on the work piece in the X direction ($F_{x\ max}$), in the Y direction ($F_{y\ max}$) and in the Z direction ($F_{z\ max}$) were computed from the force readings in Newton's collected by the Kistler dynamometer. Average cutting force in X direction ($F_{x\ avg}$), in Y direction ($F_{y\ avg}$) and in Z direction of the work piece ($F_{z\ avg}$) were also computed from the force readings in Newton's acting on the work piece. Maximum two dimensional (2 D) cutting force ($F_{xy\ max}$) and average two dimensional (2 D) cutting forces ($F_{xy\ avg}$) acting on the insert were computed using Equation's 4-7 and 4-8 respectively. Maximum three dimensional (3 D) cutting force ($F_{xyz\ max}$) and average three dimensional (3 D) cutting forces ($F_{xyz\ avg}$) acting on the work piece were computed using Equation's 4-7 and 4-8 respectively.

$$F_{x\ max} = Max\ (F_x) \qquad (4\text{-}1)$$

$$F_{x\ avg} = Avg\ (F_x) \qquad (4\text{-}2)$$

$$F_{y\ max} = Max\ (F_y) \qquad (4\text{-}3)$$

$$F_{y\ avg} = Avg\ (F_y) \qquad (4\text{-}4)$$

$$F_{z\ max} = Max\ (F_z) \qquad (4\text{-}5)$$

$$F_{z\ avg} = Avg\ (F_z) \qquad (4\text{-}6)$$

$$F_{xy\ max} = Max\ \left(\sqrt{F_x^{\,2} + F_y^{\,2}}\right) \qquad (4\text{-}7)$$

$$\mathbf{F}_{xy\ avg} = \boldsymbol{Avg}\ (\sqrt{F_x^{\ 2} + F_y^{\ 2}}\ ) \qquad \textbf{\textit{(4-8)}}$$

$$\mathbf{F}_{xyz\ max} = \boldsymbol{Max}\ (\sqrt{F_x^{\ 2} + F_y^{\ 2} + F_z^{\ 2}}\ ) \qquad \textbf{\textit{(4-9)}}$$

$$\mathbf{F}_{xyz\ avg} = \boldsymbol{Avg}\ (\sqrt{F_x^{\ 2} + F_y^{\ 2} + F_z^{\ 2}}\ ) \qquad \textbf{\textit{(4-10)}}$$

Maximum cutting power (P_{max}) and Total cutting power (P_{total}) were calculated by multiplying power sensor relative maximum and total cutting power readings obtained from the VIDI© software with nominal spindle power of 5.5 KW.

Average surface roughness (R_a) in µm of machined work piece surface was measured using the Surtronic 3+ surface profiler. Averages of six readings were taken to compute the surface roughness (R_a) of a cut.

Tool life (T_{life}) was measured by the number of cuts it took for the insert flank surface to reach a maximum flank wear criterion of 0.4 mm or 400 µm under different cutting conditions shown in the Factorial experiment table (Table 3-1).

Each dependent variable was tested for ANOVA homogeneity of variance by using Bartlett test using MINITAB. The results as shown in Table 4 -1 indicate that $F_{z\ max}$, $F_{z\ avg}$, $F_{xyz\ avg}$ and P_{total} at 95 % of confidence level do not seem to meet equivalence of covariance matrices assumption. $F_{z\ max}$ however meets the assumption at 99 % confidence level.

Table 4-1 Results of the Tests for ANOVA Homogeneity of Variance

Variable	P-Value	Result	Meaning
$F_{x\ max}$	0.244	Insignificance	Equal Variance
$F_{x\ avg}$	0.937	Insignificance	Equal Variance
$F_{y\ max}$	0.364	Insignificance	Equal Variance
$F_{y\ avg}$	0.683	Insignificance	Equal Variance
$F_{z\ max}$	0.019*	Significance	Unequal Variance
$F_{z\ avg}$	0.000	Significance	Unequal Variance
$F_{xy\ max}$	0.290	Insignificance	Equal Variance
$F_{xy\ avg}$	0.323	Insignificance	Equal Variance
$F_{xyz\ max}$	0.090	Insignificance	Equal Variance
$F_{xyz\ avg}$	0.006	Significance	Unequal Variance
P_{max}	0.173	Insignificance	Equal Variance
P_{total}	0.000	Significance	Unequal Variance
R_a	0.435	Insignificance	Equal Variance
T_{Life}	0.972	Insignificance	Equal Variance

* Insignificance at 99% confidence level

However according to Bray and Maxwell (1986), Pillai Bartlett statistic is robust to this violation because of equal sample and cell sizes. Chi-square plot of Mahalanobis distance was used to test for multivariate normality (Appendix A, Figure A-35 and A-36)

4.1.1 MANOVA Results

The MANOVA analysis was performed using MINITAB package. The MANOVA model selected determines main factor effects and 2-way interaction effects. Some three way interaction effects between dependant variables were also significant in this analysis. Tukey test for comparison of means was used to determine the cutting combination that yield the best response (i.e. low cutting power, low cutting forces, high surface finish and tool life).

MANOVA results as shown in Table 4-2. The result shows that all main effects, two way interactions (*speed* x *condition* and *feed* x *condition)*, and three way interactions (*speed* x *feed* x *DOC*, *speed* x *feed* x *condition* and *speed* x *DOC* x *condition)* are significant. Next, univariate analysis of variance was performed in order to test for significance of dependent variables.

The univariate ANOVA results are shown in Table 4-3 through 4-16.

Table 4-2 MANOVA Test Summarized Results (At 95% Confidence Level)

Source	Statistic	Value	F	Numerator DF	Denominator DF	P	Result
Speed	Pillai's	0.964	20.984	14	11	0.000	Significant
Feed	Pillai's	1.683	4.559	28	24	0.000	Significant
Depth of cut (DOC)	Pillai's	0.957	17.428	14	11	0.000	Significant
Condition	Pillai's	0.89	6.342	14	11	0.002	Significant
Speed*Feed	**Pillai's**	**1.224**	**1.353**	**28**	**24**	**0.227**	**Not Significant**
Speed*DOC	**Pillai's**	**0.686**	**1.714**	**14**	**11**	**0.187**	**Not Significant**
Speed*Condition	Pillai's	0.845	4.29	14	11	0.01	Significant
Feed*DOC	**Pillai's**	**1.118**	**1.087**	**28**	**24**	**0.421**	**Not Significant**
Feed*Condition	Pillai's	1.420	2.098	28	24	0.035	Significant
DOC*Condition	**Pillai's**	**0.689**	**1.742**	**14**	**11**	**0.18**	**Not Significant**
Speed*Feed*DOC	Pillai's	1.394	1.971	28	24	0.048	Significant
Speed*Feed*Condition	Pillai's	1.493	2.524	28	24	0.012	Significant
Speed*DOC*Condition	Pillai's	0.856	4.675	14	11	0.007	Significant
Feed*DOC*Condition	**Pillai's**	**1.206**	**1.301**	**28**	**24**	**0.258**	**Not Significant**
Speed*Feed*DOC*Condition	**Pillai's**	**1.195**	**1.272**	**28**	**24**	**0.277**	**Not Significant**

Factors and their interactions that do not show significant at 95 % confidence level are marked in bold in Table 4-2. Independent variables and their interactions that are significant at 95 % confidence level in the MANOVA analysis (Table 4-2) are also marked in bold in subsequent ANOVA tables (Tables 4-3 to 4-16). It is to be noted that some dependant variables were transformed to meet the normality requirements for the MANOVA and subsequent ANOVA analyses.

Table 4-3 Univariate ANOVA Test Summarized Results for $F_{x\ max}$

Source	DF	SS	MS	F	P
Speed	**1**	**1253612**	**1253612**	**33.28**	**0.000**
Feed	**2**	**5123727**	**2561863**	**68.02**	**0.000**
DOC	**1**	**6050286**	**6050286**	**160.64**	**0.000**
Condition	1	18258	18258	0.48	0.493
Speed*Feed	2	28120	14060	0.37	0.692
Speed*DOC	1	151953	151953	4.03	0.056
Speed*Condition	1	3058	3058	0.08	0.778
Feed*DOC	2	212619	106309	2.82	0.079
Feed*Condition	**2**	**261049**	**130525**	**3.47**	**0.048**
DOC*Condition	1	68658	68658	1.82	0.190
Speed*Feed*DOC	2	21084	10542	0.28	0.758
Speed*Feed*Condition	2	70082	35041	0.93	0.408
Speed*DOC*Condition	1	65	65	0.00	0.967
Feed*DOC*Condition	2	23942	11971	0.32	0.731
Speed*Feed*DOC*Condition	2	71046	35523	0.94	0.403
Error	24	903913	37663		
Total	47	14261471			

Table 4-4 Univariate ANOVA Test Summarized Results for $F_{x\ avg}$

Source	DF	SS	MS	F	P
Speed	1	24668	24668	3.07	0.093
Feed	2	14015	7008	0.87	0.431
DOC	**1**	**51027**	**51027**	**6.35**	**0.019**
Condition	1	428	428	0.05	0.819
Speed*Feed	2	2130	1065	0.13	0.877
Speed*DOC	1	4886	4886	0.61	0.443
Speed*Condition	1	13116	13116	1.63	0.214
Feed*DOC	2	3799	1899	0.24	0.791
Feed*Condition	2	11668	5834	0.73	0.494
DOC*Condition	1	14912	14912	1.85	0.186
Speed*Feed*DOC	2	11993	5997	0.75	0.485
Speed*Feed*Condition	2	485	242	0.03	0.970
Speed*DOC*Condition	**1**	**38042**	**38042**	**4.73**	**0.040**
Feed*DOC*Condition	2	8328	4164	0.10	0.602
Speed*Feed*DOC*Condition	2	10511	5256	0.65	0.109
Error	24	192989	8041		
Total	47	402998			

Table 4-5 Univariate ANOVA Test Summarized Results for $F_{y\,max}$

Source	DF	SS	MS	F	P
Speed	1	641	641	0.01	0.931
Feed	**2**	**1819545**	**909772**	**11.02**	**0.000**
DOC	**1**	**6884819**	**6884819**	**83.40**	**0.000**
Condition	1	17690	17690	0.21	0.648
Speed*Feed	2	22496	11248	0.14	0.873
Speed*DOC	1	13396	13396	0.16	0.691
Speed*Condition	1	100596	100596	1.22	0.281
Feed*DOC	2	261641	130821	1.58	0.226
Feed*Condition	2	27598	13799	0.17	0.847
DOC*Condition	1	25532	25532	0.31	0.583
Speed*Feed*DOC	2	117715	58857	0.71	0.500
Speed*Feed*Condition	2	171135	85567	1.04	0.370
Speed*DOC*Condition	1	102223	102223	1.24	0.277
Feed*DOC*Condition	2	76920	38460	0.47	0.633
Speed*Feed*DOC*Condition	2	109535	54768	0.66	0.104
Error	24	1981154	82548		
Total	47	11732636			

Table 4-6 Univariate ANOVA Test Summarized Results for $F_{y\,avg}$

Source	DF	SS	MS	F	P
Speed	1	21320	21320	4.28	0.050
Feed	2	21090	10545	2.11	0.143
DOC	1	10529	10529	2.11	0.159
Condition	1	8061	8061	1.62	0.216
Speed*Feed	2	17461	8731	1.75	0.195
Speed*DOC	1	36	36	0.01	0.933
Speed*Condition	1	1065	1065	0.21	0.648
Feed*DOC	2	12670	6335	1.27	0.299
Feed*Condition	2	25799	12900	2.59	0.096
DOC*Condition	1	2497	2497	0.50	0.486
Speed*Feed*DOC	2	7041	3520	0.71	0.504
Speed*Feed*Condition	2	15247	7624	1.53	0.237
Speed*DOC*Condition	1	3230	3230	0.65	0.429
Feed*DOC*Condition	2	16920	8460	1.70	0.205
Speed*Feed*DOC*Condition	2	2074	1037	0.21	0.814
Error	24	119678	4987		
Total	47	284716			

Table 4-7 Univariate ANOVA Test Summarized Results for $F_{z\ max}$

Source	DF	SS	MS	F	P
Speed	**1**	**2921693**	**2921693**	**14.03**	**0.001**
Feed	2	1378035	689017	3.31	0.054
DOC	**1**	**2851656**	**2851656**	**13.69**	**0.001**
Condition	**1**	**1088901**	**1088901**	**5.23**	**0.031**
Speed*Feed	2	3681661	1840831	8.84	0.001
Speed*DOC	1	25398	25398	0.12	0.730
Speed*Condition	**1**	**1689537**	**1689537**	**8.11**	**0.009**
Feed*DOC	2	389919	194959	0.94	0.406
Feed*Condition	2	72402	36201	0.17	0.841
DOC*Condition	1	27650	27650	0.13	0.719
Speed*Feed*DOC	2	795414	397707	1.91	0.170
Speed*Feed*Condition	2	465152	232576	1.12	0.344
Speed*DOC*Condition	**1**	**1365225**	**1365225**	**6.56**	**0.017**
Feed*DOC*Condition	2	708733	354366	1.70	0.204
Speed*Feed*DOC*Condition	2	597972	298986	1.44	0.258
Error	24	4997572	208232		
Total	47	23056920			

Table 4-8 Univariate ANOVA Test Summarized Results for $(1/\sqrt{F_{z\ avg}})$

Source	DF	SS	MS	F	P
Speed	**1**	**0.0020718**	**0.0020718**	**10.91**	**0.003**
Feed	**2**	**0.0040410**	**0.0020205**	**10.64**	**0.000**
DOC	1	0.0007441	0.0007441	3.92	0.059
Condition	1	0.0001267	0.0001267	0.67	0.422
Speed*Feed	2	0.0043502	0.0021751	11.45	0.000
Speed*DOC	1	0.0004427	0.0004427	2.33	0.140
Speed*Condition	**1**	**0.0024830**	**0.0024830**	**13.07**	**0.001**
Feed*DOC	2	0.0003981	0.0001991	1.05	0.366
Feed*Condition	2	0.0000800	0.0000400	0.21	0.812
DOC*Condition	1	0.0003462	0.0003462	1.82	0.190
Speed*Feed*DOC	**2**	**0.0026862**	**0.0013431**	**7.07**	**0.004**
Speed*Feed*Condition	**2**	**0.0015367**	**0.0007683**	**4.04**	**0.031**
Speed*DOC*Condition	**1**	**0.0009070**	**0.0009070**	**4.77**	**0.039**
Feed*DOC*Condition	2	0.0006072	0.0003036	1.60	0.223
Speed*Feed*DOC*Condition	2	0.0018102	0.0009051	4.76	0.018
Error	24	0.0045591	0.0001900		
Total	47	0.0271902			

Table 4-9 Univariate ANOVA Test Summarized Results for $F_{xy\ max}$

Source	DF	SS	MS	F	P
Speed	1	53454	53454	0.74	0.400
Feed	**2**	**4972175**	**2486087**	**34.20**	**0.000**
DOC	**1**	**8563239**	**8563239**	**117.79**	**0.000**
Condition	1	25470	25470	0.35	0.559
Speed*Feed	2	4083	2041	0.03	0.972
Speed*DOC	1	72439	72439	1.00	0.328
Speed*Condition	1	558	558	0.01	0.931
Feed*DOC	2	393846	196923	2.71	0.087
Feed*Condition	2	116357	58179	0.80	0.461
DOC*Condition	1	5148	5148	0.07	0.792
Speed*Feed*DOC	2	20822	10411	0.14	0.867
Speed*Feed*Condition	2	80891	40445	0.56	0.581
Speed*DOC*Condition	1	3293	3293	0.05	0.833
Feed*DOC*Condition	2	244200	122100	1.68	0.208
Speed*Feed*DOC*Condition	2	13987	6994	0.10	0.909
Error	24	1744810	72700		
Total	47	16314770			

Table 4-10 Univariate ANOVA test summarized results for Loge ($F_{xy\ avg}$)

Source	DF	SS	MS	F	P
Speed	1	0.0456	0.0456	0.35	0.562
Feed	2	0.2135	0.1068	0.81	0.457
DOC	**1**	**0.8400**	**0.8400**	**6.36**	**0.019**
Condition	1	0.0066	0.0066	0.05	0.825
Speed*Feed	2	0.0414	0.0207	0.16	0.856
Speed*DOC	1	0.1053	0.1053	0.80	0.381
Speed*Condition	1	0.0853	0.0853	0.65	0.429
Feed*DOC	2	0.0983	0.0491	0.37	0.693
Feed*Condition	2	0.1513	0.0756	0.57	0.572
DOC*Condition	1	0.0671	0.0671	0.51	0.483
Speed*Feed*DOC	2	0.0804	0.0402	0.30	0.740
Speed*Feed*Condition	2	0.1045	0.0522	0.40	0.678
Speed*DOC*Condition	1	0.0126	0.0126	0.10	0.760
Feed*DOC*Condition	2	0.0022	0.0011	0.01	0.992
Speed*Feed*DOC*Condition	2	0.0226	0.0113	0.09	0.918
Error	24	3.1706	0.1321		
Total	47	5.0474			

Table 4-11 Univariate ANOVA Test Summarized Results for $F_{xyz\ max}$

Source	DF	SS	MS	F	P
Speed	1	82599	82599	1.57	0.222
Feed	**2**	**4811503**	**2405752**	**45.87**	**0.000**
DOC	**1**	**8676810**	**8676810**	**165.43**	**0.000**
Condition	1	3013	3013	0.06	0.813
Speed*Feed	2	10204	5102	0.10	0.908
Speed*DOC	1	62973	62973	1.20	0.284
Speed*Condition	1	4938	4938	0.09	0.762
Feed*DOC	2	504948	252474	4.81	0.017
Feed*Condition	2	129179	64590	1.23	0.310
DOC*Condition	1	40	40	0.00	0.978
Speed*Feed*DOC	2	9015	4507	0.09	0.918
Speed*Feed*Condition	2	78508	39254	0.75	0.484
Speed*DOC*Condition	1	39540	39540	0.75	0.394
Feed*DOC*Condition	2	177565	88783	1.69	0.205
Speed*Feed*DOC*Condition	2	32130	16065	0.31	0.739
Error	24	1258838	52452		
Total	47	15881802			

Table 4-12 Univariate ANOVA Test Summarized Results for ($1/\sqrt{F_{xyz\ avg}}$)

Source	DF	SS	MS	F	P
Speed	1	0.00010308	0.00010308	1.64	0.213
Feed	2	0.00035757	0.00017878	2.84	0.078
DOC	**1**	**0.00068862**	**0.00068862**	**10.94**	**0.003**
Condition	1	0.00002499	0.00002499	0.40	0.535
Speed*Feed	2	0.00012027	0.00006014	0.96	0.399
Speed*DOC	1	0.00012034	0.00012034	1.91	0.179
Speed*Condition	1	0.00000028	0.00000028	0.00	0.948
Feed*DOC	2	0.00003397	0.00001698	0.27	0.766
Feed*Condition	2	0.00005588	0.00002794	0.44	0.647
DOC*Condition	1	0.00003133	0.00003133	0.50	0.487
Speed*Feed*DOC	2	0.00000340	0.00000170	0.03	0.973
Speed*Feed*Condition	2	0.00005392	0.00002696	0.43	0.656
Speed*DOC*Condition	1	0.00000631	0.00000631	0.10	0.754
Feed*DOC*Condition	2	0.00000901	0.00000450	0.07	0.931
Speed*Feed*DOC*Condition	2	0.00008263	0.00004132	0.66	0.108
Error	24	0.00151069	0.00006295		
Total	47	0.00320229			

Table 4-13 Univariate ANOVA Test Summarized Results for P_{max}

Source	DF	SS	MS	F	P
Speed	1	1436938	1436938	0.62	0.439
Feed	**2**	**21352341**	**10676170**	**4.60**	**0.020**
DOC	1	4097930	4097930	1.76	0.197
Condition	1	317688	317688	0.14	0.715
Speed*Feed	2	2647757	1323879	0.57	0.573
Speed*DOC	1	22751	22751	0.01	0.922
Speed*Condition	1	2597026	2597026	1.12	0.301
Feed*DOC	2	4417634	2208817	0.95	0.400
Feed*Condition	2	5260601	2630301	1.13	0.339
DOC*Condition	1	1593230	1593230	0.69	0.416
Speed*Feed*DOC	2	8824051	4412026	1.90	0.171
Speed*Feed*Condition	2	11862664	5931332	2.55	0.099
Speed*DOC*Condition	1	1757588	1757588	0.76	0.393
Feed*DOC*Condition	2	4846428	2423214	1.04	0.368
Speed*Feed*DOC*Condition	2	2118382	1059191	0.46	0.639
Error	24	55749238	2322885		
Total	47	128902245			

Table 4-14 Univariate ANOVA Test Summarized Results for $(1/\sqrt{P_{total}})$

Source	DF	SS	MS	F	P
Speed	**1**	**0.000126917**	**0.000126917**	**21.65**	**0.000**
Feed	**2**	**0.000053740**	**0.000026870**	**4.58**	**0.021**
DOC	**1**	**0.000030242**	**0.000030242**	**5.16**	**0.032**
Condition	1	0.000001391	0.000001391	0.24	0.631
Speed*Feed	2	0.000039622	0.000019811	3.38	0.051
Speed*DOC	1	0.000000785	0.000000785	0.13	0.718
Speed*Condition	**1**	**0.000071248**	**0.000071248**	**12.15**	**0.002**
Feed*DOC	2	0.000012680	0.000006340	1.08	0.355
Feed*Condition	2	0.000018563	0.000009281	1.58	0.226
DOC*Condition	1	0.000002907	0.000002907	0.50	0.488
Speed*Feed*DOC	**2**	**0.000040276**	**0.000020138**	**3.43**	**0.049**
Speed*Feed*Condition	**2**	**0.000051735**	**0.000025868**	**4.41**	**0.023**
Speed*DOC*Condition	1	0.000002716	0.000002716	0.46	0.503
Feed*DOC*Condition	2	0.000013166	0.000006583	1.12	0.342
Speed*Feed*DOC*Condition	2	0.000002657	0.000001329	0.23	0.799
Error	24	0.000140710	0.000005863		
Total	47	0.000609354			

Table 4-15 Univariate ANOVA Test Summarized Results for R_a

Source	DF	SS	MS	F	P
Speed	**1**	**0.07015**	**0.07015**	**5.43**	**0.028**
Feed	**2**	**0.40816**	**0.20408**	**15.81**	**0.000**
DOC	**1**	**0.09946**	**0.09946**	**7.70**	**0.011**
Condition	1	0.01552	0.01552	1.20	0.284
Speed*Feed	2	0.01278	0.00639	0.50	0.616
Speed*DOC	1	0.00263	0.00263	0.20	0.656
Speed*Condition	1	0.02240	0.02240	1.74	0.200
Feed*DOC	2	0.00254	0.00127	0.10	0.907
Feed*Condition	2	0.00806	0.00403	0.31	0.735
DOC*Condition	1	0.00144	0.00144	0.11	0.741
Speed*Feed*DOC	2	0.02687	0.01344	1.04	0.369
Speed*Feed*Condition	2	0.00085	0.00043	0.03	0.968
Speed*DOC*Condition	1	0.01089	0.01089	0.84	0.368
Feed*DOC*Condition	2	0.01261	0.00630	0.49	0.620
Speed*Feed*DOC*Condition	2	0.01949	0.00974	0.75	0.481
Error	24	0.30986	0.01291		
Total	47	1.02371			

Table 4-16 Univariate ANOVA Test Summarized Results for T_{life}

Source	DF	SS	MS	F	P
Speed	**1**	**3538.05**	**3538.05**	**257.77**	**0.000**
Feed	**2**	**4833.98**	**2416.99**	**176.09**	**0.000**
DOC	**1**	**86.67**	**86.67**	**6.31**	**0.019**
Condition	**1**	**259.01**	**259.01**	**18.87**	**0.000**
Speed*Feed	2	691.67	345.83	25.20	0.000
Speed*DOC	1	79.83	79.83	5.82	0.024
Speed*Condition	1	1.37	1.37	0.10	0.755
Feed*DOC	2	21.14	10.57	0.77	0.474
Feed*Condition	2	46.35	23.18	1.69	0.206
DOC*Condition	1	9.28	9.28	0.68	0.419
Speed*Feed*DOC	2	66.78	33.39	2.43	0.109
Speed*Feed*Condition	**2**	**188.71**	**94.36**	**6.87**	**0.004**
Speed*DOC*Condition	**1**	**63.25**	**63.25**	**4.61**	**0.042**
Feed*DOC*Condition	2	44.26	22.13	1.61	0.220
Speed*Feed*DOC*Condition	2	111.96	55.98	4.08	0.030
Error	24	329.42	13.73		
Total	47	10371.70			

All the dependant variables met normality assumption for the ANOVA and MANOVA analysis. Some dependant variables had to be transformed using Box Cox transforms. Table 4-17 shows the transformations that were used to normalize the data.

Table 4-17 Data Transform used (Box Cox Transformation)

Variable	**Type of transform**
$F_{z\ avg}$	$1/\sqrt{F_{z\ avg}}$
$F_{xy\ avg}$	$Log_e(F_{xy\ avg})$
$F_{xyz\ avg}$	$1/\sqrt{F_{xyz\ avg}}$
P_{total}	$1/\sqrt{P_{total}}$

Normality plot for residuals and Anderson Darling test for normality for all dependant variables and their transformations are shown in Appendix A (Figure A-1 to A-36). Multivariate plot for normality (Chi-Square plots for Mahalanobis distance) before and after data transforms are also shown in Appendix A (Figure A-37 and A-38 respectively).

4.2 Effects of the Independent Variables

The main purpose of this section is to discuss the effects of independent variables cutting speed, feed, depth of cut, cutting condition and their interaction on fourteen dependant variables selected as a part of this study. The results of the multiple analyses of variance (MANOVA) are shown in Table 4-2. From the table, it can be inferred that speed, feed, depth of cut, cutting condition, *speed x condition* interaction, *feed x condition* interaction, *speed* x *feed* x *DOC* interaction, *speed* x *feed* x *condition* interaction and *speed* x *depth of cut* x *condition* interaction have an effect on at least one or more of the dependant variables being studied. In order to determine which of the fourteen dependant variables are affected by the independent variables and their significant interactions listed above, analysis of variance (ANOVA) was conducted. Main effects plot and interaction plots were plotted from the results of the MANOVA and ANOVA analysis.

4.2.1 Dependent Variable: Maximum Force in X direction on Work piece ($F_{x\ max}$)

MANOVA analysis was conducted to determine which independent variables and their significant interactions have an affect on some or all of the dependant variables. ANOVA analysis was subsequently conducted to determine whether speed, feed, depth of cut, cutting condition, and their significant interactions had an effect on the maximum force in the X direction of the work piece ($F_{x\ max}$). The force in X direction was measured by the Kistler dynamometer. The ANOVA analysis for $F_{x\ max}$ is shown in Table 4-3. Only the effects at $\alpha = 0.05$ significance level are taken into consideration in the analysis. A significant main effect is one that has a probability of occurrence (P value) less then or equal to 0.05. A significant interaction effect occurs when an independent variable along with its interaction with other independent variables cause some difference or change in the effect of the variable on the dependant variable of interest ($F_{x\ max}$ in this case).

The main effects plot for $F_{x\ max}$ is shown in Figure 4-1 and the interaction plot shown in Figure 4-2. Mean values for $F_{x\ max}$ are used to plot the main and interaction plots.

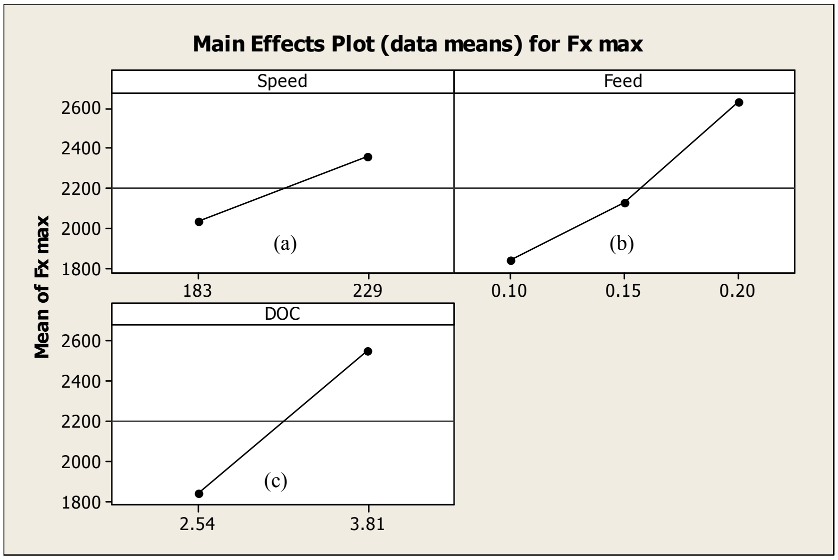


Figure 4-1 Plots of Main Effects for Maximum Cutting Force on Work piece in X Direction ($F_{x\ max}$ in Newton's)

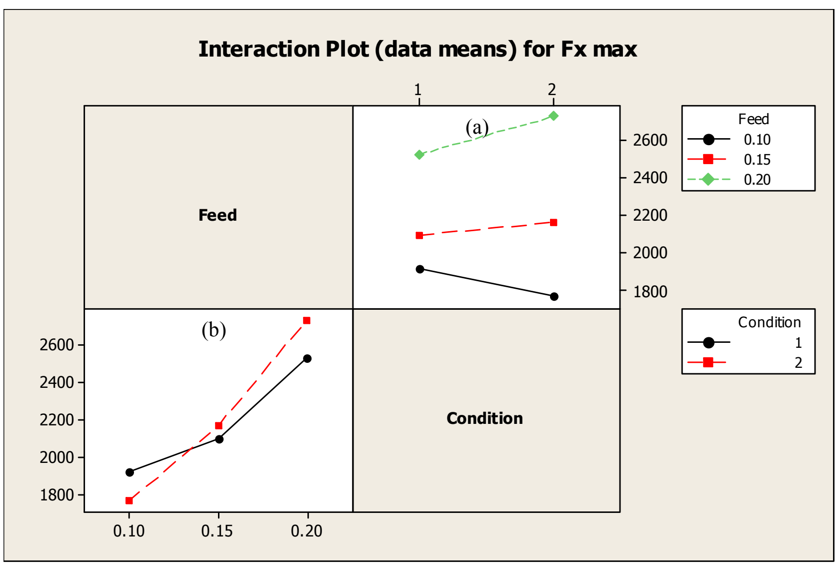


Figure 4-2 Plots of Feed & Condition Two way Interaction Effects for Response Maximum Cutting Force $F_{x\ max}$ (Newton's)

The list below shows main effects and interaction effects of independent variables and their interactions on $F_{x\ max}$ at a significance level $\alpha = 0.05$

1. Speed main effect Figure 4-1 (a)
2. Feed main effect Figure 4-1 (b)
3. DOC main effect Figure 4-1 (c)
4. *Feed x Condition* interaction effect Figure 4-2

Figure 4-1 (a) shows that maximum cutting force in X direction ($F_{x\ max}$) increases with an increase in cutting speed from 183 to 229 m/min when machining AISI 4340 steel with coated PVD TiAlN/TiN carbide inserts under dry and semi-dry end milling conditions..

The main effects plot in Figure 4-1 (b) shows that increasing feed from 0.10 to 0.15 mm /rev and from 0.15 to 0.20 mm/rev results in increase in $F_{x\ max}$. The effect of feed on $F_{x\ max}$ is not studied independently as there exists a *feed x condition* interaction that will be studied in more detail. Figure 4-1 (c) also shows that $F_{x\ max}$ also increases with an increase in DOC from 2.54 mm to 3.81 mm.

Tukey test for comparison of means of was conducted to determine if the means obtained for maximum force in X direction on work piece ($F_{x\ max}$) are statistically different from each other at different factor and interaction levels at 95 % confidence level.

4.2.1.1 Tests for contrast of means

The multivariate analysis results in Table 4-2 showed that speed, feed, depth of cut and cutting condition were all significant main effects. This means that for all independent variables, vector of means are significant. Therefore, for at least one dependant variable, there exists a group of means that is significantly different from the population. Tukey test was used for the test of means of each dependant variable. The assumption of equal sample size for Tukey test was met in this analysis. The following sections discuss the results of the Tukey test.

4.2.1.2 Contrast among means for cutting speed

Tukey test was used to compare means using Minitab. The pair wise comparison showed that $F_{x\ max}$ means obtained with cutting speeds of 183 and 229 m/min are statistically different from each other at 95 % confidence level. A lower value of $F_{x\ max}$ mean is obtained with a lower cutting speed of 183 m/min.

4.2.1.3 Contrast among means for depth of cut (DOC)

Tukey test was used to compare $F_{x\ max}$ means using Minitab. The Tukey pair wise comparison showed that mean of $F_{x\ max}$ values obtained for a DOC of 2.54 and 3.81 mm are statistically different from each other at 95 % confidence level.

4.2.1.4 Contrast among feed & condition interaction means

Tukey test for comparison of means was performed to see if there is any statistical difference between the interaction level means for $F_{x\ max}$. The *feed x condition* interaction are not significant at 95% confidence level for the following cutting conditions:

1. Increasing feed from 0.10 mm/rev to 0.20 mm/rev under semi-dry cutting conditions;

2. Increasing feed from 0.10 mm/rev and semi-dry cutting condition to 0.20 mm/rev under dry cutting condition;
3. Increasing feed from 0.10 mm/rev and dry cutting condition to 0.20 mm/rev and semi-dry machining condition;
4. Increasing feed from 0.10 mm/rev to 0.20 mm/rev under dry cutting condition, and
5. Increasing feed from 0.15 mm/rev under semi-dry cutting condition to 0.20 mm/rev under dry cutting condition.

The Tukey test for comparison of $F_{x\ max}$ means for all other cutting conditions showed significance at 95% confidence level.

4.2.1.6 Summary of results of dependant variable $F_{x\ max}$

From the MANOVA, ANOVA and Tukey test for the comparison of means, the following are the summary of results of effects of independent variables and their interactions on dependant variable $F_{x\ max}$ (Maximum cutting force in X direction on work piece in Newton's)

a) Effect of speed on $F_{x\ max}$

The Tukey test for comparison of means for $F_{x\ max}$ showed a significant statistical difference at 95 % confidence level between cutting speeds of 183 and 229 m/min. Therefore, a lower cutting speed of 183 m/min is recommended when end milling AISI 4340 hardened steel with advanced PVD coated TiN/TiAlN inserts under both dry and semi dry conditions in order to obtain low values of $F_{x\ max}$.

b) Effect of DOC

Tukey test was used to compare $F_{x\ max}$ means using Minitab. The pair wise comparison showed that mean of $F_{x\ max}$ values obtained for a DOC of 2.54 and 3.81 mm are statistically different from each other at 95 % confidence level. Therefore, in order to obtain a lower value of $F_{x\ max}$ mean, a lower depth of cut level of 2.54 mm is selected.

c) Effect of *feed & condition* interaction

The results of the Tukey test of means of $F_{x\ max}$ are summarized in Table 4-18. +Significance stands for statistical difference between mean values of $F_{x\ max}$ at 95 % confidence level, when the value shows an increasing trend amongst cutting conditions being compared. Similarly, -Significance stands for statistical difference between mean value of $F_{x\ max}$ at 95 % confidence level when the mean value of $F_{x\ max}$ shows a decreasing trend. No Significance is used to denote no statistically significant difference in $F_{x\ max}$ means being compared at 95 % confidence level between conditions.

Table 4-18 The Results of Tukey Pair wise Comparison of $F_{x\ max}$ Means for Feed & Condition Interaction

	0.10:1 (1916.2 N)	**0.10:2 (1762.0 N)**	**0.15:1 (2095.2 N)**	**0.15:2 (2162.7N)**	**0.20:1 (2528.2 N)**	**0.20:2 (2731.9 N)**
0.10:1 (1916.2 N)		No Significance	No Significance	No Significance	+ Significance	+ Significance
0.10:2 (1762.0 N)			No Significance	No Significance	+ Significance	+ Significance
0.15:1 (2095.2 N)				No Significance	No Significance	+ Significance
0.15:2 (2162.7N)					No Significance	No Significance
0.20:1 (2528.2 N)						No Significance
0.20:2 (2731.9 N)						

Note: 1 – Semi-dry machining condition, 2 – Dry machining condition; Feed levels used are 0.10, 0.15, and 0.20 mm/rev. The mean value for $F_{x\ max}$ in Newton's is stated under the cutting condition.

Table 4-18 shows that the difference in mean values for $F_{x\ max}$ obtained for the following *feed* x *condition* interaction are not statistically significant at 95% confidence level;

1) Changing cutting condition from semi-dry to dry keeping feed rate constant at 0.10 mm/rev;
2) Changing cutting condition from a feed rate of 0.10 mm/rev to 0.15 mm/rev under semi-dry cutting condition;
3) Changing cutting condition from a feed rate of 0.10 mm/rev under semi-dry cutting condition to 0.15 mm/rev under dry cutting condition;
4) Changing cutting condition from a feed rate of 0.10 mm/rev under dry cutting condition to 0.15 mm/rev under semi-dry cutting condition;
5) Changing cutting condition from a feed rate of 0.10 mm/rev to 0.15 mm/rev under dry cutting condition;
6) Changing cutting condition from semi-dry to dry keeping feed rate constant at 0.15 mm/rev;
7) Changing cutting condition from a feed rate of 0.15 mm/rev to 0.20 mm/rev under semi-dry cutting condition;
8) Changing cutting condition from a feed rate of 0.15 mm/rev under dry cutting condition to 0.20 mm/rev under semi-dry cutting condition;
9) Changing cutting condition from a feed rate of 0.15 mm/rev to 0.20 mm/rev under dry cutting condition;
10) Changing cutting condition from semi-dry to dry cutting condition at a feed rate of 0.20 mm/rev;

From Table 4-18, the following cutting conditions yield lowest mean value of $F_{x\ max}$ and are not statistically different from each other at 95 % confidence level:

1) Feed rate of 0.10 mm/rev under dry cutting condition
2) Feed rate of 0.15 mm/rev under semi-dry cutting condition
3) Feed rate of 0.15 mm/rev under dry cutting condition

A feed value of 0.15 mm/rev under semi-dry cutting condition is selected as the optimal cutting parameter when the objective is to obtain the minimum values for $F_{x\ max}$ mean when end milling AISI 4340 steel blocks with advanced PVD TiN/TiAlN coated carbide cutting inserts. If machining dry is the objective, then the dry cutting option is preferred.

4.2.2 Dependent Variable: Average Force in X direction on Work piece ($F_{x\ avg}$)

MANOVA analysis and univariate ANOVA analysis was conducted to determine whether speed, feed, depth of cut, cutting condition, and their interactions had an effect on the average force in the X direction of the work piece ($F_{x\ avg}$). $F_{x\ avg}$ was computed from the measurement of the force in X direction of work piece as measured by the Kistler dynamometer. The ANOVA analysis for $F_{x\ avg}$ is shown in Table 4-4. Only the effects at $\alpha = 0.05$ level of significance are taken into consideration in the analysis. A significant main effect is one that has a probability of occurrence (P value) less then or equal to 0.05. A significant interaction effect occurs when an independent variable along with its interaction with other independent variables causes some difference or change in the effect of the variable on the dependant variable of interest ($F_{x\ avg}$ in this case).

The main effects plot for $F_{x\ avg}$ is shown in Figure 4-3. The three way interaction effect plot for *speed* x *DOC* x *condition* interaction is shown in Figure 4-4. The mean values for $F_{x\ avg}$ are used to plot the main effect plot.

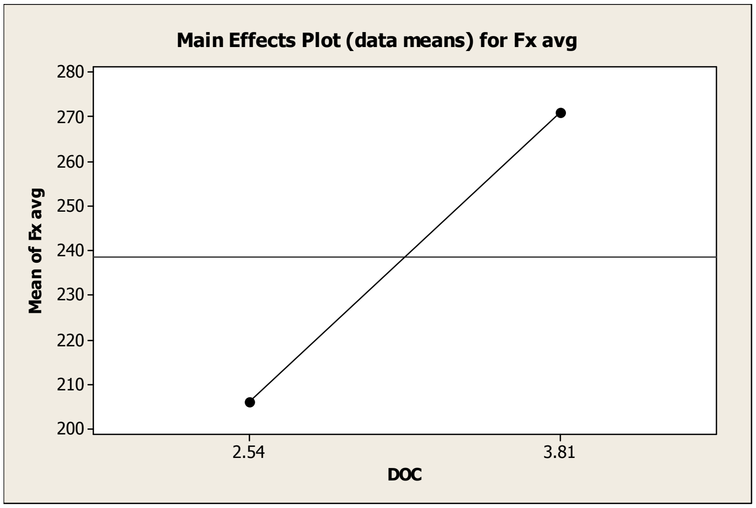


Figure 4-3 Plots of Main Effects for Average Cutting Force $F_{x\ avg}$ (Newton's)

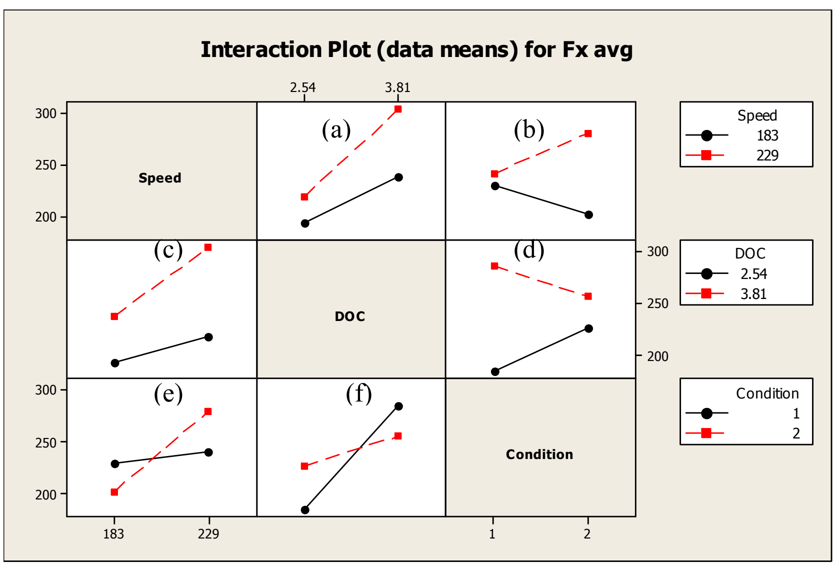


Figure 4-4 Interaction Plots for Speed, DOC & Condition Interaction for Average Cutting Force in X direction ($F_{x\ avg}$, Newton's)

The list below shows the only main effect for $F_{x\ avg}$ at a significance level $\alpha = 0.05$

1. DOC main effect Figure 4-3
2. *Speed* x *DOC* x *condition* interaction Figure 4-4

Figure 4-3 shows that average cutting force in X direction ($F_{x\ avg}$) increases with an increase in depth of cut from 2.54 to 3.81 mm when machining AISI 4340 steel with PVD TiAlN/TiN coated carbide inserts under dry and semi-dry end milling conditions. Figure 4-4 shows the three way interaction plot for *speed* x *DOC* x *condition* interaction for $F_{x\ avg}$ means. However, the main effect of DOC on $F_{x\ avg}$ will not be interpreted separately, as there exists a *speed* x *DOC* x *condition* three way interaction effect.

Tukey test for comparison of means was conducted to determine if the means obtained for average cutting force in X direction on work piece ($F_{x\ avg}$) are statistically different from each other at 95 % confidence level for different interaction levels of factors.

4.2.2.1 Contrast among means for speed, DOC & condition interaction means

Tukey test for comparison of means was performed to see if there is any statistical difference between the interaction level means for $F_{x\ avg}$. The *speed* x *DOC* x *condition* interaction is not significant at 95% confidence level for the following cutting conditions:

1. Changing cutting condition from semi-dry to dry under a depth of cut of 2.54 mm and a cutting speed of 183 m/min;
2. Changing depth of cut from 2.54 mm under semi-dry cutting condition to 3.81 mm under dry cutting condition at a cutting speed of 183 m/min;

3. Changing cutting speed from 183 to 229 m/min under semi-dry cutting condition and a DOC of 2.54 mm;
4. Changing cutting speed from 183 m/min under semi-dry cutting condition to 229 m/min under dry cutting condition at a DOC of 2.54 mm;
5. Changing depth of cut from 2.54 mm at a cutting speed of 183 m/min to a depth of cut of 3.81 mm at a cutting speed of 229 m/min under semi-dry cutting condition;
6. Changing DOC from 2.54 mm under dry cutting condition to a DOC of 3.81 mm under semi-dry cutting condition at a cutting speed of 183 m/min;
7. Changing depth of cut from 2.54 to 3.81 mm at a cutting speed of 183 m/min under dry cutting condition;
8. Changing cutting speed from 183 m/min under dry cutting condition to 229 m/min under semi-dry cutting condition at a DOC of 2.54 mm;
9. Changing cutting speed from 183 to 229 m/min at a depth of cut of 2.54 mm under dry cutting condition;
10. Changing DOC from 2.54 mm at a cutting speed of 183 m/min under dry cutting condition to a DOC of 3.81 mm at a DOC of 3.81 mm under semi-dry cutting condition;
11. Changing DOC from 3.81 mm at a cutting speed of 183 m/min to a DOC of 2.54 mm at a cutting speed of 229 m/min under dry cutting condition;
12. Changing DOC from 3.81 mm at a cutting speed of 183 m/min under semi-dry cutting condition to a DOC of 2.54 mm at a cutting speed of 229 m/min under dry cutting condition;

13. Changing cutting speed from 183 m/min to 229 m/min at a DOC of 3.81 mm under semi-dry cutting condition;
14. Changing cutting condition from semi-dry at a cutting speed of 183 m/min to dry at a cutting speed of 229 m/min at a DOC of 3.81 mm;
15. Changing cutting condition from a DOC of 3.81 mm under dry cutting condition at a cutting speed of 183 m/min to a DOC of 2.54 mm under semi-dry cutting condition at a cutting speed of 229 m/min;
16. Changing depth of cut from 3.81 mm at a cutting speed of 183 m/min to a depth of cut of 2.54 mm at a cutting speed of 229 m/min under dry cutting condition;
17. Changing cutting condition from dry at 183 m/min to semi-dry at 229 m/min at a depth of cut of 3.81 mm;
18. Changing cutting condition from semi-dry to dry at a cutting speed of 229 m/min and a depth of cut of 2.54 mm;
19. Changing depth of cut from 2.54 to 3.81 mm under semi-dry cutting condition at a cutting speed of 229 m/min;
20. Changing depth of cut from 2.54 mm under a cutting speed of 183 m/min to a under dry cutting condition to a depth of cut of 3.81 mm under a cutting speed of 229 m/min under semi-dry cutting condition;
21. Changing cutting condition from semi-dry to dry under a cutting speed of 229 m/min and a depth of cut of 3.81 mm;

The Tukey test for comparison of $F_{z\ avg}$ means for all other cutting conditions showed significant difference at 95% confidence level.

4.2.2.2 Summary of results of dependant variable $F_{x\ avg}$

From the MANOVA, ANOVA and Tukey test for the comparison of means, the following are the summary of results of effects of independent variables on dependant variable $F_{x\ avg}$ (Average force in X direction on work piece in Newton's).

From Table 4-19, the following cutting conditions yield lowest mean value of $F_{x\ avg}$:

1) Speed of 183 m/min, DOC of 2.54 mm, semi-dry cutting condition
2) Speed of 183 m/min, DOC of 2.54 mm, dry cutting condition
3) Speed of 183 m/min, DOC of 3.81 mm, dry cutting condition
4) Speed of 229 m/min, DOC of 2.54 mm, semi-dry cutting condition
5) Speed of 229 m/min, DOC of 2.54 mm, dry cutting condition
6) Speed of 229 m/min, DOC of 3.81 mm, semi-dry cutting condition

In order to obtain a low value of $F_{x\ avg}$ and the highest material removal rate, a cutting speed of 229 m/min and a depth of cut of 3.81 mm under semi-dry cutting condition are recommended when end milling AISI 4340 steel blocks with advanced PVD TiAlN/TiN coated carbide cutting inserts.

Table 4-19 The Results of Tukey Pair wise Comparison of $F_{x\ avg}$ Means for Speed, DOC & Condition Interaction

		183 m/min				229 m/min			
		2.54:1 (161.16 N)	**2.54:2 (225.63 N)**	**3.81:1 (297.75 N)**	**3.81:2 (179.11 N)**	**2.54:1 (209.57 N)**	**2.54:2 (227.55 N)**	**3.81:1 (273.90 N)**	**3.81:2 (333.99 N)**
183 m/min	**2.54:1 (161.16 N)**		No significance	+Significance	No significance	No significance	No significance	No significance	+Significance
	2.54:2 (225.63 N)			No significance	No significance	No significance	No significance	No significance	+Significance
	3.81:1 (297.75 N)				-Significance	No significance	No significance	No significance	No significance
	3.81:2 (179.11 N)					No significance	No significance	No significance	+Significance
229 m/min	**2.54:1 (209.57 N)**						No significance	No significance	+Significance
	2.54:2 (227.55 N)							No significance	+Significance
	3.81:1 (273.90 N)								No significance
	3.81:2 (333.99 N)								

Note: 1 – Semi-dry machining condition, 2 – Dry machining condition; Cutting speed levels used are 183 and 229 m/min; DOC levels used are 2.54 and 3.81 mm. The mean value for $F_{x\ avg}$ in Newton's is stated under the cutting condition.

4.2.3 Dependent Variable: Maximum Force in Y direction on Work piece ($F_{y\ max}$)

MANOVA analysis was conducted to determine which independent variables have an affect on some or all of the dependant variables. ANOVA analysis was subsequently conducted to determine whether speed, feed, depth of cut, cutting condition and their significant interactions had an effect on the maximum force in the Y direction of the work piece ($F_{y\ max}$). The force in Y direction was measured by the Kistler dynamometer. The ANOVA analysis for $F_{y\ max}$ is shown in Table 4-5. Only the effects at $\alpha = 0.05$ significance level are taken into consideration in the analysis. A significant main effect is one that has a probability of occurrence (P value) less then or equal to 0.05. A significant interaction effect occurs when an independent variable along with its interaction with other independent variables causes some difference or change in the effect of the variable on the dependant variable of interest ($F_{y\ max}$ in this case).

The main effects plot for $F_{y\ max}$ is shown in Figure 4-5. The mean values for $F_{y\ max}$ were used to plot the main effects plot.

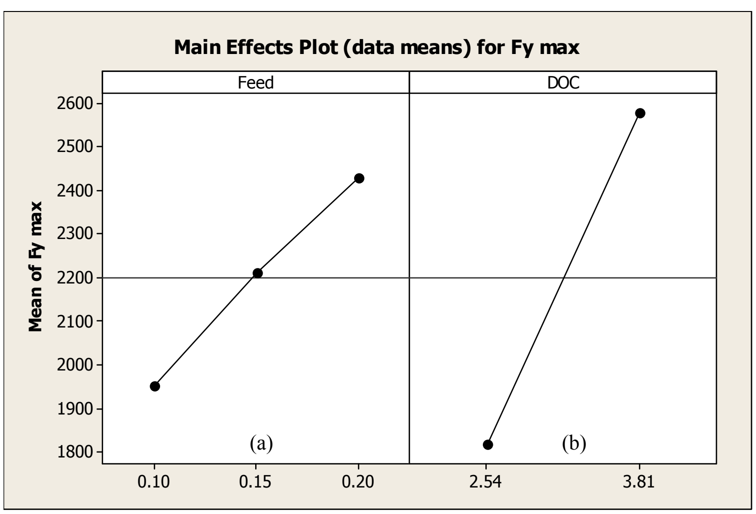


Figure 4-5 Plots of Main Effects for Maximum Cutting Force on Work piece in Y direction ($F_{y\ max}$ in Newton's)

The list below shows main effects of independent variables and their interactions on $F_{y\,max}$ at a significance level $\alpha = 0.05$

1. Feed main effect — Figure 4-5 (a)
2. DOC main effect — Figure 4-5 (b)

Figure 4-5 (a) shows that mean of maximum cutting force in Y direction ($F_{y\,max}$) increases with an increase in feed from 0.10 to 0.15 mm/rev and from 0.15 to 0.20 mm/rev when machining AISI 4340 steel with coated PVD TiAlN/TiN coated carbide inserts under dry and semi-dry end milling conditions. Figure 4-5 (b) shows that mean of $F_{y\,max}$ also increase with an increase in DOC from 2.54 mm to 3.81 mm.

Tukey test for comparison of means was conducted to determine if the means obtained for maximum force in Y direction on work piece ($F_{y\,max}$) are statistically different from each other at different factor and interaction levels at 95 % confidence level.

4.2.3.1 Tests for contrast of means

The multivariate analysis results in Table 4-2 showed that speed, feed, depth of cut and cutting condition were all significant main effects. This means that for all independent variables, vector of means are significant. Therefore for at least one dependant variable, there exists a group of means that is significantly different from the population. Tukey test was used for the test of means of each dependant variable. The equal sample size assumption was met for the Tukey test. The following sections discuss the results of the Tukey test.

4.2.3.2 Contrast among means for feed

Tukey test was used to compares means using Minitab. The pair wise comparison showed that $F_{y\ max}$ means obtained with feeds of 0.10 mm/rev and 0.15 mm/rev, and 0.15 mm/rev and 0.20 mm/rev are not statistically different from each other at 95 % confidence level.

4.2.3.3 Contrast among means for depth of cut (DOC)

Tukey test was used to compare $F_{y\ max}$ means using Minitab. The pair wise comparison showed that mean of $F_{y\ max}$ values obtained for a DOC of 2.54 and 3.81 mm are statistically different from each other at 95 % confidence level.

4.2.3.4 Summary of results of dependant variable $F_{y\ max}$

From the MANOVA, ANOVA and Tukey test for the comparison of means, the following are the summary of results of effect of independent variables and their interactions on dependant variable $F_{y\ max}$ (Maximum force in Y direction on work piece in Newton's)

a) Effect of feed

The Tukey test for comparison of means for $F_{y\ max}$ did not show a statistical difference at 95 % confidence level between the three levels of cutting feed used, i.e. 0.10 mm/rev, 0.15 mm/rev and 0.20 mm/rev respectively. The highest value of $F_{y\ max}$ mean was obtained when using a feed rate of 0.20 mm/rev, followed by feed rates of 0.15 mm/rev and 0.10 mm/rev respectively, as shown in Figure 4-5 (a). Therefore, for a higher material removal rate, the feed rate of 0.20 mm/rev is recommended.

b) Effect of DOC

The Tukey test for comparison of means for $F_{y\ max}$ showed a statistical difference at 95 % confidence level between the two levels of DOC selected, i.e. 2.54 and 3.81 mm, as shown in Figure 4-5 (b). The higher value of $F_{y\ max}$ mean was obtained when using a DOC of 3.81 mm, followed by a DOC level of 2.54 mm. However in order to obtain a lower value of $F_{y\ max}$ mean, the lower level of DOC, i.e. 2.54 mm is recommended when end milling AISI 4340 hardened steel with advanced PVD coated TiN/TiAlN inserts under dry and semi-dry cutting conditions to obtain low values of $F_{y\ max}$.

4.2.4 Dependent Variable: Maximum Force in Z direction on Work piece ($F_{z\ max}$)

MANOVA analysis was conducted to determine which independent variables have an affect on some or all of the dependant variables. ANOVA analysis was subsequently conducted to determine whether speed, feed, depth of cut, cutting condition, and their significant interactions had an effect on the maximum force in the Z direction of the work piece ($F_{z\ max}$). The force in Z direction was measured by the Kistler dynamometer. The ANOVA analysis for $F_{z\ max}$ is shown in Table 4-7. Only the effects at $\alpha = 0.05$ significance level are taken into consideration in the analysis. A significant main effect is one that has a probability of occurrence (P value) less then or equal to 0.05. A significant interaction effect occurs when an independent variable along with its interaction with other independent variables causes some difference or change in the effect of the variable on the dependant variable of interest ($F_{z\ max}$ in this case).

The main effects plot for $F_{z\ max}$ is shown in Figure 4-6. The mean values for $F_{z\ max}$ are used to plot the main effects plot. The two way *speed* x *condition* interaction plot for $F_{z\ max}$ means is shown on Figure 4-7. The three way *speed* x *DOC* x *condition* interaction plot for $F_{z\ max}$ is shown in Figure 4-8.

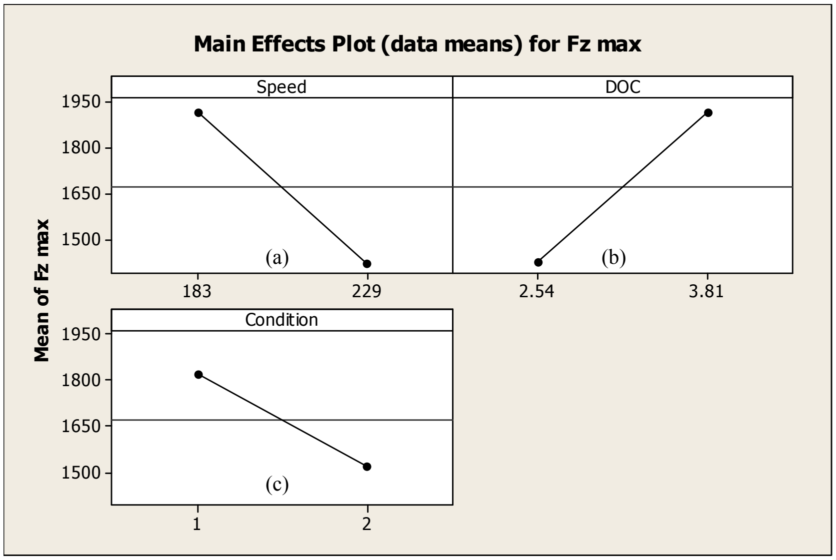


Figure 4-6 Plots of Main Effects for Maximum Cutting Force on Work piece in Z direction ($F_{z\ max}$ in Newton's)

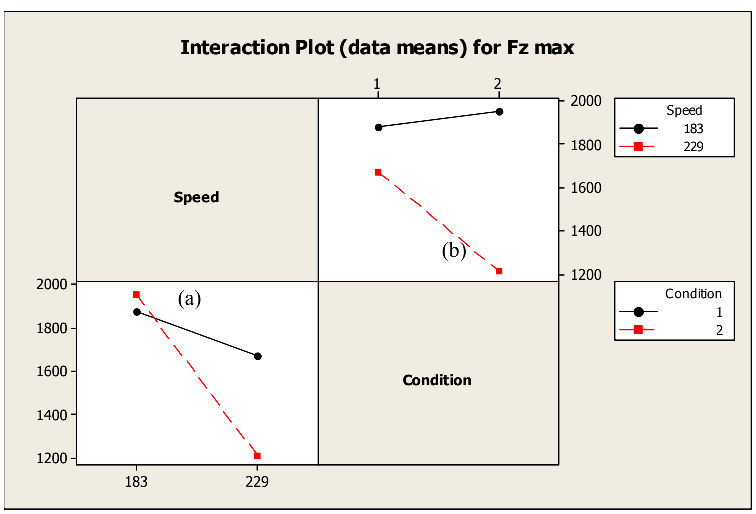


Figure 4-7 Two Way Speed & Condition Interaction Plot for Maximum Cutting Force on Work piece in Z direction ($F_{z\ max}$ in Newton's)

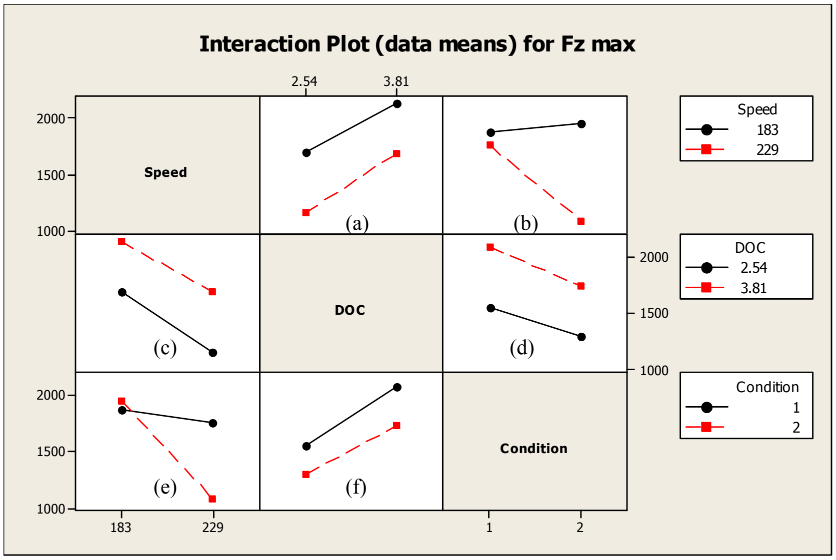


Figure 4-8 Three Way Speed, DOC & Condition Interaction Plot for Maximum Cutting Force on Work piece in Z direction ($F_{z\ max}$ in Newton's)

The list below are the main effects of independent variables and their interactions on $F_{z\ max}$ at a significance level $\alpha = 0.05$

1. Speed main effect	Figure 4-6 (a)
2. DOC main effect	Figure 4-6 (b)
3. Condition main effect	Figure 4-6 (c)
4. *Speed* x *condition* interaction	Figure 4-7
5. *Speed* x *DOC* x *condition* interaction	Figure 4-8

Figure 4-6 (a) shows that mean of maximum cutting force in Z direction ($F_{z\ max}$) decreases with an increase in cutting speed from 183 m/min to 229 m/min when machining AISI 4340 steel with TiAlN/TiN PVD coated carbide inserts under dry and semi-dry end milling. Figure 4-6 (b) shows that mean of $F_{z\ max}$ increase with an increase in DOC from 2.54 mm to 3.81 mm. Figure 4-6 (c) shows that mean of $F_{z\ max}$ decreases when cutting condition is changed from semi-dry to dry.

However, the effect of speed, DOC and condition on $F_{z\ max}$ is not interpreted separately, as there exists a *speed* x *DOC* x *condition* three way interaction effect that will be studied in more detail in the subsequent sections.

Tukey test for comparison of means was conducted to determine if the means obtained for maximum force in Z direction on work piece ($F_{z\ max}$) are statistically different from each other at different factor interaction levels at 95 % confidence level.

4.2.4.1 Tests for contrast of means

The multivariate analysis results in Table 4-2 showed that speed, feed, depth of cut and cutting condition were all significant main effects. This means that for all independent variables, vector of means are significant. Therefore, for at least one dependant variable, there exists a group of means that is significantly different from the population. Tukey test was used for the test of means of each dependant variable. The equal sample size assumption was met for the Tukey test. The following sections discuss the results of the Tukey test.

4.2.4.1 Contrast among speed, DOC & condition interaction means

Tukey test for comparison of means was performed to see if there is any statistical difference between the interaction level means for $F_{z\ max}$. The *speed* x *DOC* x *condition* interaction means are not significant at 95% confidence level for the following cutting conditions:

1. Changing cutting condition from semi-dry to dry under a depth of cut of 2.54 mm and a cutting speed of 183 m/min;

2. Changing depth of cut from 2.54 to 3.81 mm under a cutting speed of 183 m/min and semi-dry cutting conditions;
3. Changing depth of cut from 2.54 mm under a cutting speed of 183 m/min to a depth of cut of 3.81 mm under a cutting speed of 229 m/min under semi-dry cutting condition;
4. Changing DOC from 2.54 mm under dry cutting condition to a DOC of 3.81 mm under semi-dry cutting condition at a cutting speed of 183 m/min;
5. Changing cutting speed from 183 m/min under dry cutting condition to 229 m/min under semi-dry cutting condition at a DOC of 2.54 mm;
6. Changing cutting speed from 183 to 229 m/min at a depth of cut of 2.54 mm under dry cutting condition;
7. Changing DOC from 2.54 mm at a cutting speed of 183 m/min under dry cutting condition to a DOC of 3.81 mm at a DOC of 3.81 mm under semi-dry cutting condition;
8. Changing DOC from 2.54 mm at a cutting speed of 183 m/min to a DOC of 3.81 mm at a cutting speed of 229 m/min under dry cutting condition;
9. Changing cutting condition from semi-dry to dry at a depth of cut of 3.81 mm under a cutting speed of 183 m/min;
10. Changing DOC from 3.81 mm at a cutting speed of 183 m/min to a DOC of 2.54 mm at a cutting speed of 229 m/min under dry cutting condition;
11. Changing cutting speed from 183 m/min to 229 m/min at a DOC of 3.81 mm under semi-dry cutting condition;

12. Changing cutting condition from semi-dry at a cutting speed of 183 m/min to dry at a cutting speed of 229 m/min at a DOC of 3.81 mm;
13. Changing cutting condition from dry at 183 m/min to semi-dry at 229 m/min at a depth of cut of 3.81 mm;
14. Changing cutting condition from semi-dry to dry at a cutting speed of 229 m/min and a depth of cut of 2.54 mm;
15. Changing depth of cut from 2.54 mm under a cutting speed of 183 m/min to a under semi-dry cutting condition to a depth of cut of 3.81 mm under a cutting speed of 229 m/min under dry cutting condition;
16. Changing cutting speed from 2.54 to 3.81 mm under dry cutting condition at a cutting speed of 229 m/min;

The Tukey test for comparison of $F_{z\ max}$ means between all other cutting conditions showed significant difference at 95% confidence level.

4.2.4.2 Summary of results of dependant variable $F_{z\ max}$

From the MANOVA, ANOVA, and Tukey test for the comparison of means, the following are the summary of results of effects of independent variables and their interactions on dependant variable $F_{z\ max}$ (Maximum force in Z direction on work piece in Newton's)

a) Effect of speed, DOC & condition interaction

The results of the Tukey test of means of $F_{z\ max}$ are summarized in Table 4-20. +Significance stands for statistical difference between mean values of $F_{z\ max}$ at 95 % confidence level, when the value shows an increasing trend amongst cutting conditions being compared. Similarly, -Significance stands for statistical difference between mean value of $F_{z\,max}$ at 95 % confidence level when the mean value of $F_{z\,max}$ shows a decreasing trend. “No Significance” is used to denote no statistically significant difference in $F_{z\,max}$ means being compared at 95 % confidence level between conditions.

From Table 4-20, the following cutting conditions yield lowest mean value of $F_{z\,max}$:

1) Speed of 229 m/min, DOC of 2.54 mm, dry cutting condition;
2) Speed of 229 m/min, DOC of 3.81 mm, dry cutting condition;

In order to obtain a low value of $F_{z\,max}$ and the highest material removal rate, a cutting speed of 229 m/min and a depth of cut of 3.81 mm under dry cutting condition are recommended when end milling 4340 steel blocks with advanced PVD TiAlN/TiN coated carbide cutting inserts.

Table 4-20 The Results of Tukey Pair wise Comparison of $F_{z\ max}$ Means for Speed, DOC & Condition Interaction

		183 m/min				229 m/min			
		2.54:1 (1803.5 N)	**2.54:2 (1588.2 N)**	**3.81:1 (1955.7 N)**	**3.81:2 (2319.0 N)**	**2.54:1 (1302.0 N)**	**2.54:2 (1010.9 N)**	**3.81:1 (2220.8 N)**	**3.81:2 (1159.1 N)**
183 m/min	**2.54:1 (1803.5 N)**		No significance	No significance	+Significance	-Significance	-Significance	No significance	-Significance
	2.54:2 (1588.2 N)			No significance	+Significance	No significance	No significance	No significance	No significance
	3.81:1 (1955.7 N)				No significance	No significance	-Significance	No significance	No significance
	3.81:2 (2319.0 N)					-Significance	-Significance	No significance	-Significance
229 m/min	**2.54:1 (1302.0 N)**						No significance	+Significance	No significance
	2.54:2 (1010.9 N)							+Significance	No significance
	3.81:1 (2220.8 N)								-Significance
	3.81:2 (1159.1 N)								

Note: 1 – Semi-dry machining condition, 2 – Dry machining condition; Speed levels used are 183 and 229 m/min. Depth of cut levels used are 2.54 and 3.81 mm. The mean value for $F_{z\ max}$ in Newton's is stated under the cutting condition.

4.2.5 Dependent Variable: Average Force in Z Direction on Work piece ($F_{z\ avg}$)

MANOVA analysis was conducted to determine which independent variables have an affect on some or all of the dependant variables. ANOVA analysis was subsequently conducted to determine whether speed, feed, depth of cut, cutting condition and their significant interactions had an effect on the average force in the Z direction of the work piece ($F_{z\ avg}$). The force in Z direction was measured by the Kistler dynamometer. $F_{z\ avg}$ was calculated from those readings. The ANOVA analysis for $F_{z\ avg}$ is shown in Table 4-8. Only the effects at $\alpha = 0.05$ significance level are taken into consideration in the analysis. A significant main effect is one that has a probability of occurrence (P value) less then or equal to 0.05. A significant interaction effect occurs when an independent variable along with its interaction with other independent variables causes some difference or change in the effect of the variable on the dependant variable of interest ($F_{z\ avg}$ in this case).

The main effects plot for $F_{z\ avg}$ is shown in Figure 4-9. The mean values for $F_{z\ avg}$ were used to plot the main effects plot. The two way interaction plots for $F_{z\ avg}$ are shown on Figure 4-10. The three way interaction plot for $F_{z\ avg}$ are shown in Figure 4-11, 12, and 13.

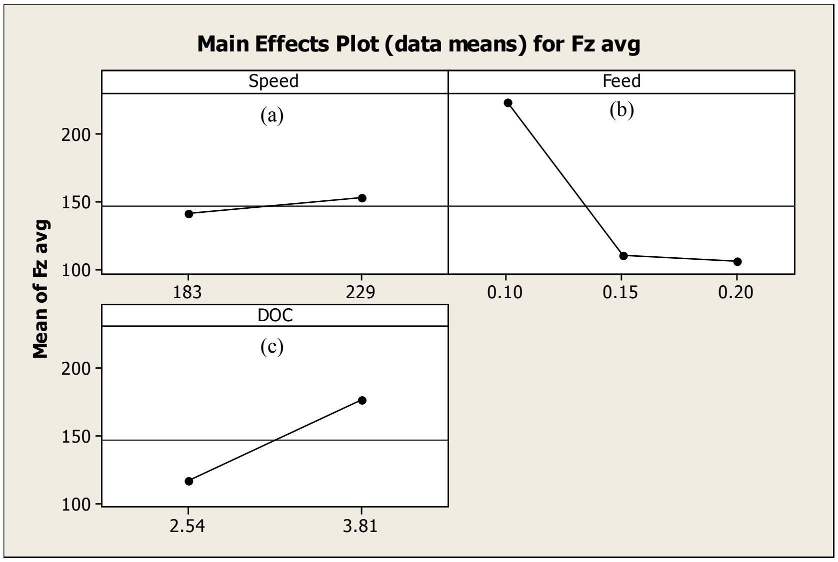


Figure 4-9 Plots of Main Effects for Average Cutting Force on Work piece in Z direction ($F_{z\ avg}$ in Newton's)

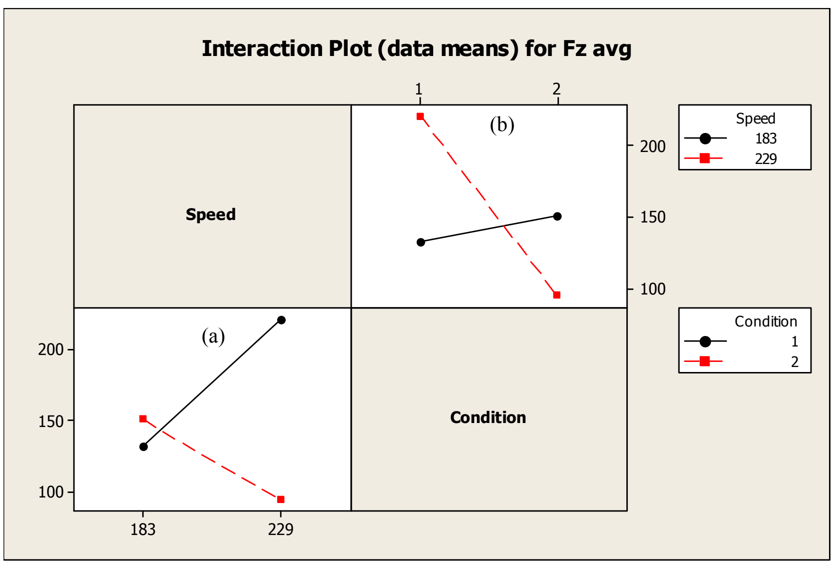


Figure 4-10 Two Way Speed & Condition Interaction Plots for Average Cutting Force on Work piece in Z direction ($F_{z\ avg}$ in Newton's)

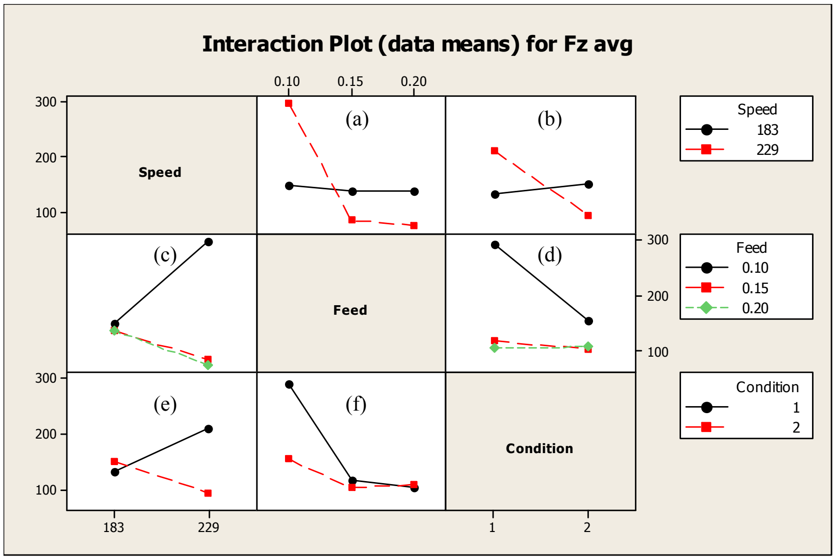


Figure 4-11 Three Way Speed, Feed & Condition Interaction Plots for Average Cutting Force on Work piece in Z direction ($F_{z\ avg}$ in Newton's)

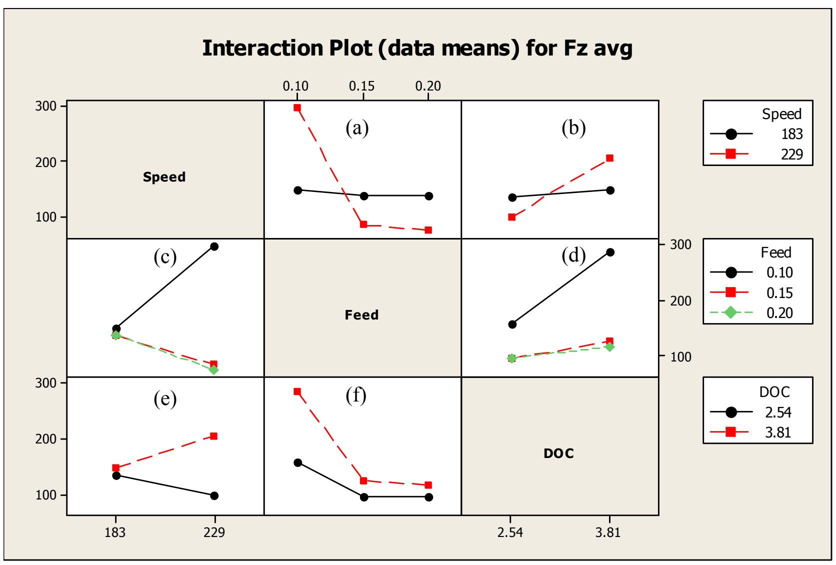


Figure 4-12 Three Way Speed, Feed & DOC Interaction Plots for Average Cutting Force on Work piece in Z direction ($F_{z\ avg}$ in Newton's)

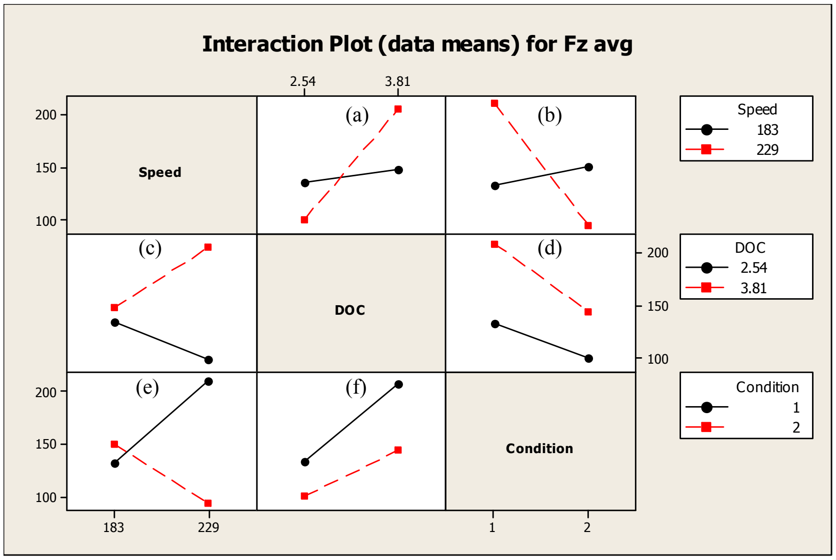


Figure 4-13 Three Way Speed, DOC & Condition Interaction Plots for Average Cutting Force on Work piece in Z direction ($F_{z\ avg}$ in Newton's)

The list below shows main effects of independent variables and their interactions on $F_{z\ avg}$ at a significance level α = 0.05

1. Speed main effect	Figure 4-9 (a)
2. Feed main effect	Figure 4-9 (b)
3. Depth of cut (DOC) main effect	Figure 4-9 (c)
4. *Speed* x *condition* interaction	Figure 4-10
5. *Speed* x *feed* x *condition* interaction	Figure 4-11
6. *Speed* x *feed* x *DOC* interaction	Figure 4-12
7. *Speed* x *DOC* x *condition* interaction	Figure 4-13

Figure 4-9 (a) shows that mean of average cutting force in Z direction ($F_{z\ avg}$) increases with an increase in speed from 183 m/min to 229 m/min when end milling AISI 4340 steel with advanced PVD TiAlN/TiN coated carbide inserts under dry and semi-dry cutting conditions. Figure 4-9 (b) shows that mean value of $F_{z\ avg}$ decrease with an increase in feed rate from 0.10 mm/rev to 0.15 mm/rev and from 0.15 mm/rev to 0.20

mm/rev. Figure 4-9 (c) shows that mean of $F_{z\ avg}$ increase with an increase in DOC from 2.54 to 3.81 mm.

However, the effect of speed, feed and depth of cut on $F_{z\ avg}$ cannot be interpreted alone, as there exists a two way *speed* x *condition* interaction and three way interactions *speed x feed x condition*, *speed* x *feed* x *DOC* and *speed* x *DOC* x *condition* that will be studied in more detail in subsequent paragraphs.

Tukey test for comparison of means was conducted to determine if the means obtained for average force in Z direction on work piece ($F_{z\ avg}$) are statistically different from each other at different factors and interaction levels at 95 % confidence level.

4.2.5.1 Tests for contrast of means

The multivariate analysis results in Table 4-2 showed that speed, feed, depth of cut and cutting condition were all significant main effects. This means that for all independent variables, vector of means are significant. Therefore, for at least one dependant variable, there exists a group of means that is significantly different from the population. Tukey test was used for the test of means of each dependant variable. The equal sample size assumption was met for the Tukey test. The following sections discuss the results of the Tukey test. It is to be noted that the Tukey test was conducted on the transformed dataset obtained for $F_{z\ avg}$. A transformation of $1 / \sqrt{F_{z\,avg}}$ was used to transform $F_{z\ avg}$ in order to meet normality assumptions for ANOVA and MANOVA analysis.

4.2.5.2 Contrast among speed, feed & condition interaction means

Tukey test for comparison of means was performed to see if there is any statistical difference between the interaction level means for $F_{z\ avg}$. The *speed x feed x condition* interaction are not significant at 95% confidence level for the following cutting conditions:

1. Changing cutting condition from semi-dry to dry cutting condition at a cutting speed of 183 m/min and a feed rate of 0.10 mm/rev;
2. Changing feed rate from 0.10 to 0.15 mm/rev at a cutting speed of 183 m/min under semi-dry cutting condition;
3. Changing feed from 0.10 mm/rev under semi-dry cutting condition to 0.15 mm/rev under dry cutting condition keeping speed constant at 183 m/min;
4. Changing feed rate from 0.10 mm/rev to 0.20 mm/rev at a cutting speed of 183 m/min under semi-dry cutting condition;
5. Changing feed rate from 0.10 mm/rev under semi-dry cutting condition to 0.20 mm/rev under dry cutting condition at a cutting speed of 183 m/min;
6. Changing cutting speed from 183 to 229 m/min keeping feed constant at 0.10 mm/rev under semi-dry cutting condition;
7. Changing cutting speed from 183 m/min under semi-dry cutting condition to 229 m/min under dry cutting condition keeping feed constant at 0.10 mm/rev;
8. Changing from a cutting speed of 183 m/min and a feed rate of 0.10 mm/rev to a cutting speed of 229 m/min and feed rate of 0.15 mm/rev under semi-dry cutting condition;

9. Changing from a cutting speed of 183 m/min and a feed rate of 0.10 mm/rev under semi-dry cutting condition to a cutting speed of 229 m/min and feed rate of 0.15 mm/rev under dry cutting condition;
10. Changing from a cutting speed of 183 m/min and a feed rate of 0.10 mm/rev to a cutting speed of 229 m/min and feed rate of 0.20 mm/rev under semi-dry cutting condition;
11. Changing from a cutting speed of 183 m/min and a feed rate of 0.10 mm/rev under semi-dry cutting condition to a cutting speed of 229 m/min and feed rate of 0.20 mm/rev under dry cutting condition;
12. Changing feed rate from 0.10 mm/rev under dry cutting condition to a feed rate of 0.15 mm/rev under semi-dry machining condition keeping cutting speed constant at 183 m/min;
13. Changing feed rate from 0.10 mm/rev to 0.15 mm/rev at a cutting speed of 183 m/min under dry cutting condition;
14. Changing feed rate from 0.10 mm/rev under dry cutting condition to 0.20 mm/rev under semi-dry cutting condition;
15. Changing feed rate from 0.10 mm/rev to 0.20 mm/rev at a cutting speed of 183 m/min under dry cutting condition;
16. Changing from a cutting speed of 183 m/min under semi-dry cutting condition to a cutting speed of 229 m/min under dry cutting condition at a constant feed rate of 0.10 mm/rev;
17. Changing cutting speed from 183 m/min to 229 m/min under a constant feed rate of 0.10 mm/rev and dry cutting condition;

18. Changing cutting condition from semi-dry to dry cutting condition at a cutting speed of 183 m/min and a feed rate of 0.15 mm/rev;
19. Changing feed rate from 0.15 mm/rev to 0.20 mm/rev at a cutting speed of 183 m/min under semi-dry cutting condition;
20. Changing feed rate from 0.15 mm/rev under semi-dry cutting condition to a feed rate of 0.20 mm/rev under dry machining condition keeping cutting speed constant at 183 m/min;
21. Changing from a cutting speed of 183 m/min and a feed rate of 0.15 mm/rev to a cutting speed of 229 m/min and a feed rate of 0.10 mm/rev under semi-dry cutting condition;
22. Changing from a cutting speed of 183 m/min and a feed rate of 0.15 mm/rev under semi-dry cutting condition to a cutting speed of 229 m/min and a feed rate of 0.10 mm/rev under dry cutting condition;
23. Changing cutting speed from 183 m/min to 229 m/min under a constant feed rate of 0.15 mm/rev under semi-dry cutting condition;
24. Changing from a cutting speed of 183 m/min under semi-dry cutting condition to a cutting speed of 229 m/min under dry cutting condition at a constant feed rate of 0.15 mm/rev;
25. Changing from a cutting speed of 183 m/min and a feed rate of 0.15 mm/rev to a cutting speed of 229 m/min and a feed rate of 0.20 mm/rev under semi-dry cutting condition;

26. Changing feed rate from 0.15 mm/rev under dry cutting condition to a feed rate of 0.20 mm/rev under semi-dry cutting condition keeping cutting speed constant at 183 m/min;
27. Changing feed rate from 0.15 mm/rev to 0.20 mm/rev under dry cutting condition keeping cutting speed constant at 183 m/min;
28. Changing from a cutting speed of 183 m/min and a feed rate of 0.15 mm/rev to a cutting speed of 229 m/min and a feed rate of 0.20 mm/rev under dry cutting condition;
29. Changing from a cutting speed of 183 m/min under semi-dry cutting condition to a cutting speed of 229 m/min under dry cutting condition at a constant feed rate of 0.15 mm/rev;
30. Changing cutting condition from semi-dry to dry under a constant feed rate of 0.20 mm/rev and cutting speed of 183 m/min;
31. Changing from a cutting speed of 183 m/min and a feed rate of 0.20 mm/rev under semi-dry cutting condition to a cutting speed of 229 m/min and a feed rate of 0.10 mm/rev under dry cutting condition;
32. Changing from a cutting speed of 183 m/min and a feed rate of 0.20 mm/rev to a cutting speed of 229 m/min and a feed rate of 0.15 mm/rev under semi-dry cutting condition;
33. Changing from a cutting speed of 183 m/min to 229 m/min with a constant feed rate of 0.20 mm/rev under semi-dry cutting condition;

34. Changing from a cutting speed of 183 m/min and a feed rate of 0.20 mm/rev under dry cutting condition to a cutting speed of 229 m/min and a feed rate of 0.10 mm/rev under semi-dry cutting condition;
35. Changing from a cutting speed of 183 m/min and a feed rate of 0.20 mm/rev to a cutting speed of 229 m/min and a feed rate of 0.10 mm/rev under dry cutting condition;
36. Changing from a cutting speed of 183 m/min and a feed rate of 0.20 mm/rev under dry cutting condition to a cutting speed of 229 m/min and a feed rate of 0.15 mm/rev under semi-dry cutting condition;
37. Changing cutting condition from semi-dry to dry cutting condition at a cutting speed of 229 m/min and a feed rate of 0.10 mm/rev;
38. Changing from a feed rate of 0.10 mm/rev under dry cutting condition to a feed rate of 0.15 mm/rev under semi-dry cutting condition at a constant speed of 229 m/min;
39. Changing from a feed rate of 0.10 mm/rev under dry cutting condition to a feed rate of 0.20 mm/rev under semi-dry cutting condition at a constant speed of 229 m/min;
40. Changing from a feed rate of 0.10 mm/rev to 0.20 mm/rev under dry cutting condition at a constant speed of 229 m/min;
41. Changing from a feed rate of 0.10 mm/rev to 0.20 mm/rev under dry cutting condition at a constant speed of 229 m/min;
42. Changing cutting condition from semi-dry to dry cutting condition at a cutting speed of 229 m/min and a feed rate of 0.15 mm/rev;

43. Changing from a feed rate of 0.15 mm/rev to a feed rate of 0.20 mm/rev under semi-dry cutting condition at a constant speed of 229 m/min;
44. Changing from a feed rate of 0.15 mm/rev under semi-dry cutting condition to a feed rate of 0.20 mm/rev under dry cutting condition at a constant speed of 229 m/min;
45. Changing from a feed rate of 0.15 mm/rev under dry cutting condition to a feed rate of 0.20 mm/rev under semi-dry cutting condition at a constant speed of 229 m/min;
46. Changing from a feed rate of 0.15 mm/rev to a feed rate of 0.20 mm/rev under dry cutting condition at a constant speed of 229 m/min;
47. Changing cutting condition from semi-dry to dry cutting condition at a cutting speed of 229 m/min and a feed rate of 0.20 mm/rev;

The Tukey test for comparison of $F_{z\ avg}$ means for all other cutting conditions showed significant difference at 95% confidence level.

4.2.5.3 Contrast among speed, feed, and DOC interaction means

Tukey test for comparison of means was performed to see if there is any statistical difference between the interaction level means for $F_{z\ avg}$. The *speed x feed x DOC* interaction are not significant at 95% confidence level for the following cutting conditions:

1. Changing DOC from 2.54 to 3.81 mm at a feed rate of 0.10 mm/rev at a cutting speed of 183 m/min;

2. Changing from a feed rate of 0.10 mm/rev at a DOC of 2.54 mm to a feed rate of 0.15 mm/rev at a DOC of 3.81 mm at a cutting speed of 183 m/min;
3. Change in feed rate from 0.10 to 0.20 mm/rev at a depth of cut of 2.54 mm and a cutting speed of 183 m/min;
4. Changing from a feed rate of 0.10 mm/rev at a DOC of 2.54 mm to a feed rate of 0.20 mm/rev at a DOC of 3.81 mm at a cutting speed of 183 m/min;
5. Changing cutting speed from 183 to 229 m/min keeping feed rate at 0.10 mm/rev and DOC at 2.54 mm respectively;
6. Changing DOC from 2.54 mm at a cutting speed of 183 m/min to a DOC of 3.81 mm at a cutting speed of 229 m/min at a feed rate of 0.10 mm/rev;
7. Changing feed rate from 0.10 mm/rev and a DOC of 3.81 mm to a feed rate of 0.15 mm/rev and a DOC level of 2.54 mm under a cutting speed of 183 m/min;
8. Changing from a feed rate of 0.10 mm/rev to a feed rate of 0.15 mm/rev at a DOC of 3.81 mm at a cutting speed of 183 m/min;
9. Changing from a feed rate of 0.10 mm/rev at a DOC of 3.81 mm to a feed rate of 0.20 mm/rev at a DOC of 2.54 mm at a cutting speed of 183 m/min;
10. Changing from a feed rate of 0.10 mm/rev to a feed rate of 0.20 mm/rev at a DOC of 3.81 mm at a cutting speed of 183 m/min;
11. Changing DOC from 3.81 mm at a cutting speed of 183 m/min to a DOC of 2.54 mm at a cutting speed of 229 m/min at a feed rate of 0.10 mm/rev;
12. Changing cutting speed from 183 to 229 m/min at a feed rate of 0.10 mm/rev and a DOC of 3.81 mm respectively;

13. Changing from a feed rate of 0.10 mm/rev, a DOC of 3.81 mm at a cutting speed of 183 m/min to a feed rate of 0.15 mm/rev, a DOC of 2.54 mm at a cutting speed of 229 m/min;
14. Changing feed rate from 0.10 mm/rev at a cutting speed of 183 m/min to a feed rate of 0.15 mm/rev at a cutting speed of 229 m/min and DOC of 3.81 mm;
15. Changing from a feed rate of 0.10 mm/rev, a DOC of 3.81 mm at a cutting speed of 183 m/min to a feed rate of 0.20 mm/rev, a DOC of 2.54 mm at a cutting speed of 229 m/min;
16. Changing from a feed rate of 0.10 mm/rev at a cutting speed of 183 m/min to a feed rate of 0.20 mm/rev at DOC of 3.81 mm at a cutting speed of 229 m/min and DOC of 3.81 mm;
17. Changing feed rate from 0.15 to 0.20 mm/rev at a cutting speed of 183 m/min and a DOC of 2.54 mm;
18. Changing from a feed rate of 0.15 mm/rev at a DOC of 2.54 mm to a feed rate of 0.20 mm/rev at a DOC of 3.81 mm at a cutting speed of 183 m/min;
19. Changing feed rate from 0.15 mm/rev at a cutting speed of 183 m/min to a feed rate of 0.10 mm/rev at a cutting speed of 229 m/min and a DOC of 2.54 mm;
20. Changing from a feed rate of 0.15 mm/rev, a depth of cut of 2.54 mm and a cutting speed of 183 m/min to a feed rate of 0.10 mm/rev at a DOC of 3.81 mm at a cutting speed of 229 m/min;
21. Changing cutting speed from 183 to 229 m/min keeping feed rate at 0.15 mm/rev and DOC at 2.54 mm respectively;

22. Changing DOC from 2.54 to 3.81 mm at a cutting speed of 183 m/min to a DOC of 3.81 mm at a cutting speed of 229 m/min and a feed rate of 0.15 mm/rev;
23. Changing from a feed rate of 0.15 mm/rev and a cutting speed of 183 m/min to a feed rate of 0.20 mm/rev at a cutting speed of 229 m/min and a DOC of 3.81 mm;
24. Changing from a feed rate of 0.15 mm/rev, a depth of cut of 2.54 mm and a cutting speed of 183 m/min to a feed rate of 0.20 mm/rev at a DOC of 3.81 mm at a cutting speed of 229 m/min;
25. Changing from a feed rate of 0.15 mm/rev and a DOC of 3.81 mm to a feed rate of 0.20 mm/rev at a DOC of 2.54 mm at a cutting speed of 183 m/min;
26. Changing from a feed rate of 0.15 to 0.20 mm/rev at a DOC of 3.81 mm at a cutting speed of 183 m/min;
27. Changing from a feed rate of 0.15 mm/rev, a depth of cut of 3.81 mm and a cutting speed of 183 m/min to a feed rate of 0.10 mm/rev at a DOC of 2.54 mm and a cutting speed of 229 m/min;
28. Changing from a feed rate of 0.15 mm/rev at a cutting speed of 183 m/min to a feed rate of 0.10 mm/rev at a cutting speed of 229 m/min and a DOC of 3.81 mm;
29. Changing DOC from 2.54 to 3.81 mm at a cutting speed of 183 m/min and a feed rate of 0.20 mm/rev;
30. Changing from a feed rate of 0.20 mm/rev at 183 m/min to a feed rate of 0.10 mm/rev and a cutting speed of 229 m/min at a DOC of 2.54 mm;
31. Changing from a feed rate of 0.20 mm/rev, a depth of cut of 2.54 mm and a cutting speed of 183 m/min to a feed rate of 0.10 mm/rev at a DOC of 3.81 mm at a cutting speed of 229 m/min;

32. Changing from a feed rate of 0.20 mm/rev and a cutting speed of 183 m/min to a feed rate of 0.15 mm/rev at a cutting speed of 229 m/min at a DOC of 2.54 mm;
33. Changing from a feed rate of 0.20 mm/rev, a depth of cut of 2.54 mm and a cutting speed of 183 m/min to a feed rate of 0.15 mm/rev at a DOC of 3.81 mm at a cutting speed of 229 m/min;
34. Changing DOC from 2.54 mm at a cutting speed of 183 m/min to a DOC of 3.81 mm at a cutting speed of 229 m/min and a feed rate of 0.20 mm/rev;
35. Changing from a feed rate of 0.20 mm/rev, a depth of cut of 3.81 mm and a cutting speed of 183 m/min to a feed rate of 0.10 mm/rev at a DOC of 2.54 mm and a cutting speed of 229 m/min;
36. Changing from a feed rate of 0.20 mm/rev at a cutting speed of 183 m/min to a feed rate of 0.10 mm/rev at a cutting speed of 229 m/min at a DOC of 3.81 mm;
37. Changing from a feed rate of 0.20 mm/rev, a depth of cut of 3.81 mm and a cutting speed of 183 m/min to a feed rate of 0.15 mm/rev at a DOC of 2.54 mm and a cutting speed of 229 m/min;
38. Changing cutting speed from 183 to 229 m/min at a feed level of 0.20 mm/rev and a DOC of 3.81 mm;
39. Changing DOC from 2.54 to 3.81 mm at a cutting speed of 229 m/min and a feed rate of 0.10 mm/rev;
40. Changing from a feed rate of 0.10 to 0.15 mm/rev at a cutting speed of 229 m/min and a DOC of 2.54 mm;
41. Changing from a feed rate of 0.10 mm/rev and a depth of cut of 2.54 mm to a feed rate of 0.15 mm/rev at a DOC of 3.81 mm at a cutting speed of 229 m/min;

42. Changing from a feed rate of 0.10 mm/rev and a depth of cut of 2.54 mm to a feed rate of 0.20 mm/rev at a DOC of 3.81 mm at a cutting speed of 229 m/min;
43. Changing DOC from 2.54 to 3.81 mm at a cutting speed of 229 m/min and a feed rate of 0.15 mm/rev;
44. Changing from a feed rate of 0.15 to 0.20 mm/rev at a DOC of 2.54 mm at a cutting speed of 229 m/min;
45. Changing from a feed rate of 0.15 mm/rev and a depth of cut of 2.54 mm to a feed rate of 0.20 mm/rev at a DOC of 3.81 mm at a cutting speed of 229 m/min;
46. Changing from a feed rate of 0.15 mm/rev and a depth of cut of 3.81 mm to a feed rate of 0.20 mm/rev at a DOC of 2.54 mm at a cutting speed of 229 m/min;
47. Changing from a feed rate of 0.15 to 0.20 mm/rev at a DOC of 3.81 mm and a cutting speed of 229 m/min;

The Tukey test for comparison of $F_{z\ avg}$ means for all other cutting conditions showed significant difference at 95% confidence level.

4.2.5.4 Contrast among speed, DOC & condition interaction means

Tukey test for comparison of means was performed to see if there is any statistical difference between the interaction level means for $F_{z\ avg}$. The *speed x DOC x condition* interaction is not significant at 95% confidence level for the following cutting conditions:

1. Changing cutting condition from semi-dry to dry under a depth of cut of 2.54 mm and a cutting speed of 183 m/min;
2. Changing depth of cut from 2.54 to 3.81 mm under a cutting speed of 183 m/min and semi-dry cutting conditions;

3. Changing depth of cut from 2.54 mm under semi-dry cutting condition to 3.81 mm under dry cutting condition at a cutting speed of 183 m/min;
4. Changing cutting speed from 183 to 229 m/min under semi-dry cutting condition and a DOC of 2.54 mm;
5. Changing DOC from 2.54 mm under dry cutting condition to a DOC of 3.81 mm under semi-dry cutting condition at a cutting speed of 183 m/min;
6. Changing cutting speed from 183 m/min under dry cutting condition to 229 m/min under semi-dry cutting condition at a DOC of 2.54 mm;
7. Changing DOC from 2.54 mm at a cutting speed of 183 m/min under dry cutting condition to a DOC of 3.81 mm at a DOC of 3.81 mm under semi-dry cutting condition;
8. Changing DOC from 2.54 mm at a cutting speed of 183 m/min to a DOC of 3.81 mm at a cutting speed of 229 m/min under dry cutting condition;
9. Changing DOC from 3.81 mm at a cutting speed of 183 m/min to a DOC of 2.54 mm at a cutting speed of 229 m/min under dry cutting condition;
10. Changing DOC from 3.81 mm at a cutting speed of 183 m/min under semi-dry cutting condition to a DOC of 2.54 mm at a cutting speed of 229 m/min under dry cutting condition;
11. Changing cutting speed from 183 m/min to 229 m/min at a DOC of 3.81 mm under semi-dry cutting condition;
12. Changing cutting condition from semi-dry at a cutting speed of 183 m/min to dry at a cutting speed of 229 m/min at a DOC of 3.81 mm;

13. Changing cutting condition from a DOC of 3.81 mm under dry cutting condition at a cutting speed of 183 m/min to a DOC of 2.54 mm under semi-dry cutting condition at a cutting speed of 229 m/min;
14. Changing cutting condition from dry at 183 m/min to semi-dry at 229 m/min at a depth of cut of 3.81 mm;
15. Changing cutting condition from semi-dry to dry at a cutting speed of 229 m/min and a depth of cut of 2.54 mm;
16. Changing depth of cut from 2.54 to 3.81 mm under semi-dry cutting condition at a cutting speed of 229 m/min;
17. Changing depth of cut from 2.54 mm under a cutting speed of 183 m/min to a under semi-dry cutting condition to a depth of cut of 3.81 mm under a cutting speed of 229 m/min under dry cutting condition;
18. Changing depth of cut from 2.54 mm under a cutting speed of 183 m/min to a under dry cutting condition to a depth of cut of 3.81 mm under a cutting speed of 229 m/min under semi-dry cutting condition;
19. Changing cutting speed from 2.54 to 3.81 mm under dry cutting condition at a cutting speed of 229 m/min;
20. Changing cutting condition from semi-dry to dry under a cutting speed of 229 m/min and a depth of cut of 3.81 mm;

The Tukey test for comparison of $F_{z\,avg}$ means for all other cutting conditions showed significant difference at 95% confidence level.

4.2.5.5 Summary of results of dependant variable $F_{z\ avg}$

From the MANOVA, ANOVA and Tukey test for the comparison of means, the following are the summary of results of effects of independent variables and their interactions on dependant variable $F_{z\ avg}$ (Average force in Z direction on work piece in Newton's).

a) Effect of speed, feed & condition interaction

The results of the Tukey test of means of transformed $F_{z\ avg}$ means are summarized in Table 4-21. +Significance stands for statistical difference between mean values of transformed $F_{z\ avg}$ at 95 % confidence level, when the value shows an increasing trend amongst cutting conditions being compared. Similarly, -Significance stands for statistical difference between mean value of transformed $F_{z\ avg}$ at 95 % confidence level when the mean value of transformed $F_{z\ avg}$ shows a decreasing trend. "No Significance" is used to denote no statistically significant difference in transformed $F_{z\ avg}$ means being compared at 95 % confidence level between conditions.

From Table 4-21, the following cutting conditions yield lowest mean value of $F_{z\ avg}$:

1) Speed of 229 m/min, feed of 0.20 mm/rev under dry cutting condition

It should be noted that the comparison of means in Table 4-21 was conducted on the transformed values of $F_{z\ avg}$ i.e. $(F_{z\ avg})^{-0.5.}$ The lowest value of $F_{z\ avg}$ mean corresponds to the highest value of $(F_{z\ avg})^{-0.5}$ mean.

A cutting speed of 229 m/min and a feed of 0.20 mm/rev under dry cutting condition give the highest material removal rate with the lowest $F_{z\ avg}$ mean value when end milling AISI 4340 steel blocks with advanced PVD TiAlN/TiN coated carbide inserts.

b) Effect of speed, feed & DOC interaction

The results of the Tukey test of means of transformed $F_{z\ avg}$ means are summarized in Table 4-22. +Significance stands for statistical difference between mean values of transformed $F_{z\ avg}$ at 95 % confidence level, when the value shows an increasing trend amongst cutting conditions being compared. Similarly, -Significance stands for statistical difference between mean value of transformed $F_{z\ avg}$ at 95 % confidence level when the mean value of transformed $F_{z\ avg}$ shows a decreasing trend. "No Significance" is used to denote no statistically significant difference in transformed $F_{z\ avg}$ means being compared at 95 % confidence level between conditions.

From Table 4-22, the following cutting conditions yield lowest mean value of $F_{z\ avg}$:

1) Cutting speed of 229 m/min, feed of 0.20 mm/rev at a depth of cut of 2.54 mm

It should be noted that the comparison of means in Table 4-21 was conducted on the transformed values of $F_{z\ avg}$ i.e. $(F_{z\ avg})^{-0.5}$. The lowest value of $F_{z\ avg}$ mean corresponds to the highest value of $(F_{z\ avg})^{-0.5}$ mean.

From the above cutting conditions, a cutting speed of 229 m/min, a feed rate of 0.20 mm/rev at a depth of cut of 2.54 mm gives the lowest mean value of $F_{z\ avg}$ when end milling AISI 4340 steel blocks with advanced PVD TiAlN/TiN coated carbide inserts.

Table 4-21 The Results of Tukey Pair wise Comparison of $F_{z\ avg}$ Transformed Means for Speed, Feed & Condition Interaction

		183 m/min						229 m/min					
		0.10:1 (0.10129)	0.10:2 (0.07679)	0.15:1 (0.08958)	0.15:2 (0.08774)	0.20:1 (0.09160)	0.20:2 (0.08454)	0.10:1 (0.05738)	0.10:2 (0.09364)	0.15:1 (0.10688)	0.15:2 (0.11697)	0.20:1 (0.11448)	0.20:2 (0.12103)
183 m/min	0.10:1 (0.10129)		No Significance	No Significance	No Significance	No Significance	No Significance	No Significance	No Significance	No Significance	No Significance	No Significance	No Significance
	0.10:2 (0.07679)			No Significance	No Significance	No Significance	No Significance	No Significance	No Significance	+Significance	+Significance	+Significance	+Significance
	0.15:1 (0.08958)				No Significance	No Significance	No Significance	No Significance	No Significance	No Significance	No Significance	No Significance	+Significance
	0.15:2 (0.08774)					No Significance	No Significance	-Significance	No Significance	No Significance	+Significance	No Significance	+Significance
	0.20:1 (0.09160)						No Significance	-Significance	No Significance	No Significance	+Significance	No Significance	+Significance
	0.20:2 (0.08454)							No Significance	No Significance	No Significance	+Significance	+Significance	+Significance
229 m/min	0.10:1 (0.05738)								No Significance	+Significance	+Significance	+Significance	+Significance
	0.10:2 (0.09364)									No Significance	No Significance	No Significance	No Significance
	0.15:1 (0.10688)										No Significance	No Significance	No Significance
	0.15:2 (0.11697)											No Significance	No Significance
	0.20:1 (0.11448)												No Significance
	0.20:2 (0.12103)												

Note: 1 – Semi-dry machining condition, 2 – Dry machining condition; Speed levels used are 183 and 229 m/min. Feed levels used are 0.10 mm/rev, 0.15 mm/rev and 0.20 mm/rev. The Tukey analysis of means was carried on transformed $F_{z\ avg}$ means, i.e. mean values of $(F_{z\ avg})^{-0.5}$.

Table 4-22 The Results of Tukey Pair wise Comparison of $F_{z\,avg}$ Transformed Means for Speed, Feed, & DOC Interaction

		183 m/min						229 m/min					
		0.10:2.54 (0.07720)	**0.10:3.81 (0.10087)**	**0.15:2.54 (0.10062)**	**0.15:3.81 (0.076701)**	**0.20:2.54 (0.09064)**	**0.20:3.81 (0.08550)**	**0.10:2.54 (0.08715)**	**0.10:3.81 (0.06386)**	**0.15:2.54 (0.11083)**	**0.15:3.81 (0.11301)**	**0.20:2.54 (0.12812)**	**0.20:3.81 (0.10739)**
183 m/min	**0.10:2.54 (0.07720)**		No Significance	+Significance	No Significance	No Significance	No Significance	No Significance	No Significance	+Significance	+Significance	+Significance	+Significance
	0.10:3.81 (0.10087)			No Significance	No Significance	No Significance	No Significance	No Significance	No Significance	No Significance	No Significance	No Significance	No Significance
	0.15:2.54 (0.10062)				-Significance	No Significance	No Significance	No Significance	No Significance	No Significance	No Significance	No Significance	No Significance
	0.15:3.81 (0.076701)					No Significance	No Significance	No Significance	No Significance	+Significance	+Significance	+Significance	+Significance
	0.20:2.54 (0.09064)						No Significance	No Significance	No Significance	No Significance	No Significance	+Significance	No Significance
	0.20:3.81 (0.08550)							No Significance	No Significance	No Significance	+Significance	+Significance	No Significance
229 m/min	**0.10:2.54 (0.08715)**								No Significance	No Significance	No Significance	+Significance	No Significance
	0.10:3.81 (0.06386)									+Significance	+Significance	+Significance	+Significance
	0.15:2.54 (0.11083)										No Significance	No Significance	No Significance
	0.15:3.81 (0.11301)											No Significance	No Significance
	0.20:2.54 (0.12812)												-Significance
	0.20:3.81 (0.10739)												

Note: Speed levels used are 183 and 229 m/min. Feed levels used are 0.10 mm/rev, 0.15 mm/rev and 0.20 mm/rev. DOC levels used are 2.54 and 3.81 mm. The Tukey analysis of means was carried on transformed $F_{z\,avg}$ means, i.e. mean values of $(F_{z\,avg})^{-0.5}$.

c) Effect of speed, DOC & condition interaction

The results of the Tukey test of means of transformed $F_{z\ avg}$ means are summarized in Table 4-23. +Significance stands for statistical difference between mean values of transformed $F_{z\ avg}$ at 95 % confidence level, when the value shows an increasing trend amongst cutting conditions being compared. Similarly, -Significance stands for statistical difference between mean value of transformed $F_{z\ avg}$ at 95 % confidence level when the mean value of transformed $F_{z\ avg}$ shows a decreasing trend. "No Significance" is used to denote no statistically significant difference in transformed $F_{z\ avg}$ means being compared at 95 % confidence level between conditions.

From Table 4-22, the following cutting conditions yield lowest mean value of $F_{z\ avg}$:

1) Cutting speed of 229 m/min, DOC of 2.54 mm under dry cutting condition;
2) Cutting speed of 229 m/min, DOC of 3.81 mm under semi-dry cutting condition;
3) Cutting speed of 229 m/min, DOC of 3.81 mm under dry cutting condition;

It should be noted that the comparison of means in Table 4-22 was conducted on the transformed values of $F_{z\ avg}$ i.e. $(F_{z\ avg})^{-0.5.}$ The lowest value of $F_{z\ avg}$ mean corresponds to the highest value of $(F_{z\ avg})^{-0.5}$ mean.

From the above cutting conditions, a cutting speed of 229 m/min, a DOC of 3.81 mm under dry cutting condition gives highest material removal rate and the lowest mean value of $F_{z\ avg}$ when end milling AISI 4340 steel blocks with advanced PVD TiAlN/TiN coated carbide inserts.

Table 4-23 The Results of Tukey Pair wise Comparison of $F_{z\,avg}$ Transformed Means for Speed, DOC & Condition Interaction

		183 m/min				229 m/min			
		2.54:1 (0.08802)	**2.54:2 (0.09095)**	**3.81:1 (0.10029)**	**3.81:2 (0.07509)**	**2.54:1 (0.10155)**	**2.54:2 (0.11586)**	**3.81:1 (0.08428)**	**3.81:2 (0.10523)**
183 m/min	**2.54:1 (0.08802)**		Not Significant	Not Significant	Not Significant	Not Significant	+Significant	-Significant	+Significant
	2.54:2 (0.09095)			Not Significant	-Significant	Not Significant	+Significant	Not Significant	Not Significant
	3.81:1 (0.10029)				-Significant	Not Significant	Not Significant	Not Significant	Not Significant
	3.81:2 (0.07509)					Not Significant	+Significant	Not Significant	+Significant
229 m/min	**2.54:1 (0.10155)**						Not Significant	Not Significant	Not Significant
	2.54:2 (0.11586)							Not Significant	Not Significant
	3.81:1 (0.08428)								Not Significant
	3.81:2 (0.10523)								

Note: Speed levels used are 183 and 229 m/min. DOC levels used are 2.54 and 3.81 mm. Cutting conditions used are 1:semi-dry and 2: dry. The Tukey analysis of means was carried on transformed $F_{z\,avg}$ means, i.e. mean values of $(F_{z\,avg})^{-0.5}$.

4.2.6 Dependent Variable: Maximum Two Dimensional (2 D) Cutting Force Acting on Work piece ($F_{xy\ max}$)

MANOVA analysis was conducted to determine which independent variables have an affect on some or all of the dependant variables. ANOVA analysis was subsequently conducted to determine whether speed, feed, depth of cut, cutting condition and their significant interactions had an effect on maximum 2D forces acting on the work piece ($F_{xy\ max}$). The force in X direction (F_x) and in Y direction (F_y) acting on the work piece was measured by the Kistler dynamometer. Maximum 2D force ($F_{xy\ max}$) was calculated from F_x and F_y measurements by the dynamometer using Equation 4-7. The ANOVA analysis for $F_{xy\ max}$ is shown in Table 4-9. Only the effects at $\alpha = 0.05$ significance level are taken into consideration in the analysis. A significant main effect is one that has a probability of occurrence (P value) less then or equal to 0.05. A significant interaction effect occurs when an independent variable along with its interaction with other independent variables causes some difference or change in the effect of the variable on the dependant variable of interest ($F_{xy\ max}$ in this case).

The main effects plot for $F_{xy\ max}$ is shown in Figure 4-14. The mean values for $F_{xy\ max}$ are used to plot the main effects plot.

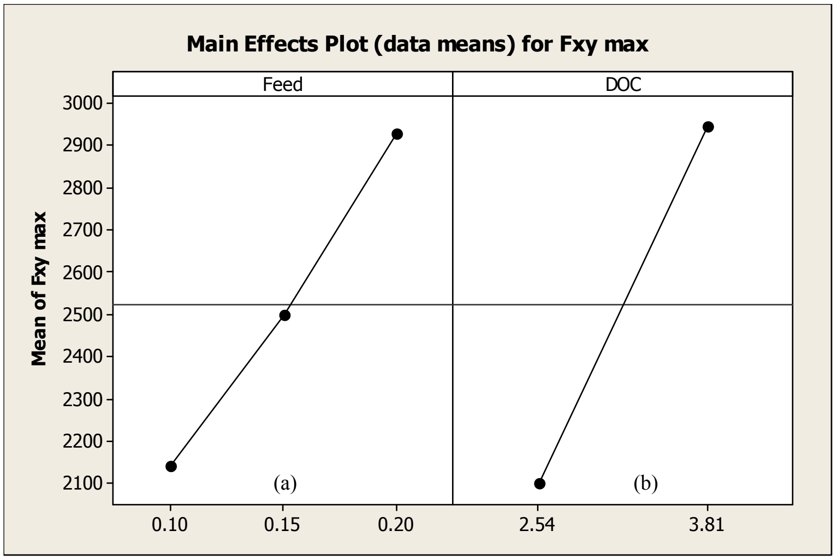


Figure 4-14 Plots of Main Effects for Maximum 2D Cutting Force on Work piece ($F_{xy\ max}$ in Newton's)

The list below shows main effects of independent variables and their interactions on $F_{xy\ max}$ at a significance level α = 0.05

1. Feed main effect Figure 4-14 (a)
2. Depth of cut (DOC) main effect Figure 4-14 (b)

Figure 4-14 (a) shows that mean of maximum 2D cutting force ($F_{xy\ max}$) increases with an increase in feed rate from 0.10 mm/rev to 0.15 mm/rev, and from 0.15 mm/rev to 0.20 mm/rev respectively. Figure 4-14 (b) shows that mean of $F_{xy\ max}$ increases with an increase in DOC from 2.54 to 3.81 mm.

Tukey test for comparison of means was conducted to determine if the means obtained for maximum 2 D cutting force ($F_{xy\ max}$) are statistically different from each other at different factors and interaction levels at 95 % confidence level.

4.2.6.1 Tests for contrast of means

The multivariate analysis results in Table 4-2 showed that speed, feed, depth of cut and cutting condition were all significant main effects. This means that for all independent variables, vector of means are significant. Therefore, for at least one dependant variable, there exists a group of means that is significantly different from the population. Tukey test was used for the test of means of each dependant variable. The equal sample size assumption was met for the Tukey test. The following sections discuss the results of the Tukey test.

4.2.6.2 Contrast among means for feed

Tukey test was used to compare $F_{xy\ max}$ means using Minitab. The pair wise comparison showed that there exists a statistically significant difference at 95 % confidence level between $F_{xy\ max}$ means obtained for a feed level of 0.10 to 0.15 mm/rev respectively. Similarly, pair wise comparison of difference in $F_{xy\ max}$ means between feed rates of 0.15 mm/rev and 0.20 mm/rev are statistically significant at 95% confidence level.

4.2.6.3 Contrast among means for DOC

Tukey test was used to compare Fxy max means using Minitab. The pair wise comparison showed that there exists a statistically significant difference at 95 % confidence level between $F_{xy\ max}$ means obtained for DOC levels of 2.54 mm and 3.81 mm respectively.

4.2.6.4 Summary of results of dependant variable $F_{xy\ max}$

From the MANOVA, ANOVA, and Tukey test for the comparison of means the following are the summary of results of effects of independent variables and their interactions on dependant variable $F_{xy\ max}$ (Maximum 2D cutting force acting on the work piece in Newton's).

a) Effect of feed on $F_{xy\ max}$

The Tukey test for comparison of means for $F_{xy\ max}$ showed that there is a statistically significant difference at 95 % confidence level between feed levels of 0.10 and 0.15 mm/rev, and 0.15 and 0.20 mm/rev respectively. It was observed that $F_{xy\ max}$ means increased with an increase in feed rate from 0.10 to 0.15 mm/rev, and from 0.15 to 0.20 mm/rev. Therefore in order to obtain low values of $F_{xy\ max}$, a lower feed rate of 0.10 mm/rev is recommended.

b) Effect of DOC on $F_{xy\ max}$

The Tukey test for comparison of means shows that there a statistically significant difference between $F_{xy\ max}$ means obtained for the two levels of DOC (i.e. 2.54 and 3.81 mm respectively) at 95% confidence level. Means of $F_{xy\ max}$ was observed to increase with an increase in depth of cut (DOC) from 2.54 to 3.81 mm. Therefore, in order to obtain low levels of $F_{xy\ max}$, a lower level of DOC (i.e. 2.54 mm) is recommended when end milling AISI 4340 steel blocks with advanced PVD TiAlN/TiN coated carbide cutting inserts.

4.2.7 Dependent Variable: Average Two Dimensional (2 D) Cutting Force Acting on Work piece ($F_{xy\ avg}$)

MANOVA analysis was conducted to determine which independent variables have an affect on some or all of the dependant variables. ANOVA analysis was subsequently conducted to determine whether speed, feed, depth of cut, cutting condition and their significant interactions had an effect on average 2D forces acting on the work piece ($F_{xy\ avg}$). The force in X direction (F_x in Newton's) and in Y direction (F_y in Newton's) acting on the work piece was measured by the Kistler dynamometer. Average 2D force ($F_{xy\ avg}$) was calculated from F_x and F_y measurements by the dynamometer by using Equation 4-8. The ANOVA analysis for $F_{xy\ avg}$ is shown in Table 4-10. Only the effects at $\alpha = 0.05$ significance level are taken into consideration in the analysis. A significant main effect is one that has a probability of occurrence (P value) less then or equal to 0.05. A significant interaction effect occurs when an independent variable along with its interaction with other independent variables causes some difference or change in the effect of the variable on the dependant variable of interest ($F_{xy\ avg}$ in this case).

The main effects plot for $F_{xy\ avg}$ is shown in Figure 4-15. The mean values for $F_{xy\ avg}$ is used to plot the main effects plot.

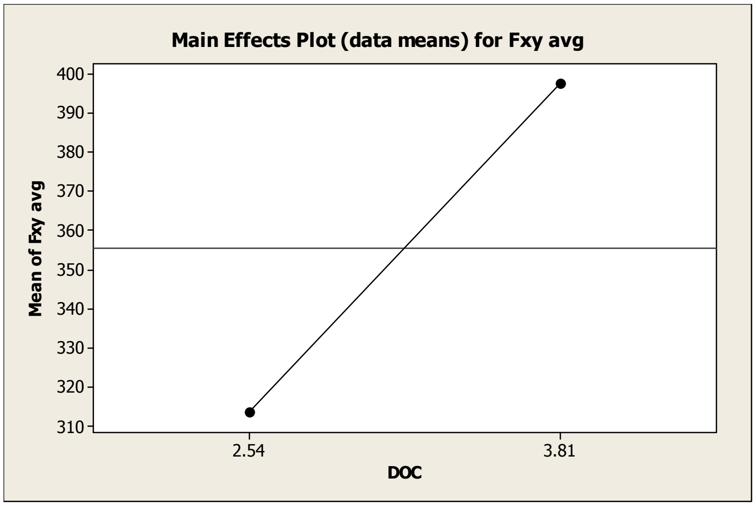


Figure 4-15 Plots of Main Effects for Average 2D Cutting Force on Work piece ($F_{xy\ avg}$ in Newton's)

The list below shows main effects of independent variables and their interactions on $F_{xy\ avg}$ at a significance level $\alpha = 0.05$

1. Depth of cut (DOC) main effect Figure 4-15

Figure 4-15 shows that mean of average 2D cutting force ($F_{xy\ avg}$) increases with an increase in DOC from 2.54 mm to 3.81 mm.

Tukey test for comparison of means was conducted to determine if the means obtained for average 2D cutting force ($F_{xy\ avg}$) are statistically different from each other at different factors and interaction levels at 95 % confidence level. It is to be noted that the Tukey test was conducted on the transformed variable ($F_{xy\ avg}$). A transformation of Log_e ($F_{xy\ avg}$) was done in order to meet normality assumptions for the ANOVA and MANOVA analysis.

4.2.7.1 Tests for contrast of means

The multivariate analysis results in Table 4-2 showed that speed, feed, depth of cut and cutting condition were all significant main effects. This means that for all independent variables, vector of means are significant. Therefore, for at least one dependant variable, there exists a group of means that is significantly different from the population. Tukey test was used for the test of means of each dependant variable. The equal sample size assumption was met for the Tukey test. The following sections discuss the results of the Tukey test.

4.2.7.2 Contrast among means for DOC

Tukey test was used to compare $F_{xy\ avg}$ means using Minitab. The pair wise comparison showed that there exists a statistically significant difference at 95 % confidence level between $F_{xy\ avg}$ means obtained for a DOC level of 2.54 and 3.81 mm respectively.

4.2.7.3 Summary of results of dependant variable $F_{xy\ avg}$

From the MANOVA, ANOVA and Tukey test for the comparison of means, the following are the summary of results of effects of independent variables and their interactions on dependant variable $F_{xy\ avg}$ (Average 2D cutting force acting on the work piece in Newton's).

a) Effect of DOC on $F_{xy\ avg}$

The Tukey test for comparison of means shows that there a statistically significant difference between $F_{xy\ avg}$ means obtained for the two levels of DOC (i.e. 2.54 and 3.81 mm) at 95% confidence level. $F_{xy\ avg}$ means were observed to increase with an increase in depth of cut (DOC) from 2.54 to 3.81 mm. Therefore, in order to obtain low levels of average 2 D cutting force ($F_{xy\ avg}$), a lower level of DOC (i.e. 2.54 mm) is recommended when end milling AISI 4340 steel blocks with advanced PVD TiAlN/TiN coated carbide inserts under dry and semi-dry cutting conditions.

4.2.8 Dependent variable: Maximum Three Dimensional (3 D) Cutting Force Acting on Work piece ($F_{xyz\ max}$)

MANOVA analysis was conducted to determine which independent variables have an affect on some or all of the dependant variables. ANOVA analysis was subsequently conducted to determine whether speed, feed, depth of cut, cutting condition and their significant interactions had an effect on maximum 3D forces acting on the work piece ($F_{xyz\ max}$). The force in X direction (F_x), Y direction (F_y) and Z direction (F_z) acting on the work piece was measured by the Kistler dynamometer. Maximum 3 D force ($F_{xyz\ max}$) was calculated from F_x, F_y and F_z force measurements by the dynamometer using Equation 4-9. The ANOVA analysis for $F_{xyz\ max}$ is shown in Table 4-9. Only the effects at $\alpha = 0.05$ significance level are taken into consideration in the analysis. A significant main effect is one that has a probability of occurrence (P value) less then or equal to 0.05. A significant interaction effect occurs when an independent variable along with its interaction with other independent variables causes some difference or change in the effect of the variable on the dependant variable of interest ($F_{xyz\ max}$ in this case).

The main effects plot for $F_{xyz\ max}$ is shown in Figure 4-16. The mean values for $F_{xyz\ max}$ is used to plot the main effects plot.

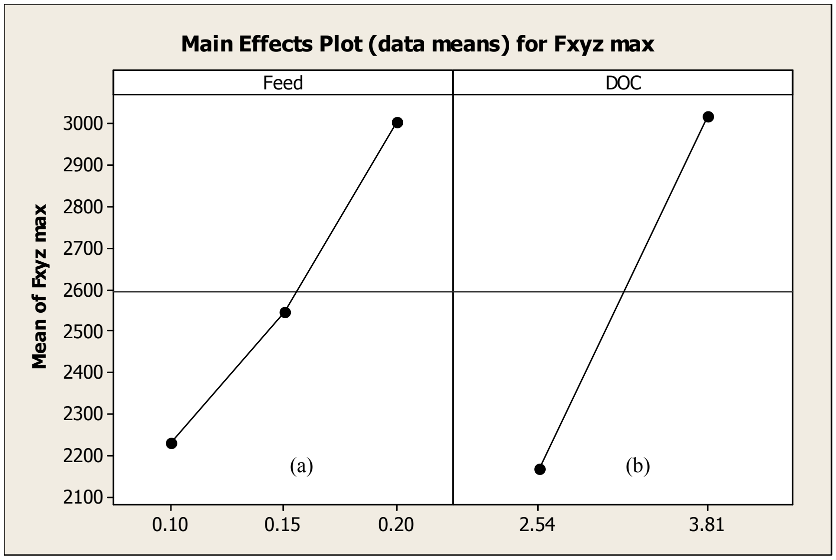


Figure 4-16 Plots of Main Effects for Maximum 3D Cutting Force on Work piece ($F_{xyz\ max}$ in Newton's)

The list below shows main effects of independent variables and their interactions on $F_{xyz\ max}$ at a significance level α = 0.05

1. Feed main effect — Figure 4-16 (a)
2. Depth of cut (DOC) main effect — Figure 4-16 (b)

Figure 4-16 (a) shows that mean of maximum 3 D cutting force ($F_{xyz\ max}$) increases with an increase in feed rate from 0.10 mm/rev to 0.15 mm/rev, and from 0.15 mm/rev to 0.20 mm/rev respectively. Figure 4-16 (b) shows that mean of $F_{xyz\ max}$ increase with an increase in DOC from 2.54 to 3.81 mm.

Tukey test for comparison of means was conducted to determine if the means obtained for maximum 3 D cutting force ($F_{xyz\ max}$) are statistically different from each other at different factors and interaction levels at 95 % confidence level.

4.2.8.1 Tests for contrast of means

The multivariate analysis results in Table 4-2 showed that speed, feed, depth of cut and cutting condition were all significant main effects. This means that for all independent variables, vector of means are significant. Therefore, for at least one dependant variable, there exists a group of means that is significantly different from the population. Tukey test was used for the test of means of each dependant variable. The equal sample size assumption was met for the Tukey test. The following sections discuss the results of the Tukey test.

4.2.8.2 Contrast among means for feed

Tukey test was used to compare $F_{xyz\ max}$ means using Minitab. The pair wise comparison showed that there exists a statistically significant difference at 95 % confidence level between $F_{xyz\ max}$ means obtained for a feed level of 0.10 mm/rev and 0.15 mm/rev respectively. Similarly, pair wise comparison of difference in $F_{xyz\ max}$ means between feed rates of 0.15 mm/rev and 0.20 mm/rev are statistically significant at 95% confidence level.

4.2.8.3 Contrast among means for DOC

Tukey test was used to compare $F_{xyz\ max}$ means using Minitab. The pair wise comparison showed that there exists a statistically significant difference at 95 % confidence level between $F_{xyz\ max}$ means obtained for DOC levels of 2.54 mm and 3.81 mm respectively.

4.2.8.4 Summary of results of dependant variable $F_{xyz\ max}$

From the MANOVA, ANOVA and Tukey test for the comparison of means, the following are the summary of results of effects of independent variables and their interactions on dependant variable $F_{xyz\ max}$ (Maximum 3D cutting force acting on the work piece in Newton's).

a) Effect of feed on $F_{xyz\ max}$

The Tukey test for comparison of means for $F_{xyz\ max}$ showed that there is a statistically significant difference at 95 % confidence level between feed levels of 0.10 and 0.15 mm/rev, and 0.15 and 0.20 mm/rev respectively. It was observed that $F_{xyz\ max}$ means increased with an increase in feed rate from 0.10 to 0.15 mm/rev, and from 0.15 to 0.20 mm/rev. Therefore in order to obtain low mean values of $F_{xyz\ max}$, a lower feed rate of 0.10 mm/rev is recommended.

b) Effect of DOC on $F_{xyz\ max}$

The Tukey test for comparison of means shows that there a statistically significant difference between $F_{xyz\ max}$ means obtained for the two levels of DOC (i.e. 2.54 and 3.81 mm) at 95% confidence level. $F_{xyz\ max}$ means were observed to increase with an increase in depth of cut (DOC) from 2.54 to 3.81 mm. Therefore, in order to obtain low levels of maximum 3 D cutting force ($F_{xyz\ max}$), a lower level of DOC (i.e. 2.54 mm) is recommended when end milling 4340 steel blocks with advanced PVD TiAlN/TiN coated carbide cutting inserts under dry and semi-dry cutting conditions.

4.2.9 Dependent Variable: Average Three Dimensional (3 D) Cutting Force Acting on Work piece ($F_{xyz\ avg}$)

MANOVA analysis was conducted to determine which independent variables have an affect on some or all of the dependant variables. ANOVA analysis was subsequently conducted to determine whether speed, feed, depth of cut, cutting condition and their significant interactions had an effect on average 3 D forces acting on the work piece ($F_{xyz\ avg}$). The force in X direction (F_x in Newton's), Y direction (F_y in Newton's) and Z direction (F_z in Newton's) acting on the work piece was measured by the Kistler dynamometer. Average 3 D force ($F_{xyz\ avg}$) was calculated from F_x, F_y and F_z measurements taken by the dynamometer using Equation 4-10. The ANOVA analysis for $F_{xyz\ avg}$ is shown in Table 4-12. Only the effects at $\alpha = 0.05$ significance level are taken into consideration in the analysis. A significant main effect is one that has a probability of occurrence (P value) less then or equal to 0.05. A significant interaction effect occurs when an independent variable along with its interaction with other independent variables causes some difference or change in the effect of the variable on the dependant variable of interest ($F_{xyz\ avg}$ in this case).

The main effects plot for $F_{xyz\ avg}$ is shown in Figure 4-17. The mean values for $F_{xyz\ avg}$ is used to plot the main effects plot.

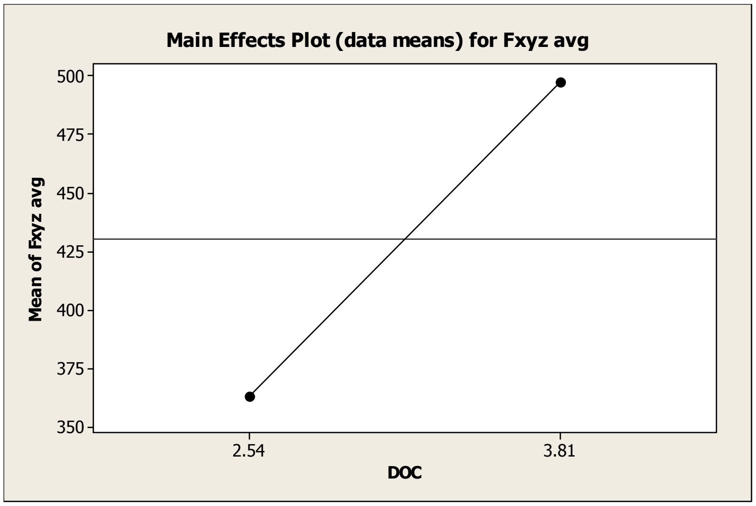


Figure 4-17 Plots of Main Effects for Average 3 D Cutting Force on Work piece ($F_{xyz\ avg}$ in Newton's)

The list below shows main effects of independent variables and their interactions on $F_{xyz\ avg}$ at a significance level $\alpha = 0.05$

1. Depth of cut (DOC) main effect Figure 4-17

Figure 4-17 shows that mean of average 3 D cutting force ($F_{xyz\ avg}$) increases with an increase in DOC from 2.54 mm to 3.81 mm.

Tukey test for comparison of means was conducted to determine if the means obtained for average 3 D cutting force ($F_{xyz\ avg}$) are statistically different from each other at different factors and interaction levels at 95 % confidence level.

4.2.9.1 Tests for contrast of means

The multivariate analysis results in Table 4-2 showed that speed, feed, depth of cut and cutting condition were all significant main effects. This means that for all independent variables, vector of means are significant. Therefore, for at least one dependant variable, there exists a group of means that is significantly different from the population. Tukey test was used for the test of means of each dependant variable. The equal sample size assumption was met for the Tukey test. It is to be noted that the Tukey test was conducted on the transformed variable $1 / \sqrt{F_{xyz\,avg}}$ in order to meet normality assumptions for ANOVA and MANOVA analysis. The following sections discuss the results of the Tukey test.

4.2.9.2 Contrast among means for DOC

Tukey test was used to compare $F_{xyz\ avg}$ means using Minitab. The pair wise comparison showed that there exists a statistically significant difference at 95 % confidence level between $F_{xyz\ avg}$ means obtained for a DOC level of 2.54 mm and 3.81 mm respectively.

4.2.9.3 Summary of results of dependant variable $F_{xyz\ avg}$

From the MANOVA, ANOVA, and Tukey test for the comparison of means, the following are the summary of results of effects of independent variables and their interactions on dependant variable $F_{xyz\ avg}$ (Average 3D cutting force acting on the work piece in Newton's).

a) Effect of DOC on $F_{xyz\ avg}$

The Tukey test for comparison of means shows that there a statistically significant difference between $F_{xyz\ avg}$ means obtained for the two levels of DOC (i.e. 2.54 and 3.81 mm) at 95% confidence level. $F_{xyz\ avg}$ means were observed to increase with an increase in depth of cut (DOC) from 2.54 to 3.81 mm. Therefore, in order to obtain low values of $F_{xyz\ avg}$, a lower level of DOC (i.e. 2.54 mm) is recommended when end milling AISI 4340 steel blocks with advanced PVD TiAlN/TiN coated carbide inserts under dry and semi-dry cutting conditions.

4.2.10 Dependent Variable: Maximum Cutting Power in Watts Consumed During a Cut (P_{max})

MANOVA analysis was conducted to determine which independent variables have an affect on some or all of the dependant variables. ANOVA analysis was subsequently conducted to determine whether speed, feed, depth of cut, cutting condition, and their significant interactions had an effect on maximum cutting power consumed during a cut (P_{max}) in Watts. The relative maximum cutting power was measured using the Artis power sensor. P_{max} in Watts was calculated from the relative maximum cutting power. The ANOVA analysis for P_{max} is shown in Table 4-13. Only the effects at α = 0.05 significance level are taken into consideration in the analysis. A significant main effect is one that has a probability of occurrence (P value) less then or equal to 0.05. A significant interaction effect occurs when an independent variable along with its interaction with other independent variables causes some difference or change in the effect of the variable on the dependant variable of interest (P_{max} in this case).

The main effects plot for P_{max} is shown in Figure 4-18. The mean values for P_{max} is used to plot the main effects plot. The list below shows main effects of independent variables and their interactions on P_{max} at a significance level $\alpha = 0.05$

1. Feed main effect Figure 4-18

Figure 4-18 shows that minimum value of P_{max} is obtained with a feed level of 0.15 mm/rev. The highest value of P_{max} is obtained with a feed level of 0.10 mm/rev, followed by a feed level of 0.20 mm/rev

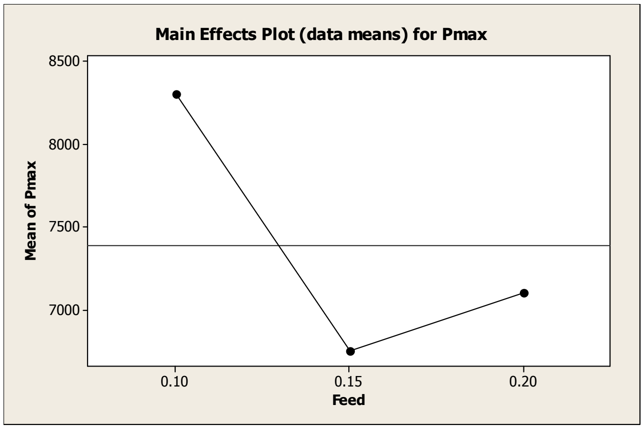


Figure 4-18 Plots of Main Effects for Maximum Cutting Power Consumed During a Cut in Watts (P_{max})

Tukey test for comparison of means was conducted to determine if there exists a statistically significant difference between maximum cutting power (P_{max}) means at different factors and interaction levels at 95 % confidence level.

4.2.10.1 Tests for contrast of means

The multivariate analysis results in Table 4-2 showed that speed, feed, depth of cut and cutting condition were all significant main effects. This means that for all independent variables, vector of means are significant. Therefore, for at least one dependant variable, there exists a group of means that is significantly different from the population. Tukey test was used for the test of means of each dependant variable. The equal sample size assumption was met for the Tukey test. The following sections discuss the results of the Tukey test.

4.2.10.2 Contrast among means for feed

Tukey test was used to compare P_{max} means using Minitab. The pair wise comparison showed that there a statistically significant difference at 95 % confidence level between P_{max} means obtained with feed rates of 0.10 mm/rev and 0.15 mm/rev. However, there is no statistically significant difference between feed levels of 0.15 to 0.20 mm/rev respectively at 95% confidence level.

4.2.10.3 Summary of results of dependant variable P_{max}

From the MANOVA, ANOVA and Tukey test for the comparison of means, the following are the summary of results of effects of independent variables and their interactions on dependant variable P_{max} (Maximum cutting power consumed during a cut):

a) Effect of feed on P_{max}

The Tukey test for comparison of means for P_{max} showed that there is a statistically significant difference at 95 % confidence level between feed levels of 0.10, and 0.15 mm/rev. However, there is no statistically significant difference between feed rates of 0.15 and 0.20 mm/rev respectively at 95 % confidence level. Therefore, in order to obtain a higher rate of material removal and low values of P_{max}, a feed rate of 0.20 mm/rev is recommended when end milling AISI 4340 steel blocks using advanced PVD TiAlN/TiN coated carbide inserts under dry and semi-dry cutting conditions.

4.2.11 Dependent Variable: Total Cutting Power in Watts Consumed During a Cut (P_{total})

MANOVA analysis was conducted to determine which independent variables have an affect on some or all of the dependant variables. ANOVA analysis was subsequently conducted to determine whether speed, feed, depth of cut, cutting condition, and their significant interactions had an effect on the total cutting power consumed during a cut (P_{total}). The relative total cutting power was measured using the Artis power sensor. Total cutting power consumed during a cut (P_{total}) was calculated from the power sensor measurement. The ANOVA analysis for P_{total} is shown in Table 4-14. Only the effects at $\alpha = 0.05$ significance level are taken into consideration in the analysis. A significant main effect is one that has a probability of occurrence (P value) less then or equal to 0.05. A significant interaction effect occurs when an independent variable along with its interaction with other independent variables causes some difference or change in the effect of the variable on the dependant variable of interest (P_{total} in this case).

The main effects plot for P_{total} is shown in Figure 4-19. The mean values for P_{total} are used to plot the main effects plot. The two way interaction plots for P_{total} are shown on Figure 4-20. Three way interaction plots for P_{total} are shown in Figure 4-21 and 4-22.

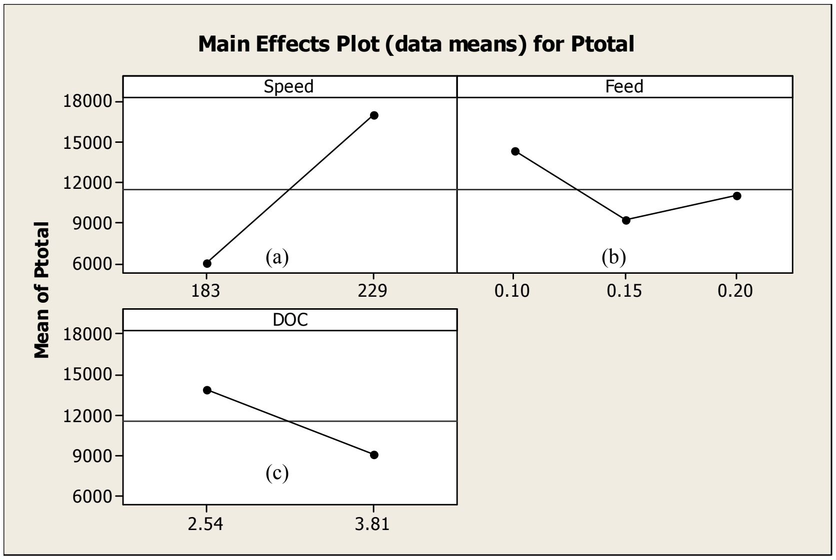


Figure 4-19 Plots of Main Effects for Total Cutting Power Consumed During a Cut in Watts (P_{total})

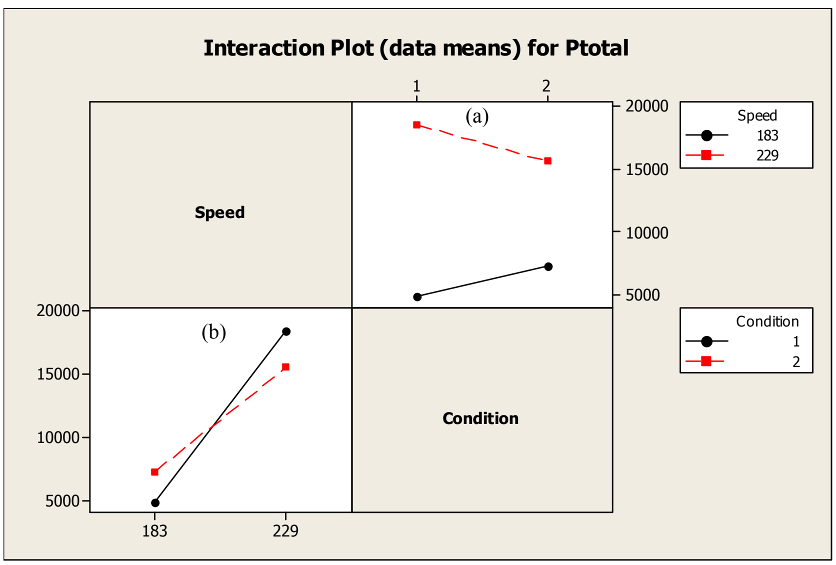


Figure 4-20 Two Way Speed & Condition Interaction Plots for Total Cutting Power Consumed During a Cut in Watts (P_{total})

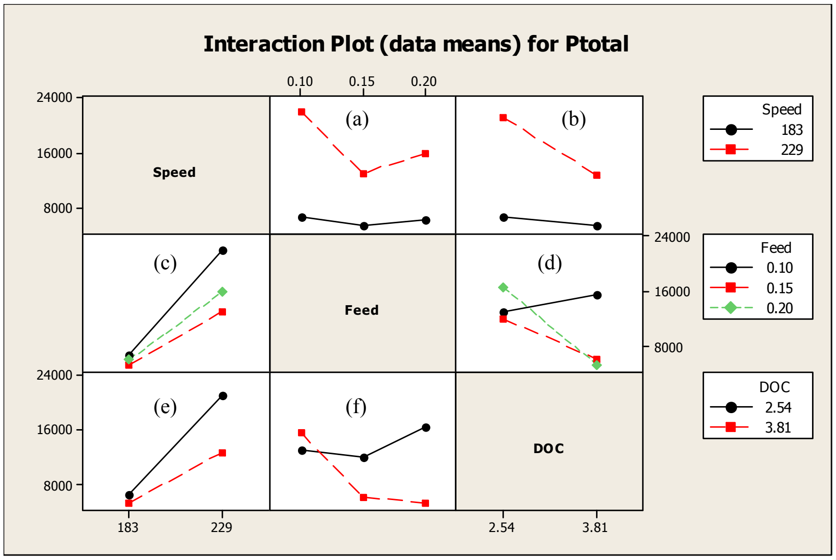


Figure 4-21 Three Way Speed, Feed & DOC Interaction Plots for Total Cutting Power Consumed During a Cut in Watts (P_{total})

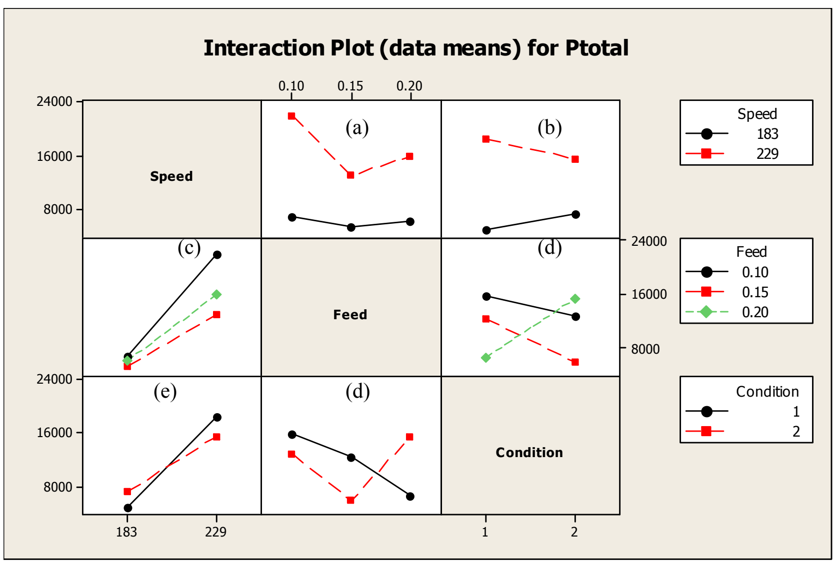


Figure 4-22 Three Way Speed, Feed & Condition Interaction Plots for Total Cutting Power Consumed During a Cut in Watts (P_{total})

The list below shows main effects of independent variables and their interactions on P_{total} at a significance level $\alpha = 0.05$

1. Speed main effect Figure 4-19 (a)

2. Feed main effect Figure 4-19 (b)

3. Depth of cut (DOC) main effect — Figure 4-19 (c)

4. *Speed* x *condition* interaction — Figure 4-20

5. *Speed* x *feed* x *DOC* interaction — Figure 4-21

6. *Speed* x *feed* x *condition* interaction — Figure 4-22

Figure 4-19 (a) shows that means for total cutting power consumed during a cut (P_{total}) increases with an increase in speed from 183 m/min to 229 m/min when machining AISI 4340 steel with coated PVD carbide inserts under dry and semi-dry end milling. Figure 4-19 (b) shows that lowest value of P_{total} means are obtained with a feed rate of 0.15 mm/rev, followed by feed rates of 0.20 mm/rev and 0.10 mm/rev respectively. Figure 4-19 (c) shows that mean of P_{total} decrease with an increase in DOC from 2.54 to 3.81 mm.

However, the effect of speed, feed and DOC on P_{total} cannot be studied separately, as there exists three way *speed* x *feed* x *DOC* and *speed* x *feed* x *condition* interactions that will be studied in more detail.

Tukey test for comparison of means was conducted to determine if the means obtained for total cutting power consumed during a cut (P_{total}) are statistically different from each other at different factors and interaction levels at 95 % confidence level. It is to be noted that Tukey test of means was conducted on the transformed data ($1 / \sqrt{P_{total}}$) in order to meet normality assumptions for ANOVA and MANOVA analysis.

4.2.11.1 Tests for contrast of means

The multivariate analysis results in Table 4-2 showed that speed, feed, depth of cut and cutting condition were all significant main effects. This means that for all independent variables, vector of means are significant. Therefore, for at least one dependant variable, there exists a group of means that is significantly different from the population. Tukey test was used for the test of means of each dependant variable. The equal sample size assumption was met for the Tukey test. The following sections discuss the results of the Tukey test.

4.2.11.2 Contrast among speed, feed & DOC interaction means

Tukey test for comparison of means was performed to see if there is any statistical difference between the interaction level means for P_{total}. The *speed x feed x DOC* interaction are not significant at 95% confidence level for the following cutting conditions:

1. Changing DOC from 2.54 to 3.81 mm at a feed rate of 0.10 mm/rev at a cutting speed of 183 m/min;
2. Changing feed rate from 0.10 to 0.15 mm/rev at a cutting speed of 183 m/min and a DOC of 2.54 mm;
3. Changing from a feed rate of 0.10 mm/rev at a DOC of 2.54 mm to a feed rate of 0.15 mm/rev at a DOC of 3.81 mm at a cutting speed of 183 m/min;
4. Change in feed rate from 0.10 to 0.20 mm/rev at a depth of cut of 2.54 mm and a cutting speed of 183 m/min;

5. Changing from a feed rate of 0.10 mm/rev at a DOC of 2.54 mm to a feed rate of 0.20 mm/rev at a DOC of 3.81 mm at a cutting speed of 183 m/min;
6. Changing cutting speed from 183 to 229 m/min keeping feed rate at 0.10 mm/rev and DOC at 2.54 mm respectively;
7. Changing from a feed rate of 0.10 mm/rev at a cutting speed of 183 m/min to a feed rate of 0.15 mm/rev at a DOC of 2.54 mm and at a cutting speed of 229 m/min;
8. Changing from a feed rate of 0.10 mm/rev, a DOC of 2.54 mm at a cutting speed of 183 m/min to a feed rate of 0.15 mm/rev, a DOC of 3.81 mm and a cutting speed of 229 m/min;
9. Changing feed rate from 0.10 mm/rev at a cutting speed of 183 m/min to a feed rate of 0.20 mm/rev at a cutting speed of 229 m/min and a depth of cut of 2.54 mm;
10. Changing from a feed rate of 0.10 mm/rev, a DOC of 2.54 mm at a cutting speed of 183 m/min to a feed rate of 0.20 mm/rev, a DOC of 3.81 mm and a cutting speed of 229 m/min;
11. Changing feed rate from 0.10 mm/rev and a DOC of 3.81 mm to a feed rate of 0.15 mm/rev and a DOC level of 2.54 mm under a cutting speed of 183 m/min;
12. Changing from a feed rate of 0.10 mm/rev to a feed rate of 0.15 mm/rev at a DOC of 3.81 mm at a cutting speed of 183 m/min;
13. Changing from a feed rate of 0.10 mm/rev at a DOC of 3.81 mm to a feed rate of 0.20 mm/rev at a DOC of 2.54 mm at a cutting speed of 183 m/min;
14. Changing from a feed rate of 0.10 mm/rev to a feed rate of 0.20 mm/rev at a DOC of 3.81 mm at a cutting speed of 183 m/min;

15. Changing from a feed rate of 0.10 mm/rev, a DOC of 3.81 mm at a cutting speed of 183 m/min to a feed rate of 0.15 mm/rev, a DOC of 2.54 mm at a cutting speed of 229 m/min;
16. Changing feed rate from 0.10 mm/rev at a cutting speed of 183 m/min to a feed rate of 0.15 mm/rev at a cutting speed of 229 m/min and DOC of 3.81 mm;
17. Changing from a feed rate of 0.10 mm/rev, a DOC of 3.81 mm at a cutting speed of 183 m/min to a feed rate of 0.20 mm/rev, a DOC of 2.54 mm at a cutting speed of 229 m/min;
18. Changing from a feed rate of 0.10 mm/rev at a cutting speed of 183 m/min to a feed rate of 0.20 mm/rev at DOC of 3.81 mm at a cutting speed of 229 m/min and DOC of 3.81 mm;
19. Changing from a depth of cut of 2.54 to 3.81 mm under a feed rate of 0.15 mm/rev at a cutting speed of 183 m/min;
20. Changing feed rate from 0.15 to 0.20 mm/rev at a cutting speed of 183 m/min and a DOC of 2.54 mm;
21. Changing from a feed rate of 0.15 mm/rev at a DOC of 2.54 mm to a feed rate of 0.20 mm/rev at a DOC of 3.81 mm at a cutting speed of 183 m/min;
22. Changing cutting speed from 183 to 229 m/min keeping feed rate at 0.15 mm/rev and DOC at 2.54 mm respectively;
23. Changing DOC from 2.54 to 3.81 mm at a cutting speed of 183 m/min to a DOC of 3.81 mm at a cutting speed of 229 m/min and a feed rate of 0.15 mm/rev;
24. Changing from a feed rate of 0.15 mm/rev and a cutting speed of 183 m/min to a feed rate of 0.20 mm/rev at a cutting speed of 229 m/min and a DOC of 3.81 mm;

25. Changing from a feed rate of 0.15 mm/rev, a depth of cut of 2.54 mm and a cutting speed of 183 m/min to a feed rate of 0.20 mm/rev at a DOC of 3.81 mm at a cutting speed of 229 m/min;
26. Changing from a feed rate of 0.15 mm/rev and a DOC of 3.81 mm to a feed rate of 0.20 mm/rev at a DOC of 2.54 mm at a cutting speed of 183 m/min;
27. Changing from a feed rate of 0.15 to 0.20 mm/rev at a DOC of 3.81 mm at a cutting speed of 183 m/min;
28. Changing from a DOC of 3.81 mm at a cutting speed of 183 m/min to a depth of cut of 2.54 mm at a cutting speed of 229 m/min at a constant feed rate of 0.15 mm/rev;
29. Changing cutting speed from 183 to 229 m/min at a feed rate of 0.15 mm/rev and a DOC of 3.81 mm;
30. Changing feed rate from 0.15 mm/rev at a cutting speed of 183 m/min to a feed rate of 0.20 mm/rev at a cutting speed of 229 m/min;
31. Changing DOC from 2.54 to 3.81 mm at a cutting speed of 183 m/min and a feed rate of 0.20 mm/rev;
32. Changing from a feed rate of 0.20 mm/rev, a depth of cut of 2.54 mm and a cutting speed of 183 m/min to a feed rate of 0.10 mm/rev at a DOC of 3.81 mm at a cutting speed of 229 m/min;
33. Changing from a feed rate of 0.20 mm/rev and a cutting speed of 183 m/min to a feed rate of 0.15 mm/rev at a cutting speed of 229 m/min at a DOC of 2.54 mm;

34. Changing from a feed rate of 0.20 mm/rev, a depth of cut of 2.54 mm and a cutting speed of 183 m/min to a feed rate of 0.15 mm/rev at a DOC of 3.81 mm at a cutting speed of 229 m/min;
35. Changing cutting speed from 183 to 229 m/min under at a feed rate of 0.20 mm/rev and a DOC of 2.54 mm;
36. Changing DOC from 2.54 mm at a cutting speed of 183 m/min to a DOC of 3.81 mm at a cutting speed of 229 m/min and a feed rate of 0.20 mm/rev;
37. Changing from a feed rate of 0.20 mm/rev, a depth of cut of 3.81 mm and a cutting speed of 183 m/min to a feed rate of 0.15 mm/rev at a DOC of 2.54 mm and a cutting speed of 229 m/min;
38. Changing feed rate from 0.20 mm/rev at a cutting speed of 183 m/min to a feed rate of 0.15 mm/rev at a cutting speed of 229 m/min at a depth of cut of 3.81 mm;
39. Changing depth of cut from 3.81 mm at a cutting speed of 183 m/min to a depth of cut of 2.54 mm at a cutting speed of 229 m/min at a feed rate of 0.20 mm/rev;
40. Changing cutting speed from 183 to 229 m/min at a feed level of 0.20 mm/rev and a DOC of 3.81 mm;
41. Changing DOC from 2.54 to 3.81 mm at a cutting speed of 229 m/min and a feed rate of 0.10 mm/rev;
42. Changing from a feed rate of 0.10 to 0.15 mm/rev at a cutting speed of 229 m/min and a DOC of 2.54 mm;
43. Changing from a feed rate of 0.10 mm/rev and a depth of cut of 2.54 mm to a feed rate of 0.15 mm/rev at a DOC of 3.81 mm at a cutting speed of 229 m/min;

44. Changing from a feed rate of 0.10 mm/rev at a depth of cut of 3.81 mm to a feed rate of 0.15 mm/rev at a depth of cut of 2.54 mm at a cutting speed of 229 m/min;
45. Changing from a feed rate of 0.10 mm/rev at a depth of cut of 3.81 mm to a feed rate of 0.20 mm/rev at a depth of cut of 2.54 mm at a cutting speed of 229 m/min;
46. Changing DOC from 2.54 to 3.81 mm at a cutting speed of 229 m/min and a feed rate of 0.15 mm/rev;
47. Changing from a feed rate of 0.15 to 0.20 mm/rev at a DOC of 2.54 mm at a cutting speed of 229 m/min;
48. Changing from a feed rate of 0.15 mm/rev and a depth of cut of 2.54 mm to a feed rate of 0.20 mm/rev at a DOC of 3.81 mm at a cutting speed of 229 m/min;
49. Changing from a feed rate of 0.15 mm/rev and a depth of cut of 3.81 mm to a feed rate of 0.20 mm/rev at a DOC of 2.54 mm at a cutting speed of 229 m/min;
50. Changing from a feed rate of 0.15 to 0.20 mm/rev at a DOC of 3.81 mm and a cutting speed of 229 m/min;

The Tukey test for comparison of P_{total} means for all other cutting conditions showed significant difference at 95% confidence level.

4.2.11.3 Contrast among speed, feed & condition interaction means

Tukey test for comparison of means was performed to see if there is any statistical difference between the interaction level means for P_{total}. The *speed x feed x condition* interaction are not significant at 95% confidence level for the following cutting conditions:

1. Changing cutting condition from semi-dry to dry cutting condition at a cutting speed of 183 m/min and a feed rate of 0.10 mm/rev;
2. Changing feed rate from 0.10 mm/rev to 0.15 mm/rev at a cutting speed of 183 m/min under semi-dry cutting condition;
3. Changing feed from 0.10 mm/rev under semi-dry cutting condition to 0.15 mm/rev under dry cutting condition keeping speed constant at 183 m/min;
4. Changing feed rate from 0.10 mm/rev to 0.20 mm/rev at a cutting speed of 183 m/min under semi-dry cutting condition;
5. Changing feed rate from 0.10 mm/rev under semi-dry cutting condition to 0.20 mm/rev under dry cutting condition at a cutting speed of 183 m/min;
6. Changing from a cutting speed of 183 m/min and a feed rate of 0.10 mm/rev under semi-dry cutting condition to a cutting speed of 229 m/min and feed rate of 0.15 mm/rev under dry cutting condition;
7. Changing from a cutting speed of 183 m/min and a feed rate of 0.10 mm/rev to a cutting speed of 229 m/min and feed rate of 0.20 mm/rev under semi-dry cutting condition;
8. Changing from a cutting speed of 183 m/min and a feed rate of 0.10 mm/rev under semi-dry cutting condition to a cutting speed of 229 m/min and feed rate of 0.20 mm/rev under dry cutting condition;
9. Changing feed rate from 0.10 mm/rev to 0.15 mm/rev at a cutting speed of 183 m/min under dry cutting condition;
10. Changing feed rate from 0.10 mm/rev under dry cutting condition to 0.20 mm/rev under semi-dry cutting condition;

11. Changing feed rate from 0.10 mm/rev to 0.20 mm/rev at a cutting speed of 183 m/min under dry cutting condition;
12. Changing cutting speed from 183 m/min to 229 m/min under a constant feed rate of 0.10 mm/rev and dry cutting condition;
13. Changing from a feed rate of 0.10 mm/rev at a cutting speed of 183 m/min under dry cutting condition to a feed rate of 0.15 mm/rev at a cutting speed of 229 m/min under semi-dry cutting condition;
14. Changing from a feed rate of 0.10 mm/rev at a cutting speed of 183 m/min to a feed rate of 0.15 mm/rev at a cutting speed of 229 m/min under dry cutting condition;
15. Changing from a feed rate of 0.10 mm/rev at a cutting speed of 183 m/min under dry cutting condition to a feed rate of 0.20 mm/rev at a cutting speed of 229 m/min under semi-dry cutting condition;
16. Changing feed rate from 0.10 mm/rev at a cutting speed of 183 m/min to a feed rate of 0.20 mm/rev at a cutting speed of 229 m/min under dry cutting condition;
17. Changing feed rate from 0.15 mm/rev to 0.20 mm/rev at a cutting speed of 183 m/min under semi-dry cutting condition;
18. Changing from a cutting speed of 183 m/min under semi-dry cutting condition to a cutting speed of 229 m/min under dry cutting condition at a constant feed rate of 0.15 mm/rev;
19. Changing from a cutting speed of 183 m/min and a feed rate of 0.15 mm/rev to a cutting speed of 229 m/min and a feed rate of 0.20 mm/rev under semi-dry cutting condition;

20. Changing from a feed rate of 0.15 mm/rev at a cutting speed of 183 m/min under semi-dry cutting condition to a feed rate of 0.20 mm/rev at a cutting speed of 229 m/min under dry cutting condition;
21. Changing feed rate from 0.15 mm/rev under dry cutting condition to a feed rate of 0.20 mm/rev under semi-dry cutting condition keeping cutting speed constant at 183 m/min;
22. Changing feed rate from 0.15 mm/rev to 0.20 mm/rev under dry cutting condition keeping cutting speed constant at 183 m/min;
23. Changing from a cutting speed of 183 m/min under semi-dry cutting condition to a cutting speed of 229 m/min under dry cutting condition at a constant feed rate of 0.15 mm/rev;
24. Changing cutting speed from 183 to 229 m/min at a feed rate of 0.15 mm/rev and a dry cutting condition;
25. Changing feed rate from 0.15 mm/rev at a cutting speed of 183 m/min under dry cutting condition to a feed rate of 0.20 mm/rev at a cutting speed of 229 m/min under semi-dry cutting condition;
26. Changing feed rate from 0.15 mm/rev at a cutting speed of 183 m/min to a feed rate of 0.20 mm/rev at a cutting speed of 229 m/min under dry cutting condition;
27. Changing cutting condition from semi-dry to dry under a constant feed rate of 0.20 mm/rev and cutting speed of 183 m/min;

28. Changing from a cutting speed of 183 m/min and a feed rate of 0.20 mm/rev to a cutting speed of 229 m/min and a feed rate of 0.15 mm/rev under semi-dry cutting condition;
29. Changing from a feed rate of 0.20 mm/rev at a cutting speed of 183 m/min under semi-dry cutting condition to a feed rate of 0.15 mm/rev at a cutting speed of 229 m/min under dry cutting condition;
30. Changing from a cutting speed of 183 m/min to 229 m/min with a constant feed rate of 0.20 mm/rev under semi-dry cutting condition;
31. Changing cutting condition from semi-dry at a cutting speed of 183 m/min to dry at a cutting speed of 229 m/min at a feed rate of 0.20 mm/rev;
32. Changing from a cutting speed of 183 m/min and a feed rate of 0.20 mm/rev under dry cutting condition to a cutting speed of 229 m/min and a feed rate of 0.15 mm/rev under semi-dry cutting condition;
33. Changing feed rate from 0.20 mm/rev at a cutting speed of 183 m/min to a feed rate of 0.15 mm/rev at a cutting speed of 229 m/min under dry cutting condition;
34. Changing cutting condition from dry at a cutting speed of 183 m/min to semi-dry at a cutting speed of 229 m/min at a feed rate of 0.20 mm/rev;
35. Changing cutting speed from 183 to 229 m/min at a feed rate of 0.20 mm/rev under dry cutting condition;
36. Changing cutting condition from semi-dry to dry cutting condition at a cutting speed of 229 m/min and a feed rate of 0.10 mm/rev;
37. Changing feed rate from 0.10 to 0.15 mm/rev at a cutting speed of 229 m/min under semi-dry cutting condition;

38. Changing feed rate from 0.10 mm/rev under semi-dry cutting condition to a feed rate of 0.20 mm/rev under dry cutting condition at a cutting speed of 229 m/min;
39. Changing from a feed rate of 0.10 mm/rev under dry cutting condition to a feed rate of 0.15 mm/rev under semi-dry cutting condition at a constant speed of 229 m/min;
40. Changing from a feed rate of 0.10 mm/rev to 0.20 mm/rev under dry cutting condition at a constant speed of 229 m/min;
41. Changing from a feed rate of 0.10 mm/rev to 0.20 mm/rev under dry cutting condition at a constant speed of 229 m/min;
42. Changing from a feed rate of 0.15 mm/rev to a feed rate of 0.20 mm/rev under semi-dry cutting condition at a constant speed of 229 m/min;
43. Changing from a feed rate of 0.15 mm/rev under semi-dry cutting condition to a feed rate of 0.20 mm/rev under dry cutting condition at a constant speed of 229 m/min;
44. Changing from a feed rate of 0.15 mm/rev under dry cutting condition to a feed rate of 0.20 mm/rev under semi-dry cutting condition at a constant speed of 229 m/min;
45. Changing from a feed rate of 0.15 mm/rev to a feed rate of 0.20 mm/rev under dry cutting condition at a constant speed of 229 m/min;
46. Changing cutting condition from semi-dry to dry cutting condition at a cutting speed of 229 m/min and a feed rate of 0.20 mm/rev;

The Tukey test for comparison of P_{total} means for all other cutting conditions showed significant difference at 95% confidence level.

4.2.11.4 Summary of results of dependant variable P_{total}

From the MANOVA, ANOVA and Tukey test for the comparison of means, the following are the summary of results of effects of independent variables and their interactions on dependant variable P_{total} (Total cutting power consumed during a cut in Watts).

a) Effect of speed, feed & DOC interaction

The results of the Tukey test of means of transformed P_{total} are summarized in Table 4-24. +Significance stands for statistical difference between mean values of transformed P_{total} at 95 % confidence level, when the value shows an increasing trend amongst cutting conditions being compared. Similarly, -Significance stands for statistical difference between mean value of transformed P_{total} at 95 % confidence level when the mean value of transformed P_{total} shows a decreasing trend. "No Significance" is used to denote no statistically significant difference in transformed P_{total} means being compared at 95 % confidence level between conditions.

From Table 4-23, the following cutting conditions yield lowest mean value of P_{total}:

1) Cutting speed of 183 m/min, feed rate of 0.10 mm/rev, DOC of 3.81 mm
2) Cutting speed of 183 m/min, feed rate of 0.15 mm/rev, DOC of 2.54 mm
3) Cutting speed of 183 m/min, feed rate of 0.15 mm/rev, DOC of 3.81 mm
4) Cutting speed of 183 m/min, feed rate of 0.20 mm/rev, DOC of 2.54 mm
5) Cutting speed of 183 m/min, feed rate of 0.20 mm/rev, DOC of 3.81 mm
6) Cutting speed of 229 m/min, feed rate of 0.15 mm/rev, DOC of 2.54 mm
7) Cutting speed of 229 m/min, feed rate of 0.15 mm/rev, DOC of 3.81 mm

8) Cutting speed of 229 m/min, feed rate of 0.20 mm/rev, DOC of 2.54 mm

9) Cutting speed of 229 m/min, feed rate of 0.20 mm/rev, DOC of 3.81 mm

It should be noted that the comparison of means in Table 4-24 was conducted on the transformed values of P_{total} i.e. $(P_{total})^{-0.5}$. The lowest value of P_{total} mean corresponds to the highest value of $(P_{total})^{-0.5}$ mean.

From the above cutting conditions, a cutting speed of 229 m/min, a feed rate of 0.20 mm/rev at a depth of cut of 3.81 mm gives the highest material removal rate and the lowest mean value of P_{total} when end milling AISI 4340 steel blocks with advanced PVD TiAlN/TiN coated carbide inserts.

b) Effect of speed, feed & condition interaction

The results of the Tukey test of means of transformed P_{total} are summarized in Table 4-25. +Significance stands for statistical difference between mean values of transformed P_{total} at 95 % confidence level, when the value shows an increasing trend amongst cutting conditions being compared. Similarly, -Significance stands for statistical difference between mean value of transformed P_{total} at 95 % confidence level when the mean value of transformed P_{total} shows a decreasing trend. “No Significance” is used to denote no statistically significant difference in transformed P_{total} means being compared at 95 % confidence level between conditions.

From Table 4-25, the following cutting conditions yield lowest mean value of P_{total}:

1) Cutting speed of 183 m/min, depth of cut of 0.15 mm, under semi-dry cutting condition

2) Cutting speed of 183 m/min, depth of cut of 0.20 mm, under semi-dry cutting condition
3) Cutting speed of 229 m/min, feed rate of 0.15 mm/rev, dry cutting condition
4) Cutting speed of 229 m/min, feed rate of 0.20 mm/rev, semi-dry cutting condition
5) Cutting speed of 229 m/min, feed rate of 0.20 mm/rev, dry cutting condition

It should be noted that the comparison of means in Table 4-24 was conducted on the transformed values of P_{total} i.e. $(P_{total})^{-0.5.}$ The lowest value of P_{total} mean corresponds to the highest value of $(P_{total})^{-0.5}$ mean.

From the above cutting conditions, a cutting speed of 229 m/min, a feed rate of 0.20 mm/rev and semi-dry cutting condition gives the highest material removal rate and the lowest mean value of P_{total} when end milling AISI 4340 steel blocks with advanced PVD TiAlN/TiN coated carbide inserts.

Table 4-24 The Results of Tukey Pair wise Comparison of Transformed P_{total} Means for Speed, Feed & DOC Interaction

		183 m/min						229 m/min					
		0.10:2.54 (0.011918)	0.10:3.81 (0.014569)	0.15:2.54 (0.011211)	0.15:3.81 (0.014362)	0.20:2.54 (0.012588)	0.20:3.81 (0.013331)	0.10:2.54 (0.008339)	0.10:3.81 (0.006590)	0.15:2.54 (0.010598)	0.15:3.81 (0.012739)	0.20:2.54 (0.008805)	0.20:3.81 (0.013944)
183 m/min	0.10:2.54 (0.011918)		No Significance	No Significance	No Significance	No Significance	No Significance	No Significance	-Significance	No Significance	No Significance	No Significance	No Significance
	0.10:3.81 (0.014569)			No Significance	No Significance	No Significance	No Significance	-Significance	-Significance	No Significance	No Significance	No Significance	No Significance
	0.15:2.54 (0.011211)				No Significance	No Significance	No Significance	-Significance	-Significance	No Significance	No Significance	No Significance	No Significance
	0.15:3.81 (0.014362)					No Significance	No Significance	-Significance	-Significance	No Significance	No Significance	-Significance	No Significance
	0.20:2.54 (0.012588)						No Significance	-Significance	No Significance	No Significance	No Significance	No Significance	No Significance
	0.20:3.81 (0.013331)							-Significance	-Significance	No Significance	No Significance	No Significance	No Significance
229 m/min	0.10:2.54 (0.008339)								No Significance	No Significance	No Significance	+Significance	+Significance
	0.10:3.81 (0.006590)									No Significance	+Significance	No Significance	+Significance
	0.15:2.54 (0.010598)										No Significance	No Significance	No Significance
	0.15:3.81 (0.012739)											No Significance	No Significance
	0.20:2.54 (0.008805)												+Significance
	0.20:3.81 (0.013944)												

Note: Speed levels used are 183 and 229 m/min. Feed levels used are 0.10 mm/rev, 0.15 mm/rev and 0.20 mm/rev. DOC levels used are 2.54 and 3.81 mm. The Tukey analysis of means was carried on transformed P_{total} means, i.e. mean values of $(P_{total})^{-0.5}$.

Table 4-25 The Results of Tukey Pair wise Comparison of Transformed P_{total} Means for Speed, Feed, & Condition Interaction

		183 m/min						229 m/min					
		0.10:1 (0.015328)	0.10:2 (0.011160)	0.15:1 (0.015637)	0.15:2 (0.012485)	0.20:1 (0.013466)	0.20:2 (0.012454)	0.10:1 (0.006414)	0.10:2 (0.008515)	0.15:1 (0.008687)	0.15:2 (0.014650)	0.20:1 (0.012263)	0.20:2 (0.010486)
183 m/min	0.10:1 (0.015328)		No Significance	No Significance	No Significance	No Significance	No Significance	-Significant	-Significant	-Significant	No Significance	No Significance	No Significance
	0.10:2 (0.011160)			+Significant	No Significance	No Significance	No Significance	-Significant	No Significance	No Significance	No Significance	No Significance	No Significance
	0.15:1 (0.015637)				-Significant	No Significance	-Significant	-Significant	-Significant	-Significant	No Significance	No Significance	No Significance
	0.15:2 (0.012485)					No Significance	No Significance	-Significant	-Significant	No Significance	No Significance	No Significance	No Significance
	0.20:1 (0.013466)						No Significance	-Significant	-Significant	No Significance	No Significance	No Significance	No Significance
	0.20:2 (0.012454)							-Significant	-Significant	No Significance	No Significance	No Significance	No Significance
229 m/min	0.10:1 (0.006414)								No Significance	No Significance	+Significant	+Significant	No Significance
	0.10:2 (0.008515)									No Significance	+Significant	No Significance	No Significance
	0.15:1 (0.008687)										+Significant	No Significance	No Significance
	0.15:2 (0.014650)											No Significance	No Significance
	0.20:1 (0.012263)												No Significance
	0.20:2 (0.010486)												

Note: Speed levels used are 183 and 229 m/min. Feed levels used are 0.10 mm/rev, 0.15 mm/rev and 0.20 mm/rev. Cutting condition 1:semi-dry and 2:dry cutting condition were used. The Tukey analysis of means was carried on transformed P_{total} means, i.e. mean values of $(P_{total})^{-0.5}$.

4.2.12 Dependent Variable: Surface Finish of Work piece (R_a)

MANOVA analysis was conducted to determine which independent variables have an affect on some or all of the dependant variables. ANOVA analysis was subsequently conducted to determine whether speed, feed, depth of cut, cutting condition and their significant interactions had an effect on the average surface roughness of the work piece (R_a measured in μm). The surface finish of every fourth cut on a fresh work piece surface was recorded using a Surtronic 3+ profilometer. The ANOVA analysis for R_a is shown in Table 4-15. Only the effects at $\alpha = 0.05$ significance level are taken into consideration in the analysis. A significant main effect is one that has a probability of occurrence (P value) less then or equal to 0.05. A significant interaction effect occurs when an independent variable along with its interaction with other independent variables causes some difference or change in the effect of the variable on the dependant variable of interest (R_a in this case).

The main effects plot for R_a is shown in Figure 4-23. The mean values for R_a are used to plot the main effects plot.

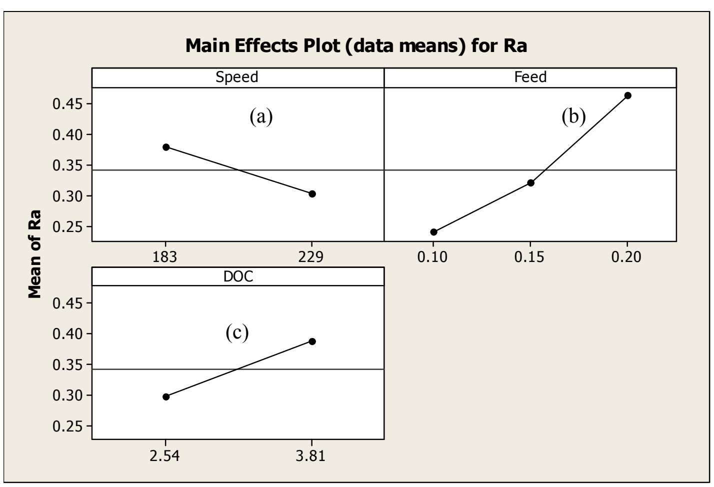


Figure 4-23 Plots of Main Effects for Surface Finish (R_a)

The list below shows main effects of independent variables at a significance level $\alpha = 0.05$

1. Speed main effect — Figure 4-23 (a)
2. Feed main effect — Figure 4-23 (b)
3. Depth of cut (DOC) main effect — Figure 4-23 (c)

Figure 4-23 (a) shows that surface finish (R_a) decreases with an increase in speed from 183 m/min to 229 m/min when machining AISI 4340 steel with coated PVD TiAlN/TiN coated carbide inserts under dry and semi-dry end milling. Figure 4-23 (b) shows that mean of R_a decrease with an increase in feed from 0.10 mm/rev to 0.15 mm/rev, and from 0.15 mm/rev to 0.20 mm/rev respectively. Figure 4-23 (c) shows that mean of R_a increases with an increase in DOC from 2.54 to 3.81 mm.

Tukey test for comparison of means was conducted to determine if the means obtained for surface roughness (R_a) are statistically different from each other at different factor and interaction levels at 95 % confidence level.

4.2.12.1 Tests for contrast of means

The multivariate analysis results in Table 4-2 showed that speed, feed, depth of cut and cutting condition were all significant main effects. This means that for all independent variables, vector of means are significant. Therefore, for at least one dependant variable, there exists a group of means that is significantly different from the population. Tukey test was used for the test of means of each dependant variable. The equal sample size assumption was met for the Tukey test. The following sections discuss the results of the Tukey test.

4.2.12.2 Contrast among means for speed

Tukey test was used to compares means using Minitab. The pair wise comparison showed that difference in R_a means obtained with cutting speeds of 183 and 229 m/min are not statistically significant at 95 % confidence level.

4.2.12.3 Contrast among means for feed

Tukey test was used to compare R_a means using Minitab. The pair wise comparison of the difference in mean values of R_a obtained for feed levels of 0.10 and 0.15 mm/rev are not statistically significant at 95% confidence level. However, pair wise comparison of difference in R_a means for feed rates of 0.15 mm/rev and 0.20 mm/rev are statistically significant at 95% confidence level.

4.2.12.4 Contrast among means for DOC

Tukey test was used to compares means using Minitab. The pair wise comparison showed that the difference between R_a means obtained with cutting speeds of 183 and 229 m/min are statistically significant at 95 % confidence level.

4.2.12.5 Summary of results of dependant variable R_a

From the MANOVA, ANOVA and Tukey test for the comparison of means, the following are the summary of results of effects of independent variables and their interactions on dependant variable R_a (Surface finish measured in μm).

a) Effect of speed

The Tukey test for comparison of means for surface finish (R_a) showed that there is no statistically significant difference at 95 % confidence level between cutting speed levels of 183 and 229 m/min. Therefore for higher material removal rate, a higher speed level of 229 m/min is recommended in order to obtain better surface finish.

b) Effect of feed

The Tukey test for comparison of means shows that there is no statistically significant difference between R_a means obtained when using feed rates of 0.10 mm/rev and 0.15 mm/rev. However, there is a statistically significant difference between R_a means obtained with feed rates of 0.15 and 0.20 mm/rev respectively. It was observed that surface finish (R_a) increased when cutting feed rate was increased from 0.10 to 0.15 mm/rev, and 0.15 to 0.20 mm/rev respectively. Therefore, a feed rate of 0.15 mm/rev is recommended to obtain a higher material removal rate and a better surface finish.

c) Effect of DOC

The Tukey test for comparison of means for R_a showed that there is a statistically significant difference at 95 % confidence level between R_a means obtained with DOC levels of 2.54 and 3.81 mm. It can be seen that a better surface finish is obtained at the low DOC level of 2.54 mm.

4.2.13 Dependent Variable: Tool Life (T_{life})

MANOVA analysis was conducted to determine which independent variables have an affect on some or all of the dependant variables. ANOVA analysis was subsequently conducted to determine whether speed, feed, depth of cut, cutting condition and their significant interactions had an effect on tool life (T_{life}) measured by the number of cuts (6 inch or 152.4 mm long) needed to reach flank wear criterion of 400 µm under different cutting conditions. The ANOVA analysis for T_{life} is shown in Table 4-16. Only the effects at $\alpha = 0.05$ significance level are taken into consideration in the analysis. A significant main effect is one that has a probability of occurrence (P value) less then or equal to 0.05. A significant interaction effect occurs when an independent variable along with its interaction with other independent variables causes some difference or change in the effect of the variable on the dependant variable of interest (T_{life} in this case).

The main effects plot for T_{life} is shown in Figure 4-24. The mean values for T_{life} are used to plot the main effects plot. The three way interaction plot for T_{life} is shown in Figure 4-25 and 4-26.

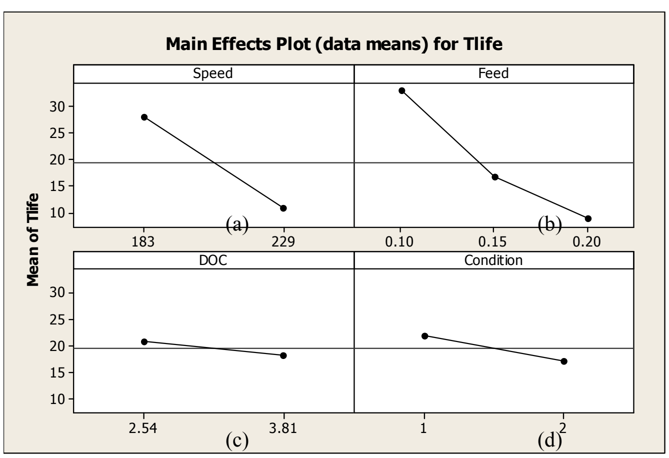


Figure 4-24 Plots of Main Effects for Tool Life (T_{life})

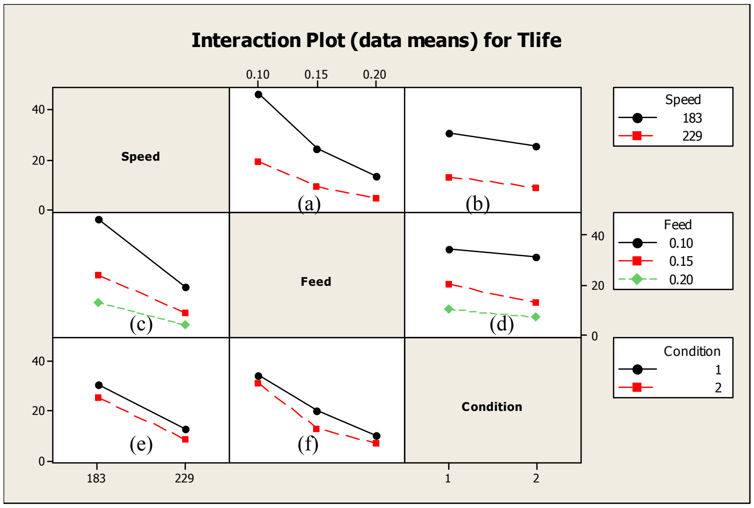


Figure 4-25 Three Way Interaction Plot of Speed, Feed & Condition for Tool Life (T_{life})

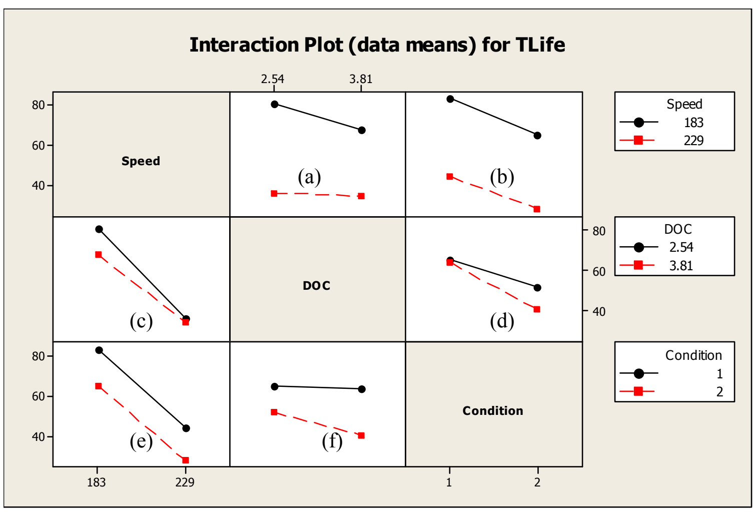


Figure 4-26 Three Way Interaction Plot for Speed, DOC & Condition Interaction for Tool Life (T_{life})

The list below shows main effects of independent variables and their interactions on T_{life} at a significance level $\alpha = 0.05$

1. Speed main effect — Figure 4-24 (a)
2. Feed main effect — Figure 4-24 (b)
3. Depth of cut (DOC) main effect — Figure 4-24 (c)
4. Condition main effect — Figure 4-24 (d)

4. *Speed* x *feed* x *condition* interaction Figure 4-25

5. *Speed* x *DOC* x *condition* interaction Figure 4-26

Figure 4-24 (a) shows that mean of T_{life} decreases with an increase in speed from 183 m/min to 229 m/min when machining 4340 steel with PVD TiAlN/TiN coated carbide inserts under dry and semi-dry end milling. Figure 4-24 (b) shows that T_{life} mean decreases with an increase in feed rate from 0.10 mm/rev to 0.15 mm/rev, and from 0.15 mm/rev to 0.20 mm/rev respectively. Figure 4-24 (c) shows that mean of T_{life} decreases with an increase in DOC from 2.54 to 3.81 mm. Figure 4-24 (d) shows that mean of T_{life} decreases with change in cutting condition from semi-dry to dry.

However, the effect of speed, feed, and DOC and condition on T_{life} are not studied separately, as there exists a three way *speed* x *feed* x *condition* and a three way *speed x DOC x condition* interaction which will be studied in more detail.

Tukey test for comparison of means was conducted to determine if the means obtained for T_{life} are statistically different from each other at different factors and interaction levels at 95 % confidence level.

4.2.13.1 Tests for contrast of means

The multivariate analysis results in Table 4-2 showed that speed, feed, depth of cut and cutting condition were all significant main effects. This means that for all independent variables, vector of means are significant. Therefore, for at least one dependant variable, there exists a group of means that is significantly different from the population. Tukey test was used for the test of means of each dependant variable. The equal sample size assumption was met for the Tukey test.

The following sections discuss the results of the Tukey test.

4.2.13.2 Contrast among speed, feed & condition interaction means

Tukey test for comparison of means was performed to see if there is any statistical difference between the interaction level means for T_{life}.

The *speed x feed x condition* interaction are not significant at 95% confidence level for the following cutting conditions:

1. Changing cutting condition from semi-dry to dry cutting condition at a cutting speed of 183 m/min and a feed rate of 0.10 mm/rev;
2. Changing feed rate from 0.10 mm/rev to 0.15 mm/rev at a cutting speed of 183 m/min under semi-dry cutting condition;
3. Changing feed from 0.10 mm/rev under dry cutting condition to 0.15 mm/rev under semi-dry cutting condition keeping speed constant at 183 m/min;
4. Changing feed rate from 0.15 mm/rev under dry cutting condition to a feed rate of 0.20 mm/rev under semi-dry machining condition keeping cutting speed constant at 183 m/min;
5. Changing feed rate from 0.15 mm/rev to a feed rate of 0.20 mm/rev under dry cutting condition keeping cutting speed constant at 183 m/min;
6. Changing from a cutting speed of 183 m/min and a feed rate of 0.15 mm/rev under dry cutting condition to a cutting speed of 229 m/min and a feed rate of 0.10 mm/rev under semi-dry cutting condition;

7. Changing from a cutting speed of 183 m/min and a feed rate of 0.15 mm/rev to a cutting speed of 229 m/min and a feed rate of 0.10 mm/rev under dry cutting condition;
8. Changing from a cutting speed of 183 m/min and under dry cutting condition to a cutting speed of 229 m/min under semi-dry cutting condition at a constant feed rate of 0.15 mm/rev;
9. Changing from a cutting speed of 183 m/min and a feed rate of 0.20 mm/rev to a cutting speed of 229 m/min and a feed rate of 0.10 mm/rev under semi-dry cutting condition;
10. Changing from a cutting speed of 183 m/min and a feed rate of 0.20 mm/rev under dry cutting condition to a cutting speed of 229 m/min and a feed rate of 0.10 mm/rev under semi-dry cutting condition;
11. Changing from a cutting speed of 183 m/min and a feed rate of 0.20 mm/rev to a cutting speed of 229 m/min and a feed rate of 0.10 mm/rev under dry cutting condition;
12. Changing from a cutting speed of 183 m/min and a feed rate of 0.20 mm/rev under dry cutting condition to a cutting speed of 229 m/min and a feed rate of 0.15 mm/rev under semi-dry cutting condition;
13. Changing cutting condition from semi-dry to dry cutting condition at a cutting speed of 229 m/min and a feed rate of 0.10 mm/rev;
14. Changing from a feed rate of 0.10 mm/rev to a feed rate of 0.15 mm/rev at a cutting speed of 229 m/min under semi-dry cutting condition;

15. Changing from a feed rate of 0.10 mm/rev under dry cutting condition to a feed rate of 0.15 mm/rev under semi-dry cutting condition at a cutting speed of 229 m/min;
16. Changing from a feed rate of 0.10 mm/rev to 0.15 mm/rev under dry cutting condition and at a constant speed of 229 m/min;
17. Changing from a feed rate of 0.10 mm/rev under dry cutting condition to 0.20 mm/rev under semi-dry cutting condition at a constant speed of 229 m/min;
18. Changing from a feed rate of 0.10 mm/rev to 0.20 mm/rev under dry cutting condition at a constant speed of 229 m/min;
19. Changing from a feed rate of 0.15 mm/rev under dry cutting condition to a feed rate of 0.20 mm/rev under semi-dry cutting condition at a constant speed of 229 m/min;
20. Changing from a feed rate of 0.15 mm/rev to a feed rate of 0.20 mm/rev under dry cutting condition at a constant speed of 229 m/min;
21. Changing cutting condition from semi-dry to dry cutting condition at a cutting speed of 229 m/min and a feed rate of 0.20 mm/rev;

The Tukey test for comparison of T_{life} means between all other cutting conditions showed significant difference at 95% confidence level.

4.2.13.3 Contrast among speed, DOC, & condition interaction means

Tukey test for comparison of means was performed to see if there is any statistical difference between the interaction level means for T_{life}. The *speed x DOC x condition* interaction is not significant at 95% confidence level for the following cutting conditions:

1. Changing cutting condition from semi-dry to dry cutting condition at a depth of cut level of 2.54 mm at a cutting speed of 183 m/min;
2. Changing DOC from 2.54 mm to 3.81 mm under semi-dry cutting condition at a cutting speed of 183 m/min;
3. Changing DOC from 2.54 mm under dry cutting condition to 3.81 mm under semi-dry cutting condition at a cutting speed of 183 m/min;
4. Changing DOC from 2.54 mm to 3.81 mm under dry cutting condition at a cutting speed of 183 m/min;
5. Changing DOC from 2.54 mm under dry cutting condition at a cutting speed of 183 m/min to 3.81 mm under semi-dry cutting condition at a cutting speed of 229 m/min;
6. Changing cutting condition from semi-dry to dry for a DOC level of 3.81 mm at a cutting speed of 183 m/min;
7. Changing DOC from 3.81 mm under dry cutting condition and a cutting speed of 183 m/min to a DOC of 2.54 mm under semi-dry cutting condition at a cutting speed of 229 m/min;
8. Changing cutting condition from dry at 183 m/min to semi-dry at 229 m/min for a DOC level of 3.81 mm;
9. Changing cutting condition from semi-dry to dry for a DOC level of 2.54 mm at a cutting speed of 229 m/min;
10. Changing DOC from 2.54 mm to 3.81 mm under semi-dry cutting condition at a cutting speed of 229 m/min;

11. Changing DOC from 2.54 mm under dry cutting condition to 3.81 mm under semi-dry cutting condition at a cutting speed of 229 m/min
12. Changing DOC level from 2.54 mm to 3.81 mm under dry cutting condition at a cutting speed of 229 m/min
13. Changing cutting condition from semi-dry to dry for a DOC level of 3.81 mm at a cutting speed of 229 m/min;

The Tukey test for comparison of T_{life} means for all other cutting conditions showed significant difference at 95% confidence level.

4.2.13.4 Summary of results of dependant variable T_{life}

From the MANOVA, ANOVA and Tukey test for the comparison of means, the following are the summary of results of effects of independent variables and their interactions on dependant variable T_{life}.

a) Effect of speed, feed & condition interaction

The results of the Tukey test of means of T_{life} are summarized in Table 4-26. +Significance stands for statistical difference between mean values of T_{life} at 95 % confidence level, when the value shows an increasing trend amongst cutting conditions being compared. Similarly, -Significance stands for statistical difference between mean value of T_{life} at 95 % confidence level when the mean value of T_{life} shows a decreasing trend. "No Significance" is used to denote no statistically significant difference in T_{life} means being compared at 95 % confidence level between conditions.

From Table 4-26, the following cutting conditions yield highest mean value of T_{life}, and are not statistically different from each other at 95 % confidence level:

1) Speed of 183 m/min with a feed rate of 0.10 mm/rev under dry cutting condition

2) Speed of 183 m/min with a feed rate of 0.15 mm/rev under semi-dry cutting condition

In order to obtain the longer tool life (T_{life}), the optimal condition is a speed level of 183 m/min and a feed level of 0.15 mm/rev under semi-dry cutting condition when end milling 4340 steel blocks with advanced PVD TiAlN/TiN coated carbide cutting inserts. The higher feed level of 0.15 mm/rev is selected in order to facilitate a higher material removal rate.

b) Effect of speed, DOC & condition interaction

The results of the Tukey test of means of T_{life} are summarized in Table 4-27. +Significance stands for statistical difference between mean values of T_{life} at 95 % confidence level, when the value shows an increasing trend amongst cutting conditions being compared. Similarly, -Significance stands for statistical difference between mean value of T_{life} at 95 % confidence level when the mean value of T_{life} shows a decreasing trend. "No Significance" is used to denote no statistically significant difference in T_{life} means being compared at 95 % confidence level between conditions.

From Table 4-27, the following cutting conditions yield lowest mean value of mean T_{life}, and are not statistically different from each other at 95 % confidence level:

1) Cutting speed of 183 m/min, depth of cut level of 2.54, semi-dry cutting condition
2) Cutting speed of 183 m/min, depth of cut level of 2.54, dry cutting condition
3) Cutting speed of 183 m/min, depth of cut level of 3.81 mm under semi-dry cutting condition

From the above cutting conditions, a cutting speed of 183 m/min and a DOC level of 3.81 mm under semi-dry cutting condition give the highest material removal rate with the longest T_{life} means when end milling 4340 steel blocks with advanced PVD TiN/TiAlN coated carbide cutting inserts.

4.3 Multiple Regression Model for Tool Life

A regression model for tool life was developed from the data collected for the experiment. The independent or predictor variables in this case are speed, feed, depth of cut (DOC) and cutting condition. Minitab was used to conduct the multiple regression analysis. The model consists of both quantitative and qualitative variables. The qualitative variable in this case is the cutting condition used. Speed, feed and DOC are quantitative variables. The terms used in the model are significant terms at $\alpha = 0.05$

4.3.1 Model for Tool Life

In end milling operation, the relationship between tool life and independent variables cutting speed, feed and axial depth of cut can be expressed by Equation 4-11 (Alauddin and El Baradie, 1997).

$$\mathbf{T}_{life} = \mathbf{C}\ \mathbf{S}^{a}\ \mathbf{f}_{z}^{\,b}\mathbf{D}^{c} \qquad (4\text{-}11)$$

Where, T_{life} = Tool life, min

C, a, b, c = Constants

S = Cutting speed, m/min

f_z = feed per tooth (same as feed per revolution in this case)

Equation 4-12 shows the regression model for tool life. The value of coefficient of multiple determination (R^2) for the model is 91.4 % with a corresponding F statistic of 72.87. The R^2 adjusted value for the model is 90.2 %. The experimental data used to generate the model is shown in Appendix B (Table B-1). It is to be noted that units of tool life are in minutes. No patterns were observed in the residual versus fit plot for the model. Also, normality plot of residuals show normal data (Appendix B, Figure B-1, 2). The multiple regression equation is shown below in Equation 4-12.

$$\mathbf{T}_{life} = \mathbf{10}^{9.91}\ \mathbf{S}^{-4.40*C1-4.44*C2}\ \mathbf{f}_z^{\ -1.87*C1-2.01*C2}\ \mathbf{D}^{-0.187*C1-0.503*C2} \qquad \textbf{\textit{(4-12)}}$$

Where, T_{life} = Tool life, min

C 1 = 1 if semi-dry machining

= 0 otherwise

C2 = 1 if dry machining

= 0 otherwise

S = Cutting speed, m/min

f_z = Feed rate, mm/rev

D = Depth of cut, mm

Table 4-26 The Results of Tukey Pair wise Comparison of T_{life} Means for Speed, Feed & Condition Interaction

		183 m/min						229 m/min					
		0.10:1 (93)	0.10:2 (97)	0.15:1 (91)	0.15:2 (58)	0.20:1 (67)	0.20:2 (42)	0.10:1 (60)	0.10:2 (38)	0.15:1 (43)	0.15:2 (28)	0.20:1 (23)	0.20:2 (21)
183 m/min	0.10:1 (93)		No Significance	No Significance	-Significance	-Significance	-Significance	-Significance	-Significance	-Significance	-Significance	-Significance	-Significance
	0.10:2 (97)			No Significance	-Significance	-Significance	-Significance	-Significance	-Significance	-Significance	-Significance	-Significance	-Significance
	0.15:1 (91)				-Significance	-Significance	-Significance	-Significance	-Significance	-Significance	-Significance	-Significance	-Significance
	0.15:2 (58)					No Significance	No Significance	No Significance	No Significance	No Significance	-Significance	-Significance	-Significance
	0.20:1 (67)						-Significance	No Significance	-Significance	-Significance	-Significance	-Significance	-Significance
	0.20:2 (42)							No Significance	No Significance	No Significance	-Significance	-Significance	-Significance
229 m/min	0.10:1 (60)								No Significance	No Significance	-Significance	-Significance	-Significance
	0.10:2 (38)									No Significance	No Significance	No Significance	No Significance
	0.15:1 (43)										-Significance	-Significance	-Significance
	0.15:2 (28)											No Significance	No Significance
	0.20:1 (23)												No Significance
	0.20:2 (21)												

Note: 1 – Semi-dry machining condition, 2 – Dry machining condition; Speed levels used are 183 and 229 m/min. Feed levels used are 0.10, 0.15 and 0.20 mm/rev. The mean value for T_{life} (nos. of cuts to flank wear criterion) is stated under the cutting condition.

Table 4-27 The Results of Tukey Pair wise Comparison of T_{life} Means for Speed, DOC & Condition Interaction

		183 m/min				229 m/min			
		2.54 :1 (92)	2.54 :2 (70)	3.81 :1 (75)	3.81 :2 (61)	2.54 :1 (39)	2.54 :2 (34)	3.81 :1 (45)	3.81 :2 (24)
183 m/min	2.54 :1 (92)		No Significance	No Significance	-Significance	-Significance	-Significance	-Significance	-Significance
	2.54 :2 (70)			No Significance	No Significance	-Significance	-Significance	No Significance	-Significance
	3.81 :1 (75)				No Significance	-Significance	-Significance	-Significance	-Significance
	3.81 :2 (61)					No Significance	-Significance	No Significance	-Significance
229 m/min	2.54 :1 (39)						No Significance	No Significance	-Significance
	2.54 :2 (34)							No Significance	No Significance
	3.81 :1 (45)								No Significance
	3.81 :2 (24)								

Note: 1 – Semi-dry machining condition, 2 – Dry machining condition; Speed levels used are 183 and 229 m/min. DOC levels used are 2.54 mm and 3.81 mm. The mean value for T_{life} in is stated under the cutting condition.

4.4 Analysis of Flank and Crater Surface of Inserts using the Zeiss Optical Microscope, the Environmental Scanning Electron Microscope (ESEM) and Energy Dispersive Spectroscopy (EDS)

Images of worn out flank surfaces of inserts were taken using the Zeiss Axioskop 2 Mat optical microscope. Figure 4-27 shows the worn out flank surface of the insert after the tool reached it flank wear criterion of 0.40 mm or 400 μm. In all cases, non-uniform flank wear was observed. Uniform flank wear progression was rarely observed when machining the AISI 4340 normalized steel (26 HRc hardness) using PVD TiAlN/TiN coated multilayered carbide tools under semi-dry and dry cutting conditions.

Tool life on average increased two fold when using semi-dry over dry cutting conditions (Please refer to Table 4-28). At a cutting speed of 183 m/min, a marked improvement of tool life was observed when end milling at higher feed rates under semi-dry machining conditions at an axial depth of cut of 2.54 mm. Tool life did not significantly change when increasing depth of cut from 2.54 to 3.81 mm under semi-dry cutting conditions. This is due to the fact that the coolant mist particles are not able to reach the work piece-tool interface as effectively compared to lower axial depth of cuts and therefore the beneficial effect of mist coolant is lost.

At a higher cutting speed of 229 m/min, tool life was observed to increase when using semi-dry over dry cutting conditions. At a feed rate of 0.10 mm/rev, tool life improved threefold during semi-dry machining compared to dry machining conditions.

In general, no chipping of inserts was observed during dry or semi-dry machining. The only exception was at a cutting speed of 183 m/min, a feed rate of 0.20 mm/tooth and a depth of cut of 2.54 mm under semi-dry cutting conditions as (Please refer to Figure 4.27 c). This may be because of the higher fee rate used.

Primary and secondary backscatter images of the crater face of a brand new insert and of worn out inserts were taken after the flank wear criterion of 0.40 mm or 400 µm was reached. Figure 4-28 (a) shows the EDX spectrum for a brand new PVD TiAlN/TiN multilayer coated carbide end mill insert used for this study. Titanium (Ti), aluminum (Al) and nitrogen (N) peaks can be seen in the spectrum. These elements are the constituents of the TiAlN/TiN coating of the carbide insert.

Figure 4-28 (b) and (c) respectively show the EDX spectra obtained from the crater face of a worn out insert subjected to semi-dry and dry machining conditions at a cutting speed of 229 m/min, a feed rate of 0.20 mm/rev and a depth of cut of 3.81 mm. A comparison of the two spectra shows a higher iron (Fe K_{α}) peak obtained during dry machining conditions. This is an indication of an iron built up edge that forms during dry machining conditions.

Other elemental peaks that show up in the spectra of the worn out inserts are oxygen (O), carbon (C), silicon (Si), tungsten (W) L_{α} and M_{α} peaks, titanium (Ti) K_{α} and K_{β} peaks, chromium (Cr), manganese (Mn) and nickel (Ni). The elements mentioned above are alloying elements used in AISI 4340 medium carbon low alloy steel blocks used in this experiment. Some material got transferred over to the tool crater surface by diffusion wear that takes places at the tool chip interface. Diffusion wear occurs at the work piece/tool material interface where temperatures in the range of 700°C to 900°C exist. During the diffusion process, metal and carbon particles diffuse into the stream of work piece material flowing past the insert crater surface in the form of chips generated during the machining process.

At the same time, atoms of alloying elements present in the work piece material diffuse onto the insert crater surface or react with the insert coating to degrade it further (Trent, 1991).

A higher level of oxygen on the crater surface of the insert used in dry machining indicates the presence of oxide layers on the surface. Oxidation during dry machining is also aided by the fact that titanium carbide (TiC) and Tungsten carbide (WC) have a high tendency to oxidize (Rahman et al, 2002). The mist used in semi-dry machining shields the tool/work piece interface from direct exposure to oxygen in air, thus lowering the tendency of TiC and WC to oxidize. Oxide layers are formed during semi-dry machining also, as shown in Figure 4-28 (b) but to a lesser extent. It is to be noted that oxide layers form on carbide tools at a temperature range of 900°C (Rahman et al., 2002). It can be inferred that the tool crater surface is subjected to this high temperature during dry machining conditions.

Figure 4-29 (a) and (b) show backscattered electron images of the crater surface of the PVD TiAlN/TiN multi-coated carbide end mill inserts subjected to a cutting speed of 229 m/min, a feed rate of 0.20 mm/rev and a depth of cut of 3.81 mm under dry and semi-dry cutting conditions. The backscatter image provides valuable information about elemental composition as it is atomic number dependant. Elements with higher atomic numbers appear brighter in the back scatter image.

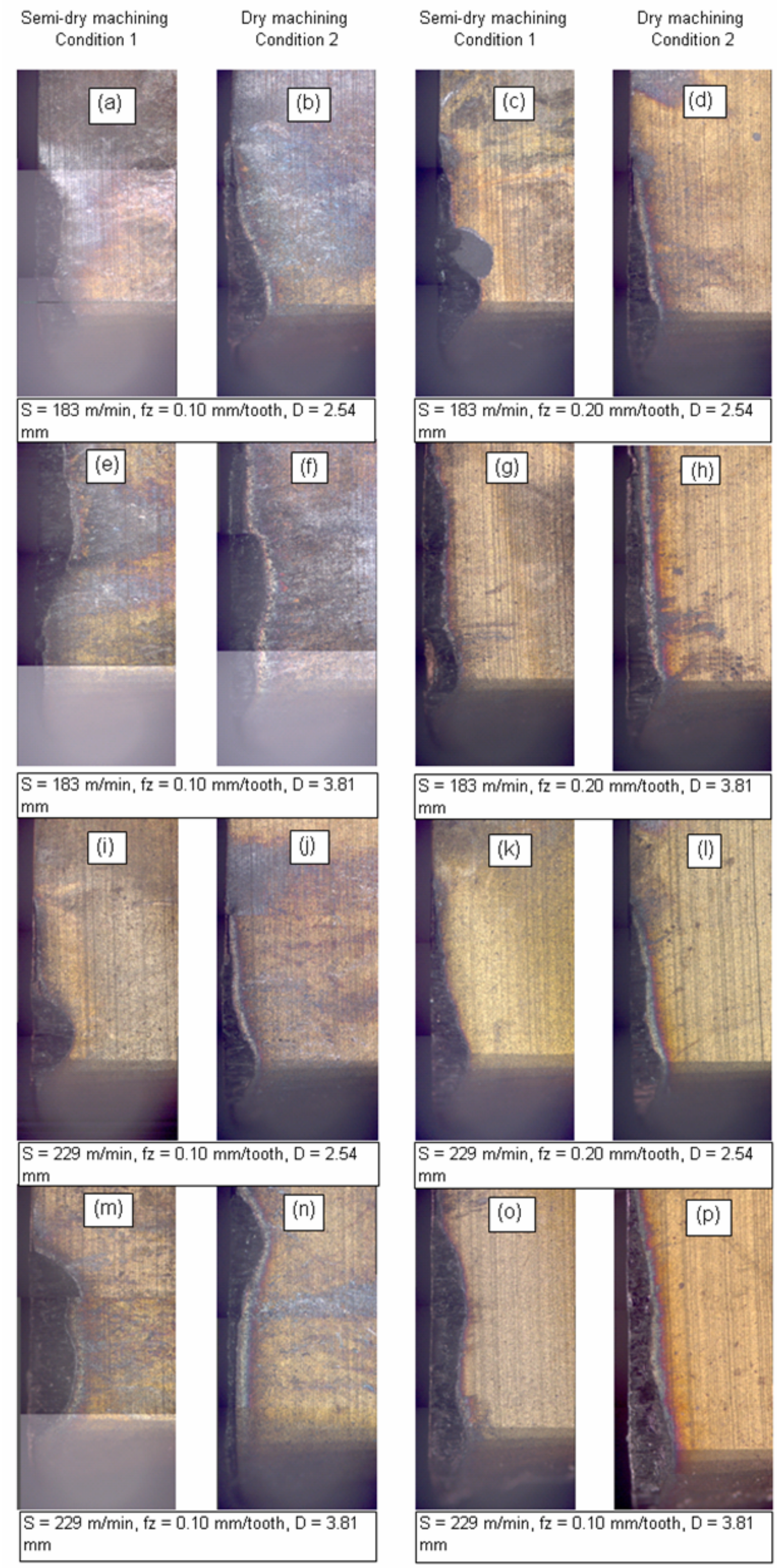


Figure 4-27 Worn out Flank Face of PVD TiAlN/TiN Multilayered Coated Carbide Tools after the Insert Reached its Flank Wear Criterion of 0.40 mm (400 µm)

Table 4-28 Tool Life Obtained under Semi-dry and Dry Cutting Conditions when Machining AISI 4340 Steel with PVD TiAlN/TiN Coated Carbide End Mill Inserts

						Tool life (min's)						Ratio of tool life increase
						Semi-dry machining			Dry machining			
Speed (m/min)	RPM	Feed (mm/rev)	Feed (mm/min)	Time/cut (min)	DOC (mm)	Trial 1	Trial 2	Average	Trial 1	Trial 2	Average	(semi-dry/dry)
183	3056	0.1	305.58	0.49	2.54	52.0	52.0	52.0	44.2	25.5	34.9	1.5
183	3056	0.15	458.37	0.33	2.54	29.5	34.7	32.1	19.0	11.4	15.2	2.1
183	3056	0.2	611.15	0.25	2.54	18.2	17.2	17.7	8.6	4.2	6.4	2.8
183	3056	0.1	305.58	0.49	3.81	34.4	44.2	39.3	44.2	21.7	32.9	1.2
183	3056	0.15	458.37	0.33	3.81	24.9	29.5	27.2	15.1	9.6	12.3	2.2
183	3056	0.2	611.15	0.25	3.81	18.2	12.3	15.2	12.3	3.0	7.6	2.0
229	3820	0.1	381.97	0.39	2.54	14.9	21.2	18.1	14.9	8.3	11.6	1.6
229	3820	0.15	572.96	0.26	2.54	14.1	8.9	11.5	7.3	2.3	4.8	2.4
229	3820	0.2	763.94	0.20	2.54	5.1	5.1	5.1	4.3	1.0	2.7	1.9
229	3820	0.1	381.97	0.39	3.81	32.2	25.9	29.1	7.1	10.2	8.6	3.4
229	3820	0.15	572.96	0.26	3.81	11.0	11.0	11.0	7.9	2.9	5.4	2.0
229	3820	0.2	763.94	0.20	3.81	4.1	3.5	3.8	3.5	0.7	2.1	1.8
											Average	2.1

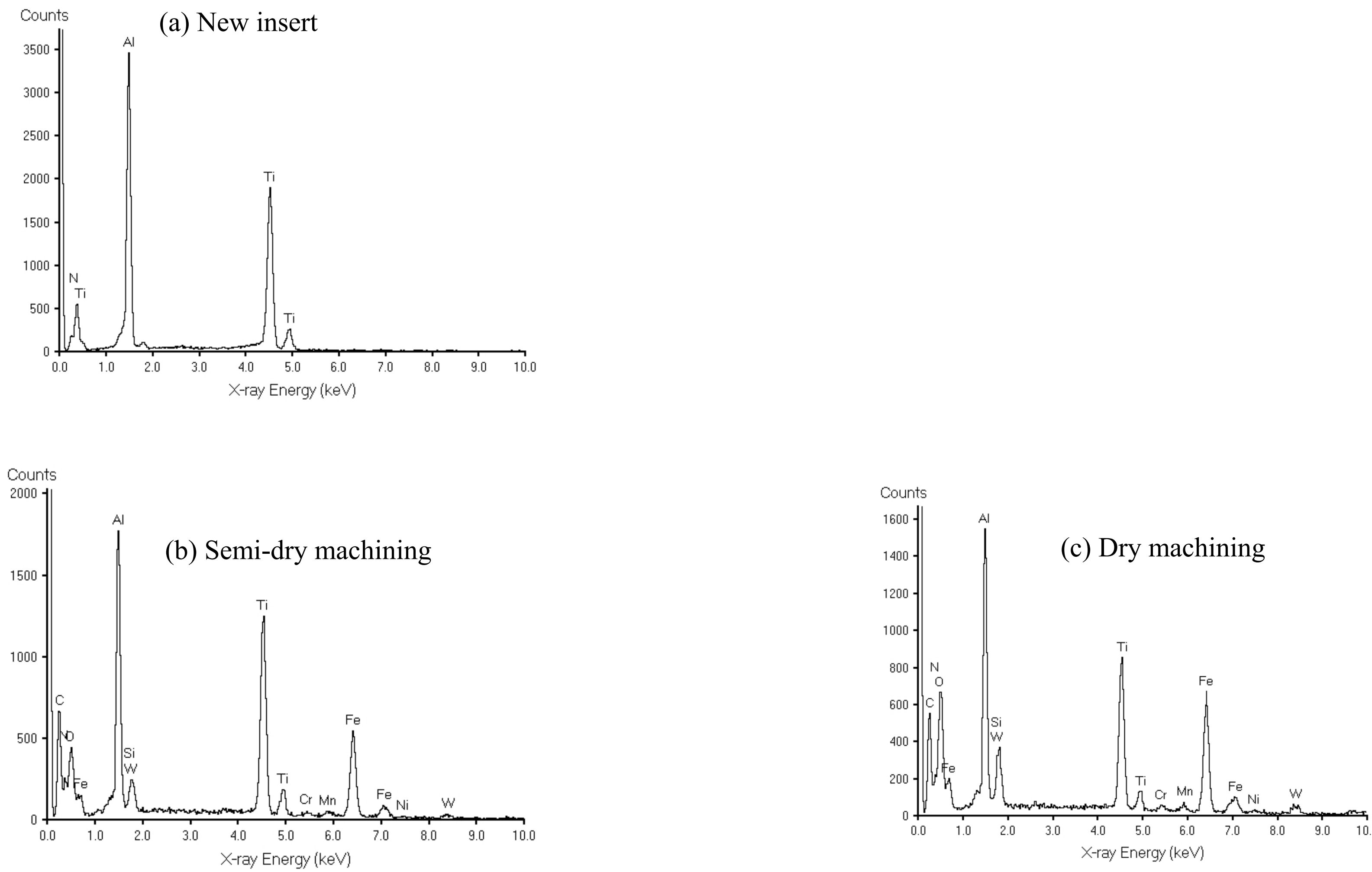
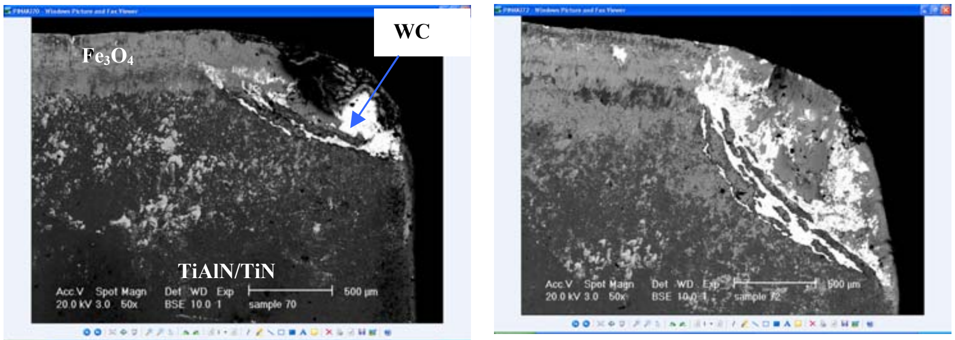


Figure 4-28 Energy Dispersive X Ray (EDX) Spectra Obtained for the Rake Face of the Coated Carbide Insert under Semi-dry and Dry Machining Conditions (Cutting Speed - 229 m/min, Feed rate - 0.20 mm/rev, DOC - 3.81 mm).



(a) Semi-dry cutting condition (b) Dry cutting condition

Figure 4-29 Backscattered Electron Image of the Worn out Crater Face of an Insert under Semi-dry and Dry Machining Conditions (Cutting speed – 229 m/min, Feed rate – 0.20 mm/rev, DOC – 3.81 mm)

As seen in Figure 4-29 (a), the dark patches on the crater surface are the actual TiAlN/TiN coating material. The bright spot on the back scatter image corresponds to tungsten carbide (WC) substrate material exposed. The gray patch towards the top edge of the insert is built up edge material, primary composed of iron oxide (Fe_3O_4).

Under dry machining conditions, the TiAlN/TiN coating layer gets eroded due to diffusion wear that takes places on the crater face of the coated carbide cutting insert at high cutting temperatures, exposing the tungsten carbide (WC) substrate layer underneath. The higher level of diffusion wear in dry machining exposes more substrate tungsten carbide material, as shown by the bright spots in the backscatter image of the insert subjected to dry cutting conditions (Figure 4-29 b). This can also be verified from the higher elemental tungsten M_α peak obtained during dry machining (Figure 4-28 c). Also, the built up iron oxide layer formed on the crater face of the insert during dry machining is much higher, as indicated by the higher presence of gray patches (Fe_3O_4 built up layer) and fewer dark patches (TiAlN/TiN coating material) on the crater surface during dry machining conditions (Figure 4-29 b). The same inference can be drawn from the EDX spectral images in Figure 4-28 (b) and (c). Higher titanium and aluminum K_α peaks are observed during semi-dry machining, which can be attributed to the protected TiAlN/TiN coating on the crater face of the multilayer coated carbide insert.

4.5 Mixed Effects Modeling of Flank Wear Progression

Maximum flank wear of the PVD TiAlN/TiN coated carbide insert on the side cutting edge was measured every four cuts using the Zeiss Axioskop 2 Mat microscope till the insert reached the maximum wear criterion of 0.4 mm or 400 μm. Figure 4-30 shows the scatter plot of flank wear (μm) versus cut number (*CutNo*). From the plot, it can be seen that the relationship between flank wear and cut number is non-linear in nature. In the absence of mechanistic argument, it is not advisable to fit a non-linear curve to the data (Onar et al., 2005). Box Cox procedure in Minitab was used to suggest a suitable transformation in order to fit a linear model to the relationship. Natural log was suggested as a transformation. Figure 4-31 shows the scatter plot of natural log of wear (*LnWear*) versus cut number (*CutNo*). It can be seen that there is much more overlap between the graphs of wear progression and perhaps a polynomial of the third degree would be adequate to capture the relationship between *LnWear* and *CutNo*.

S Plus statistical software package was used to obtain the best cubic model to fit the transformed data for the individual profiles. During the model fitting process, the residuals versus fitted values plots and the square root of absolute residual versus fitted plots were analyzed to check for constant variance and non-linearity. The normal quantile-quantile (QQ) plot of residuals was also analyzed to check for normality.

Auto-correlation plots in S Plus were used to determine the correlation amongst the residuals associated with consecutive observations. It is to be noted that the mixed effects models fit a set of subject-specific random effects to the model. In this case, each 4340 alloy steel blocks are the subjects. One of the sources of between and within block variation is block hardness. It was observed that the initial and final hardness readings of each block varied from one another (Refer to Table 4-29).

Also, surface hardness of the blocks initially increases due to work hardening of surface during both dry and semi-dry machining and subsequently decreased as successive cuts exposed inner layers of the blocks that are softer. Figure 4-32 shows the variation of the surface hardness of a typical 4340 alloy steel work piece (block 21) from initial surface (surface # 1) to the final surface (surface # 7) the insert sees before flank wear criterion is reached.

These are some of the subject (block) specific random effects which will be captured by the random effects component of the mixed effects model. Tool wear models developed in metal cutting literature assume that the work pieces have homogeneous chemical composition and have uniform hardness throughout work piece and across work pieces.

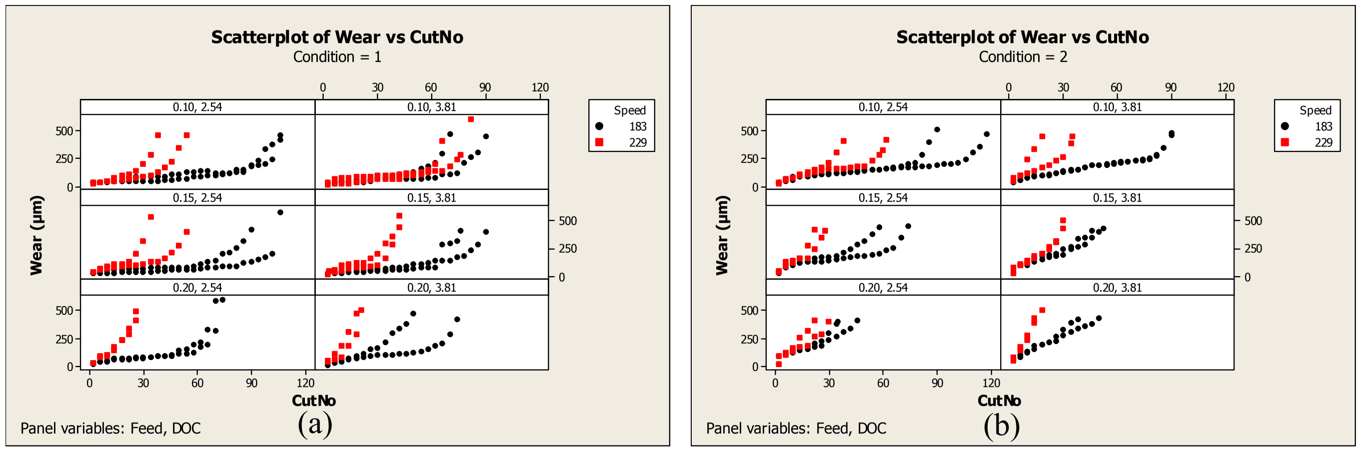


Figure 4-30 Scatter Plot of Flank Wear in µm versus Cut Number (*CutNo*) under (a) Semi-dry, (b) and Dry machining conditions

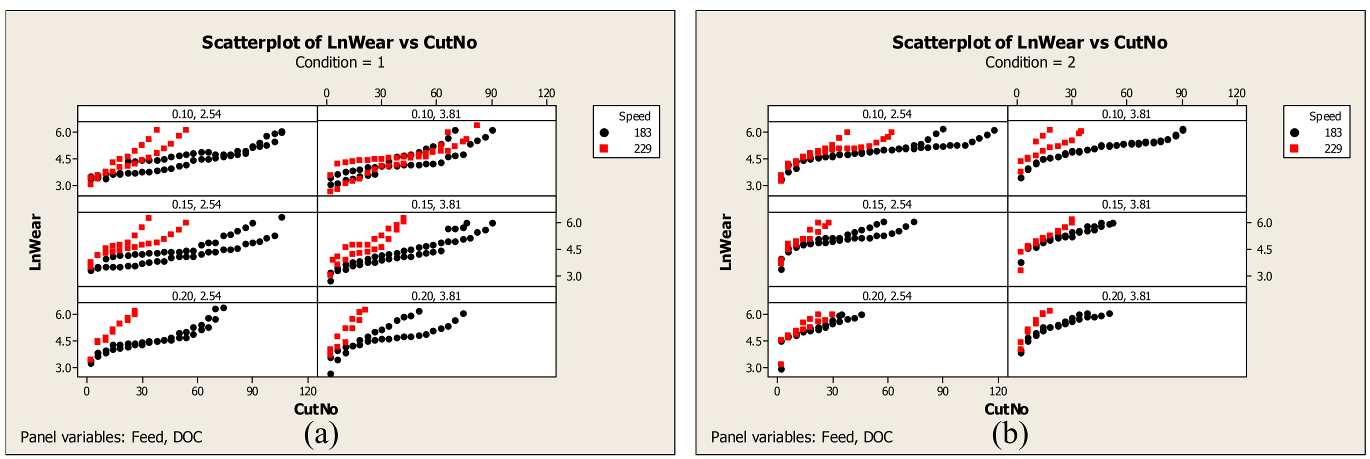


Figure 4-31 Scatter Plot of *LnWear* versus *CutNo* under (a) Semi-dry, and (b) Dry machining conditions

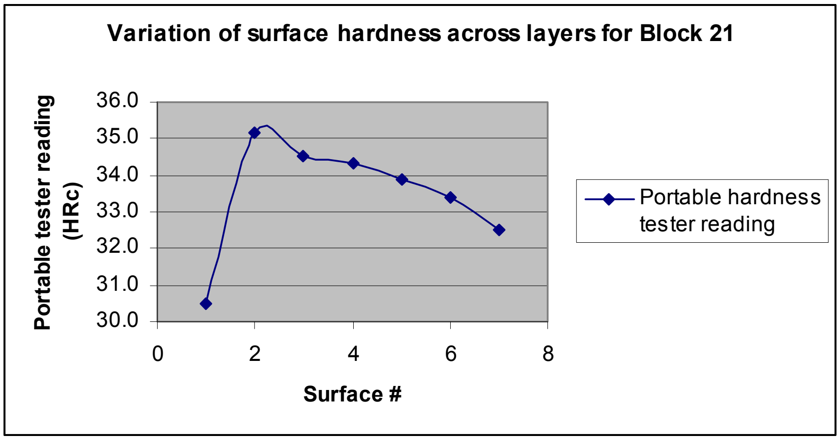


Figure 4-32 Variation in Surface Hardness of Block 21 across Subsequent Layers of Metal Removed

As seen from hardness measurements done during the case, this assumption may not always be true. One of the main reasons for selecting normalized and tempered 4340 alloy steel work piece material for this tool wear experiment was to minimize variation in hardness from the top of the work piece to the inner core. The normalization heat treatment process employed to increase the hardness of alloy steel and other ferrous materials makes the outer layer of the material much harder than the inner core. The hardness progressively decreases from the surface of the block to the inner core. The test blocks were tempered by the supplier in order to stress relieve after the normalization process.

The mixed effects modeling technique is perfectly suited for modeling variations within and across test blocks. The model captures within-block variation as a block effect and though it does not make an attempt to model it, the model estimates the size of the within block variation and removes it from the random error component. It should also be noted that in every experiment, there are factors which cannot be controlled as well as heterogeneity which cannot be accounted for.

Table 4-29 Hardness of Initial and Final Layer for the Forty Eight AISI 4340 Alloy Steel Blocks used for the 48 Experimental Runs

				Hardness			
	Cut combination			First layer		Last layer	
S.No.	British units	Metric units	Block number	Bench top tester	Portable tester	Bench top tester	Portable tester
1	C600_.004_.10_M_1	C183_.10_2.54_M_1	15	25.18	23.70	36.48	35.20
2	C600_.004_.10_M_2	C183_.10_2.54_M_2	79	24.53	23.90	35.26	33.70
3	C600_.004_.10_D_1	C183_.10_2.54_D_1	41	26.55	26.70	35.15	34.1
4	C600_.004_.10_D_2	C183_.10_2.54_D_1	35	27.93	25.70	34.45	32.4
5	C600_.004_.15_M_1	C183_.10_3.81_M_1	49	28.79	28.00	35.62	34.70
6	C600_.004_.15_M_2	C183_.10_3.81_M_2	45	30.50	29.70	36.73	35.10
7	C600_.004_.15_D_1	C183_.10_3.81_D_1	39	25.87	24.60	34.46	31.40
8	C600_.004_.15_D_2	C183_.10_3.81_D_2	38	27.11	26.00	32.77	30.1
9	C600_.006_.10_M_1	C183_.15_2.54_M_1	5	22.32	23.3	35.39	33.5
10	C600_.006_.10_M_2	C183_.15_2.54_M_2	28	24.11	21.7	32.68	31
11	C600_.006_.10_D_1	C183_.15_2.54_D_1	40	27.23	25.5	34.99	34.1
12	C600_.006_.10_D_2	C183_.15_2.54_D_1	9	24.25	24.2	34.02	31.5
13	C600_.006_.15_M_1	C183_.15_3.81_M_1	24	28.35	27.4	34.23	32
14	C600_.006_.15_M_2	C183_.15_3.81_M_2	44	26.66	26.2	34.45	32.7
15	C600_.006_.15_D_1	C183_.15_3.81_D_1	21	31.28	30.5	34.32	32.5
16	C600_.006_.15_D_2	C183_.15_3.81_D_2	75	25.18	24.7	32.82	31.3
17	C600_.008_.10_M_1	C183_.20_2.54_M_1	70	28.51	27.5	33.64	31.8
18	C600_.008_.10_M_2	C183_.20_2.54_M_2	61	22.4	22.4	34	32.8
19	C600_.008_.10_D_1	C183_.20_2.54_D_1	34	24.89	23.40	35.66	35.5
20	C600_.008_.10_D_2	C183_.20_2.54_D_1	46	21.28	21.3	32.74	33.3
21	C600_.008_.15_M_1	C183_.20_3.81_M_1	62	23.34	24	32.58	31.4
22	C600_.008_.15_M_2	C183_.20_3.81_M_2	63	27.26	26.20	35.13	34.1
23	C600_.008_.15_D_1	C183_.20_3.81_D_1	23	26.54	25.70	33.52	33.3
24	C600_.008_.15_D_2	C183_.20_3.81_D_2	64	23.44	23.4	33.58	32.6
25	C750_.004_.10_M_1	C229_.10_2.54_M_1	29	26.5	23.7	35.60	35.50
26	C750_.004_.10_M_1	C229_.10_2.54_M_2	19	27.27	25.3	32.89	32.5
27	C750_.004_.10_D_1	C229_.10_2.54_D_1	10	27.76	28.70	34.92	34.10
28	C750_.004_.10_D_2	C229_.10_2.54_D_1	2	23.73	22.8	33.59	32.4
29	C750_.004_.15_M_1	C229_.10_3.81_M_1	48	21.75	21.6	33.49	32.3
30	C750_.004_.15_M_2	C229_.10_3.81_M_2	65	29.3	28.3	35.16	32.7
31	C750_.004_.15_D_1	C229_.10_3.81_D_1	32	24.96	24.5	34.35	34.4
32	C750_.004_.15_D_2	C229_.10_3.81_D_2	25	28.21	26.4	34.03	32.8
33	C750_.006_.10_M_1	C229_.15_2.54_M_1	26	28.13	26.7	33.61	33.4
34	C750_.006_.10_M_2	C229_.15_2.54_M_2	36	28.26	27.6	35.32	35.8
35	C750_.006_.10_D_1	C229_.15_2.54_D_1	51	21.63	21.8	34.05	34.4
36	C750_.006_.10_D_2	C229_.15_2.54_D_1	27	22.88	20.8	33.44	32.9
37	C750_.006_.15_M_1	C229_.15_3.81_M_1	74	30.37	28.90	34.69	35.1
38	C750_.006_.15_M_2	C229_.15_3.81_M_2	59	26.9	29.1	36.05	35.4
39	C750_.006_.15_D_1	C229_.15_3.81_D_1	18	24.05	23.7	32.96	32.2
40	C750_.006_.15_D_2	C229_.15_3.81_D_2	20	27.32	26	32.6	31.8
41	C750_.008_.10_M_1	C229_.20_2.54_M_1	56	25.43	27	34.13	34.6
42	C750_.008_.10_M_2	C229_.20_2.54_M_2	53	27.79	27	35.64	35.1
43	C750_.008_.10_D_1	C229_.20_2.54_D_1	80	29.21	28.9	35.09	35
44	C750_.008_.10_D_2	C229_.20_2.54_D_1	76	24.99	23.1	33.12	33.1
45	C750_.008_.15_M_1	C229_.20_3.81_M_1	73	25.59	28.1	34.45	34.5
46	C750_.008_.15_M_2	C229_.20_3.81_M_2	55	29.36	29.1	34.34	34.3
47	C750_.008_.15_D_1	C229_.20_3.81_D_1	4	24.41	26.8	35.62	34.4
48	C750_.008_.15_D_2	C229_.20_3.81_D_2	54	27.76	27.2	33.6	34.2
			Mean	26.19	25.60	34.32	33.40
			Min	21.28	20.80	32.58	30.10
Example	**C750_0.008_0.15_D1**	**C229_.20_3.81_D1**	**Max**	31.28	30.50	36.73	35.80
	Cutting speed = 750 surface feet per min	Cutting speed = 229 m/min					
	Feed rate = 0.008 inch p	Feed rate = 0.20 mm/rev					
	Depth of cut = 0.15 inch	Depth of cut = 3.81 mm					
	Replication 1	Replication 1					

Thus by allowing this subject-to-subject variability due to unobserved heterogeneity to be absorbed by the random effects and thus keeping them from being absorbed into random error, mixed effects models can provide substantially higher levels of power to detect significant factor effects.

In this case, a cubic model is used to represent the relationship between flank wear values and cut number. Therefore, we have the overall cubic model for all the blocks and also the block-specific intercept, linear, quadratic and cubic effect terms. In essence, the overall cubic model is taken and slightly adjusted for each block to achieve a better fit at the block level.

Since we have 48 runs for 24 treatment combinations with two replicates, we have 48 block-specific intercept, linear, quadratic and cubic random effect terms (adjustments to the overall model). The assumption for the random effect term is that it is normally distributed with zero mean and a fixed variance. Since the overall model captures the average intercept, linear, quadratic and cubic effects, the random effects associated with them are mere departures from the corresponding fixed effect in order to achieve good fit at the block level. The mean being zero is guaranteed by the model (as it is a regression model). The normality of the random effect terms can be checked with normal probability plots of each random effect. In general, the intercept, linear, cubic and quadratic terms tend to be highly dependant on each other as indicated by the matrix plots of intercept, linear, square and cubic terms respectively as shown in Figure 4-33. Typically this poses no problem in fitting the model as mixed effects models can accommodate a very general variance-covariance structure among the random effects.

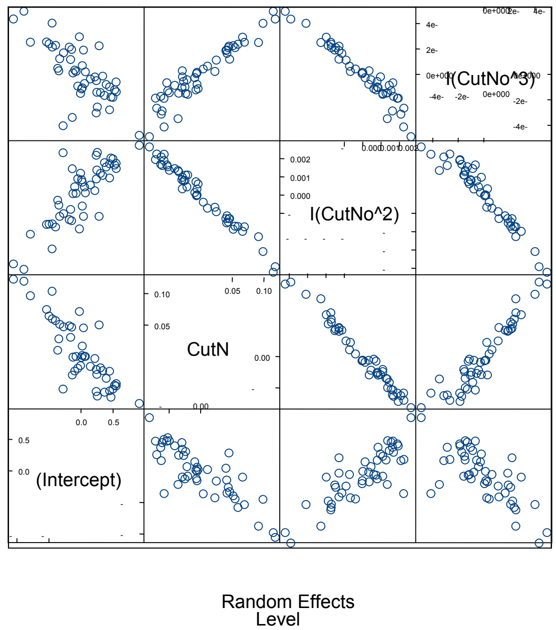


Figure 4-33 Matrix plots of intercept, linear, quadratic and cubic terms of the model

In our case we only assume that the 4-dimensional variance covariance matrix of the random effects is positive definite and allow the data to estimate the covariance structure.

Akaike information criterion (AIC), the Bayesian (Schwarz) information criterion (BIC), and Log likelihood values are goodness-of-fit statistics generated as part of the S Plus mixed effects model analysis. These criteria penalize for the number of terms in the model as per the parsimony principle (Onar et al., 2005). In general, smaller values of AIC and BIC are an indication of good model fit. However, these values have to be considered in conjunction with residual versus fits, and normal QQ plots of model and random error terms as well as auto correlation plots in order to determine best model fit.

The Log likelihood value is akin to coefficient of multiple determination (R^2) in statistical parlance. A lower value of Log likelihood is an indication of better model fit; however it suffers from the drawback that as new variables are added to the model, the log likelihood value decreases, regardless of whether these variables are important or not. Therefore, in order to compare models based on numerical goodness-of-fit statistics AIC and BIC values are preferred as they penalize for variables that add no value to the model (in a similar way that the $R^2_{adjusted}$ works in a multiple regression setting). It should be noted however that these values cannot be used if one is interested in comparing models based on dependent variables measured on different scales. For example, if one would like to compare the goodness-of-fit between Wear and *LnWear* based models, this cannot be done via AIC and BIC. In this case, one has to resort to residual plots. The mixed effects model developed for flank wear progression is shown in equation 4-13.

$$LnWear = 2.793556 - 0.169965\, Speed_I + 0.065649\, Feeed_{0.15} + 0.584323\, Condition_I + 0.383269\, Feed_{0.2} + 0.093071\, CutNo - 0.002188\, CutNo^2 + 0.000021\, CutNo^3 + 0.361818\, Speed_I\, Feed_{0.15} + 0.276316\, Speed_I\, Condition_I + 0.438458\, Feed_{0.15}\, Condition_I + 0.595798\, Speed_I\, Feed_{0.2} + 0.237607\, Feed_{0.2}\, Condition_I + 0.065860\, Speed_I\, CutNo - 0.002444\, Speed_I\, CutNo^2 + 0.000045\, Speed_I\, CutNo^3 - 0.720437\, Speed_I\, Feed_{0.15}\, Condition_I - 0.656587\, Speed_I\, Feed_{0.2}\, Condition_I \quad \textbf{(4-13)}$$

Where,

$Speed_I$ = Indicator variable for speed = 1, if cutting speed is 229 m/min,

= 0, if cutting speed is 183 m/min

$Feed_{0.15}$ = Indicator variable for feed = 1, if feed rate = 0.15 mm/rev

= 0, otherwise

$Feed_{0.20}$ = Indicator variable for feed = 1, if feed rate = 0.20 mm/rev

= 0, otherwise

DOC_I = Indicator variable of depth of cut (DOC) = 1, if DOC = 3.81 mm

$Condition_I$ = Indicator variable for condition = 1, for dry cutting condition

= 0, otherwise

CutNo = Number of cuts taken (Cut length = 6 inch, radial depth of cut = 12.7 mm)

Indicator variables were chosen for speed, feed, depth of cut and condition as the wear progression curves obtained are specific to those conditions. Treating speed and feed as continuous data created problems with model fit as indicated by the residual versus fitted plots of fixed effects and QQ plot of random error terms for the fitted model. For independent variables speed and condition with two levels, the smaller value was coded as 0 and the larger value was coded as 1. These are indicated as $Speed_I$ and $Condition_I$ and the coefficients for these represent the change that can be expected when one moves from level 0 to 1, i.e. from the lower level to the higher level. Feed had three levels that were modeled by using two indicator variables, namely $Feed_{0.15}$ and $Feed_{0.2}$. In each case, the coefficients for these variables would be compared to their baseline value i.e. the $Feed_{0.10}$ level.

It was observed that the curvature, as captured by the cubic model of the *LnWear* versus *CutNo* curve is related to $Speed_I$ and thus the interaction of speed with linear, quadratic and cubic terms of *CutNo* have been included in the model. The interaction of independent variable $Speed_I$ with *CutNo* dominates compared to interaction of feed, cutting condition, and depth of cut with *CutNo* as seen from Figure 4-31 (a and b).

From the model, it can be seen that flank wear is allowed to depend on cutting speed, feed, cutting condition, and the cut number. Depth of cut did not have a significant effect on flank wear progression as indicated by the statistical analysis. This can also be graphically seen in Figure 4-31 (a and b).

The 2nd column in Table 4-30 shows the parameter estimates of the model. The last column shows the associated p values which are used to determine if the parameter is to be included in the model or not. All main effect and two way interactions associated with terms included in the three way interactions have been included in the model. The mixed effects model shown in Equation 4-3 had AIC and BIC values of -149.69 and -18.98 respectively and a Log likelihood value of 103.84. These test statistics in conjunction with residual versus fits and normal QQ plots of model and random error terms were used to obtain the mixed effects model that best fit the data.

Table 4-30 Parameter Estimates for the Model (95 % confidence level)

Terms	Value	Std.error	Degree of freedom (DF)	t-value	p-value
(Intercept)	2.793556	0.1460276	634	19.13033	<.0001
SpeedI	-0.169965	0.2086849	36	-0.81446	0.4207
Feed0.15	0.065649	0.1733734	36	0.37865	0.7072
ConditionI	0.584323	0.1733273	36	3.37121	0.0018
Feed0.2	0.383269	0.1736924	36	2.2066	0.0338
CutNo	0.093071	0.0116852	634	7.96485	<.0001
I($CutNo^2$)	-0.002188	0.0003875	634	-5.64694	<.0001
I($CutNo^3$)	0.000021	0.0000051	634	4.18553	<.0001
SpeedI:Feed0.15	0.361818	0.2466279	36	1.46706	0.151
SpeedI:ConditionI	0.276316	0.2477171	36	1.11545	0.272
Feed0.15:ConditionI	0.438458	0.2455002	36	1.78598	0.0825**
SpeedI:Feed0.2	0.595798	0.2516326	36	2.36773	0.0234
Feed0.2:ConditionI	0.237607	0.2463095	36	0.96467	0.3411
SpeedI:CutNo	0.06586	0.01716	634	3.83799	0.0001
SpeedI:I($CutNo^2$)	-0.002444	0.0006099	634	-4.00782	0.0001
SpeedI:I($CutNo^3$)	0.000045	0.0000086	634	5.27395	<.0001
SpeedI:Feed0.15:ConditionI	-0.720437	0.3521165	36	-2.04602	0.0481
SpeedI:Feed0.2:ConditionI	-0.656587	0.355677	36	-1.84602	0.0731**

* Terms significant at 95 % confidence level, ** Significant at 90 % confidence level

From Table 4-30, it can be seen that indicator variables speed, feed and condition were included in the best mixed effects model. Following the parsimony principle, depth of cut was not included in the model as it did not improve the model fit. The first column is Table 4-30 includes the coefficients of the model terms.

Among the two way interaction terms, the $Speed_I$:$Feed_{0.2}$ interaction is significant at 95 % confidence level (p value = 0.0234). This means that when cutting conditions are changed from a speed level of 183 m/min and a feed level of 0.10 mm/rev to 229 m/min and 0.20 mm/rev respectively under semi-dry cutting conditions, average initial wear values are high.

The $Condition_I$ main effect term (p value = 0.0018) is also significant at 95 % confidence level. This means that when cutting condition is changed from semi-dry to dry keeping other machining parameters constant, a high initial wear value is obtained. It is to be noted that this main effect has the highest positive coefficient amongst other main effect terms. The same can be inferred from Figure 4-34 and Figure 4-35 respectively.

The curvature in the *LnWear* versus *CutNo* curved is modelled using the cubic model involving *CutNo* and the interaction of $Speed_I$ (229 m/min) with liner, quadratic and cubic terms of *CutNo*. The coefficient of model terms *CutNo* and $Speed_I$:*CutNo* interaction are positive and have the highest value compared to the coefficients of the quadratic and cubic effects terms of *CutNo* and *CutNo*:$Speed_I$ interaction. *CutNo* has the higest slope associated with it. The coefficents of $CutNo^3$ and $Speed_I$:$CutNo^3$ are also positive but are much smaller in magnitude than coefficients of *CutNo* and $Speed_I$:$CutNo^2$ interaction.

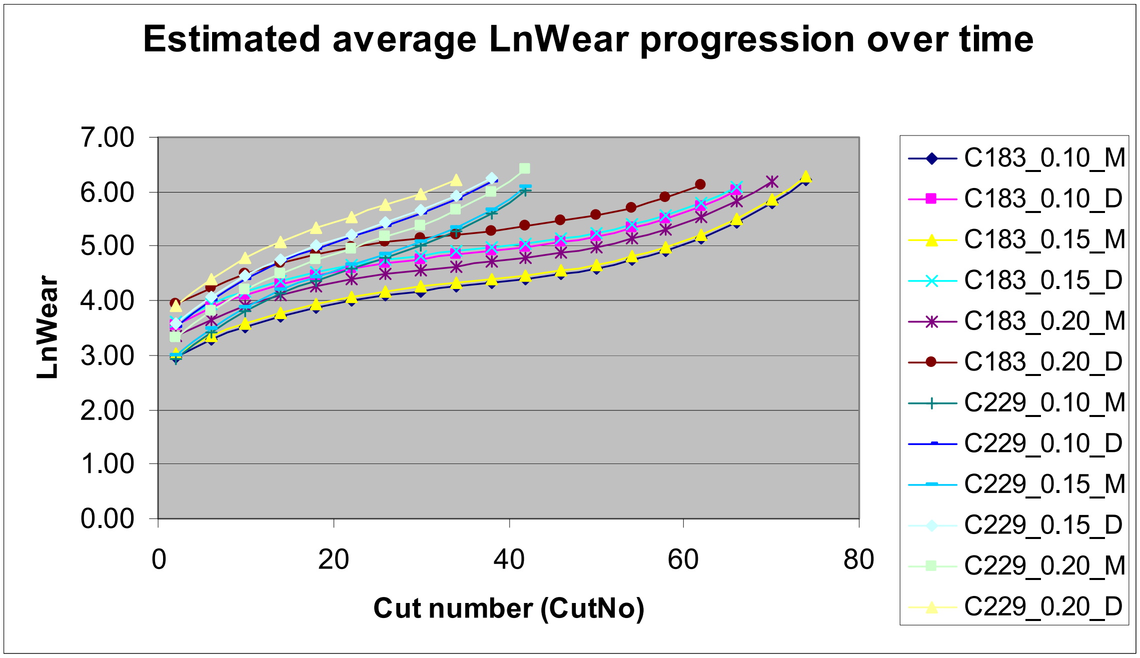


Figure 4-34 Plot of Average Estimated LnWear (*LnWear*) Progression with Number of Cuts (*CutNo*) for Mixed Effects Model

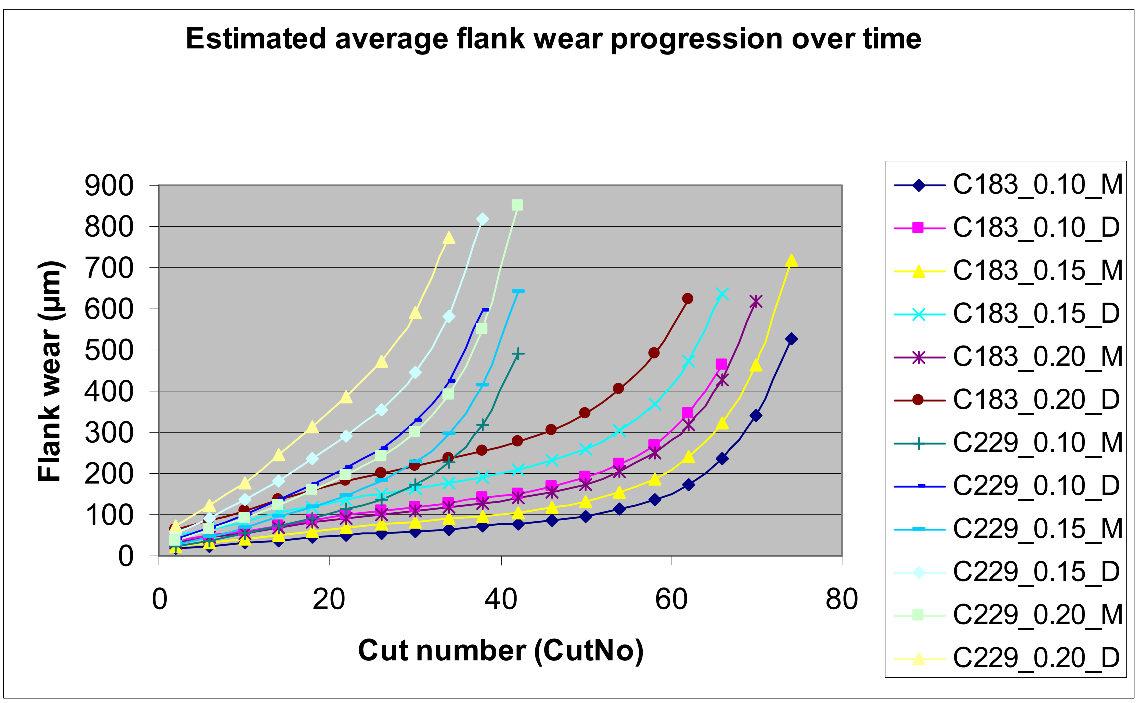


Figure 4-35 Plot of Average Estimated Flank Wear Progression with Number of Cuts for Mixed Effects Model

With respect to the rate of flank wear progression, it can be seen from Table 4-30 and Figure 4-34 and 4-35 that a significantly higher rate of flank wear progression indicated by a steeper wear progression curve is obtained with a higher cutting speed level of 229 m/min. This can be inferred from the effect of $Speed_I$ on the slope of *CutNo* (the first order parameter of the model). However, the effect of the higher level of speed ($Speed_I$) on the slope of the second and third order parameter of the model is not as pronounced as indicated by the coeffcient terms of $Speed_I$:*I*($CutNo^2$) and $Speed_I$:*I*($CutNo^3$). It is observed that at the higher speed level of 229 m/min, the coefficients of the linear, quadratic and cubic *CutNo* terms combine together to form larger positive coefficients thus increasing the slope of the *LnWear* versus *CutNo* progression curve. Therfore, at a higher level of speed (229 m/min), the wear progression curves are much steeper compared to a lower cutting speed level of 183 m/min (Figure 4-34 and Figure 4-35).

The standard deviations for the random effect terms are shown in Table 4-31. It can be seen that the standard deviation of the model intercept term is substantially higher than the standrad deviation of the error residual term, i.e approximately 3.5 times higher. This indicates that the model takes into account the variation betweem blocks under similar cutting combinations that dominate compared to the within block variation as indicated by the standard deviation of the residual error term.

Table 4-31 Estimates of the Variance Components of the Random Effect Terms

Random Effect	Standard Deviation	Correlation		
(Intercept)	0.442199818	(Intr)	CutNo	I(CutNo^2)
CutNo	0.055357362	-0.816		
I(CutNo^2)	0.001813018	0.782	-0.977	
I(CutNo^3)	0.000024124	-0.666	0.91	-0.952
Residual	0.124201767			

Thus we can see that the the mixed effects modeling technique takes into account variations between blocks as well as within blocks that is captured by the random effect terms in the model. Failure to account for variations between blocks while machining can affect the models ability to detect significant main and interaction effects of independent variables.

Table 4-31 also shows that there is a high correlation (0.977) between linear and quadratic effects of *CutNo*, and quadratiic and cubic effects of *CutNo* (0.952). A correlation of 0.91 was also observed between linear and cubic effects of *CutNo*. Also, moderately high correlation coefficient values were obsrved between intercept and linear, quadratic and cubic terms of *CutNo*. The model allows the random effects to be correlated using the most general form of a disperion matrix, i.e. general positive definite matrx.

A simplified model was also developed from the full model by the process of backward elimination utilizing residual plots and AIC and BIC goodness of fit criterion described in previous patagraphs. This model retains retains all of the previously 'significant' variables, except now in more simpler and easy to interpret form. The simplified mixed effects model is shown in Equation 4.14.

$$LnWear = 2.709441 + 0.045327\, Speed_I + 0.313842\, Feeed_{0.15} + 0.678739\, Condition_I + 0.595547\, Feed_{0.2} + 0.092218\, CutNo - 0.002188\, CutNo^2 + 0.000021\, CutNo^3 + 0.069427\, Speed_I\, CutNo - 0.002645\, Speed_I\, CutNo^2 + 0.000048\, Speed_I\, CutNo^3 \qquad \textbf{(4-14)}$$

From Equation 4-14, it can be seen that the simpfied model includes the effect speed, feed, cutting condition and cut number on flank wear progression. Per the parsimony principal, depth of cut was left out of the model as it did not improve model fit. A good model fit was obtained as seen in the response versus fitted value plot shown in Figure 4-36 and goodness of fit statistic (AIC, BIC and Log likelihood) discussed earlier. Table 4-32 shows the parameter estimates of the model under the 2nd column. The terms that are significant at 95 % confidence level (as indicated by the p-value) are highlighted.

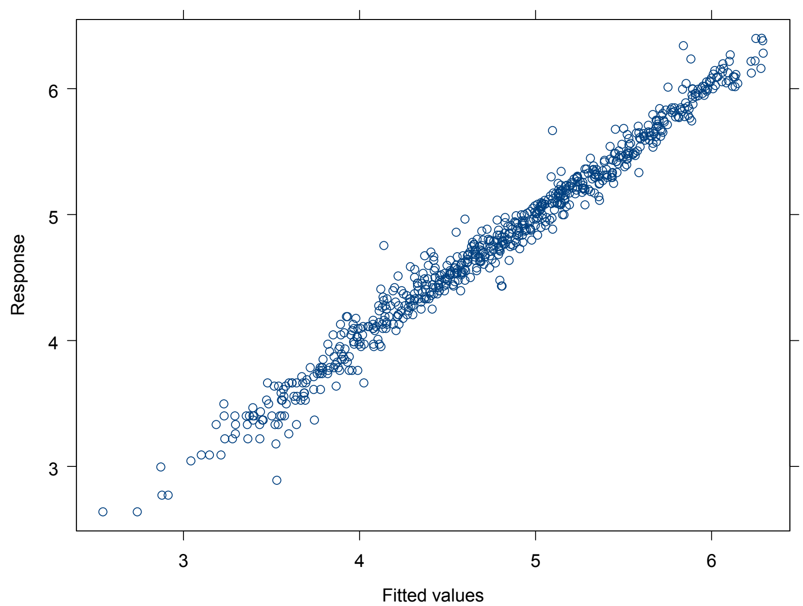


Figure 4-36 Plot of Average Estimated Flank Wear Progression with Number of Cuts for Mixed Effects Model

Table 4-32 Parameter Estimates for the Mixed Effects Model with Associated p Values*

Terms	Value	Std.error	Degree of freedom (DF)	t-value	p-value
Intercept	2.709441	0.109888	634	24.65638	< 0.0001
SpeedI	0.045327	0.1235976	43	0.36673	0.7156
Feed0.15	0.313842	0.0950245	43	3.30275	0.0019
ConditionI	0.678739	0.0778535	43	8.71816	< 0.0001
Feed0.2	0.595547	0.0955489	43	6.2329	< 0.0001
CutNo	0.092218	0.0113641	634	8.11486	< 0.0001
I($CutNo^2$)	-0.002151	0.000359	634	-5.98998	< 0.0001
I($CutNo^3$)	0.000021	0.0000048	634	4.42299	< 0.0001
SpeedI:CutNo	0.069427	0.0166875	634	4.16041	< 0.0001
SpeedI:I($CutNo^2$)	-0.002645	0.0005721	634	-4.62236	< 0.0001
SpeedI:I($CutNo^3$)	0.000048	0.0000082	634	5.77437	< 0.0001

* Significant terms at 95 % confidence level have been highlighted

From Table 4-32, it can be seen that $Condition_I$ has a positive, highly significant coefficient (p value < 0.0001) amongst the main effects. This implies that the average initial wear obtained under dry cutting conditions are higher compared to semi-dry cutting conditions, keeping all other cutting parameters in the model at the same level. Also, positive coefficients were obtained for the feed main effect $Feed_{0.20}$ (p-value <0.0001) followed by $Feed_{0.15}$ (p value 0.0019) that are also highly significant. This imples that keeping all other cutting parameters in the model constant, changing feed levels from the baseline feed level of $Feed_{0.10}$ to $Feed_{0.20}$ and $Feed_{0.15}$ respectively results in higher average initial wear values. It is to be noted that the coefficient obtained with term $Feed_{0.20}$ is greater than that of $Feed_{0.15}$ that may indicate a positive trend. However, such an inference cannot be conclusively drawn as the number of feed levels used in the experiment was few. Also, the effect of higher speed level ($Speed_I$) was not significant at 95 % confidence level. However, this term was kept in the model as it has significant interactions with number of cuts (*CutNo*).

The curvature of the *LnWear* versus *CutNo* plot (Figure 4-37) has also been modelled using a cubic model involving $Speed_I$ and the interaction of $Speed_I$ with linear, cubic and quadratic terms of *CutNo*. It can be observed from Figure 4-37 that a steeper wear progression curve is obtained for the higher level of cutting speed ($Speed_I$). Also the coefficients of *SpeedI* - *CutNo* interactions are highly significant ($p < 0.0001$) which implies that switching from the baseline to a higher speed level (229 m/min) changes the shape of the wear progression curve (steeper curve for higher cutting speed) as seen in Figure 4-37.

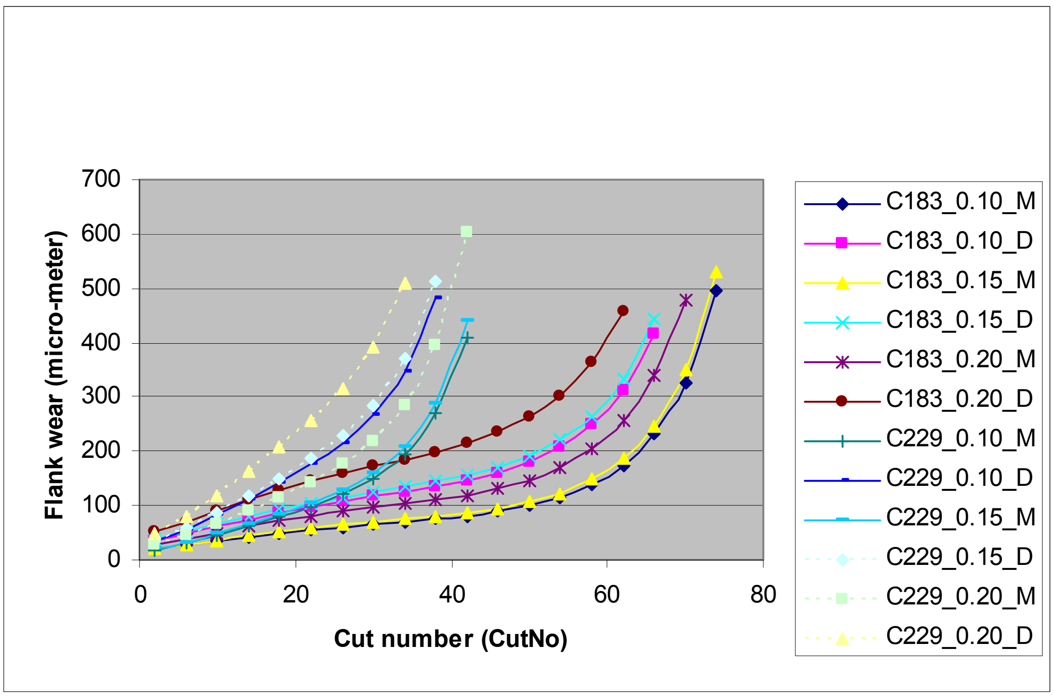


Figure 4-37 Plot of Average Estimated Flank Wear Progression with Number of Cuts for Mixed Effects Model (Index: C183_.10_M; Speed - 183 m/min, Feed - 0.10 mm/rev or mm/tooth, M- Mist cutting condition.; D - Dry cutting condition)

Comparison of the magnitude of the coefficients of the interaction terms with each other or with main effect terms is not appropriate as $Speed_l$ is multiplied by different order of *CutNo* which changes the associated scale. For the higher speed setting (229 m/min), the coefficients of linear and cubic terms of *CutNo* add up to large positve coefficients that results in a steeper wear progression curve as seen in Figure 4-37.

The standard deviations for the random effect terms for the simplified model is shown in Table 4-33. For the simplified model, the standard deviation of the intercept random effects term that accounts for inter block variation is also larger (approximately 3.3 times) than the standard deviation of the error residual term that accounts for within block variation. As indicated for the full model earlier, failure to account for the inter block variation would result in an inflated residual error standard deviation that would hinder the models ability to detect significant effects.

Table 4-33 Estimates of the Variance Components of the Random Effect Terms

Random effect	Standard deviation	Correlation matrix		
(Intercept)	0.40772743632	(Intercept)	CutNo	I(CutNo^2)
CutNo	0.05388482331	-0.757		
I(CutNo^2)	0.00167926364	0.733	-0.975	
I(CutNo^3)	0.00002238862	-0.581	0.841	-0.920
Residual StdDev	**0.12484468916**			

The correlation between the linear, quadratic, and cubic effects of *CutNo* for the simplified model shown in Table 4-33 is of a very similar nature when compared to that of the full model as shown in Table 4-31. The magnitude of the correlation is slightly larger for the simplified model. As mentioned earlier, the model allows the random effect terms to be correlated using a general positive definite matrix that is the most general form of a dispersion matrix.

4.5 Summary

In this chapter, MANOVA analysis showed that main effects of independent variables (speed, feed, depth of cut and cutting condition), two way interactions of speed and DOC with cutting condition, and three way interactions involving speed, feed, depth of cut and cutting condition had statistically significant effects on the dependant variables. Main effects plots, interaction plots, and Tukey comparison of means was used to suggest optimal cutting conditions that would yield low cutting force and cutting power acting on the work piece during end milling. For the tool-work piece combination and cutting conditions selected, a cutting speed of 229 m/min, a feed rate of 0.15 mm/min and a depth of cut of 2.54 mm will yield the highest material removal rate and the best surface finish. Also, a cutting speed of 183 m/min and a DOC of 3.81 mm under semi-dry cutting condition will yield the highest tool life. A multiple regression model for tool life prediction has been developed with an $R^2_{adjusted}$ value of 90.2 %. An analysis of the flank surface of the insert showed that non-uniform flank wear occurs during semi-dry and dry machining of AISI 4340 steel with PVD TiAlN/TiN multi-layer coated carbide inserts. The electron dispersive X ray spectral analysis showed higher levels of iron and oxygen on the crater surface during dry machining condition. From the elemental analysis, it was confirmed that diffusion wear prevails during dry machining at temperatures in excess of 900°C. A full and a simplified mixed effects model of tool wear progression has also been developed for the first time metal cutting literature. This model takes into account between and across block variations while end milling and has a substantial higher power in terms of significant effects compared to traditional regression models for tool wear progression.

Chapter 5

Summary of Results, Conclusions and Recommendations for Future Research

The objective of this research is to study the effect of dry and semi-dry machining of AISI 4340 medium carbon low alloy steel with advanced TiAlN/TiN PVD coated carbide end mill inserts in order to come up with recommendations on speed, feed, DOC and cutting conditions that will reduce cutting forces and cutting power, improve surface finish and increase tool life. A statistical model of tool life was developed using multiple regression technique. Also, an accurate tool wear estimation model has been developed using mixed effects modeling technique. The model takes into unobserved heterogeneity within and across test blocks as a random effect. Energy dispersive X ray analysis (EDX) and backscattered electron images were used for analyzing the type of wear on the tool-work piece interface. The following is a summary of results for the effect of independent variables and their interactions on dependant variables.

5.1 Summary of Results

The following are the results of each of the independent variables investigated. A 95 % confidence level was used for all statistical analysis.

5.1.1 Effect of speed

Independent variable speed showed a significant effect on some of the dependant variables.

The effect of this variable in some cases was not considered separately because two and three way interactions of speed showed a significant effect on some dependant variables.

5.1.1.1 Effect of speed on $F_{x\ max}$

Speed has a statistically significant effect on $F_{x\ max}$ as shown in Figure 4-1 (a). It was observed that maximum cutting force in X direction on the work piece ($F_{x\ max}$) increased with increase in speed. The lowest value of $F_{x\ max}$ was obtained for a cutting speed of 183 m/min.

5.1.1.2 Effect of speed on $F_{x\ avg}$

Speed x *DOC* x *condition* interaction has a statistically significant effect on $F_{x\ avg}$ as shown in Figure 4-4 and Table 4-19. It was noted that $F_{x\ avg}$ increases with an increase in cutting speed from 183 to 229 m/min at a depth of cut of 3.81 mm under dry cutting condition.

A cutting speed of 229 m/min and a depth of cut of 3.81 mm under semi-dry cutting condition are recommended to obtain the highest material removal rate and low values of $F_{x\ avg.}$.

5.1.1.3 Effect of speed on $F_{z\ max}$

It was observed that *speed* x *DOC* x *condition* interaction had a significant effect on $F_{z\ max}$ as shown in Figure 4-8 and Table 4-20. It was observed that increasing cutting speed from 183 to 229 m/min at a depth of cut of 2.54 mm under semi-dry cutting condition decreased $F_{z\ max}$ values. Also, a reduction in $F_{z\ max}$ values were observed when increasing cutting speed from 183 to 229 m/min at a depth of cut of 3.81 mm under dry cutting condition. A cutting speed of 229 m/min and a depth of cut of 3.81 mm under dry cutting condition are recommended to obtain the highest material removal rate and low values of $F_{z\ max.}$

5.1.1.4 Effect of speed on $F_{z\ avg}$

It was observed that three way interactions *speed* x *feed* x *condition*, *speed* x *feed* x *DOC*, and *speed* x *DOC* x *condition* interactions have a significant effect on $F_{z\ avg}$ as shown in Figures 4-11,12, and 13, and Tables 4-21, 22 and 23.

From the three way interaction plots, it can be see that $F_{z\ avg}$ decreases with increase in cutting speed from 183 to 229 m/min for feed levels of 0.15 and 0.20 mm/rev under dry cutting condition. Also, $F_{z\ avg}$ decreases with an increase in cutting speed from 183 to 229 m/min for feed rate/depth of cut levels of 0.15 mm/rev/3.81 mm and 0.20 mm/rev/ 2.54 mm respectively.

From the *speed x feed x condition* interaction plot (Figure 4-11) and the Tukey comparison of means (Table 4-21), a cutting speed of 229 m/min with a feed rate of 0.20 mm/rev under dry cutting conditions gives the highest material removal rate with low values of $F_{z\ avg}$.

From the *speed x feed x DOC* interaction plot (Figure 4-12) and the Tukey comparison of means (Table 4-22), a cutting speed of 229 m/min with a feed rate of 0.20 mm/rev and a depth of cut of 2.54 mm gives the highest material removal rate with low values of $F_{z\ avg}$.

From the *speed x DOC x condition* interaction plot (Figure 4-13) and the Tukey comparison of means (Table 4-23), a cutting speed of 229 m/min with a DOC of 3.81 mm under dry cutting condition gives the highest material removal rate with low values of $F_{z\ avg}$.

5.1.1.5 Effect of speed on P_{total}

It was observed that *speed* x *feed* x *DOC* and *speed* x *feed* x *condition* three way interactions have a significant effect on P_{total} as shown in Figure 4-21 and 22 and Table 4-24 and 25 respectively. From the three way interaction plots, it was observed that total power consumed during a cut (P_{total}) increased with an increase in cutting speed from 183 to 229 m/min at a feed rate of 0.10 mm/rev for a depth of cut of 3.81 mm. Also, P_{total} increased when cutting speed was increased from 183 to 229 m/min for feed rates of 0.10 and 0.15 mm/rev under semi-dry cutting condition.

From the *speed x feed x DOC* interaction plot (Figure 4-21) and the Tukey comparison of means (Table 4-24), a cutting speed of 229 m/min with a feed rate of 0.20 mm/rev and a depth of cut of 3.81 mm gives the highest material removal rate with low values of P_{total}.

From the *speed x feed x condition* interaction plot (Figure 4-22) and the Tukey comparison of means (Table 4-25), a cutting speed of 229 m/min with a feed rate of 0.20 mm/rev under semi-dry machining condition gives the highest material removal rate with low values of P_{total}.

5.1.1.6 Effect of speed on R_a

It was observed that *speed* main effect had a significant effect on surface roughness R_a as shown in Figure 4-23 (a).

It was observed that a lower R_a is obtained at the higher cutting speed of 229 m/min. In order to obtain the best surface finish, the optimal condition is a cutting speed of 229 m/min.

5.1.1.7 Effect of speed on T_{life}

It was observed that the *speed* x *feed x condition* and *speed* x *DOC* x *condition* three way interactions have a significant effect on T_{life} as shown in Figure 4-25, 26 and Table 4-26, 27 respectively.

From the three way interaction plots, it can be seen that increase in cutting speed from 183 to 229 m/min resulted in decrease in tool life for all feed/cutting condition and depth of cut/cutting condition combinations.

From the *speed x feed x condition* interaction plot (Figure 4-25) and the Tukey comparison of means (Table 4-26), a cutting speed of 183 m/min with a feed rate of 0.15 mm/rev under semi-dry cutting condition gives the highest material removal rate with the longest tool life (T_{life}).

From the *speed x DOC x condition* interaction plot (Figure 4-26) and the Tukey comparison of means (Table 4-27), a cutting speed of 183 m/min with depth of cut of 3.81 mm under semi-dry cutting condition gives the highest material removal rate with the longest tool life (T_{life}).

5.1.2 Effect of feed

Independent variable feed showed a significant effect on some of the dependant variables. The effect of this variable in some cases was not considered separately because two and three way interactions of feed showed a significant effect on some dependant variables.

5.1.2.1 Effect of feed on $F_{x\,max}$

Feed x *condition* interaction has a significant effect on $F_{x\,max}$ as shown in Figure 4-2 and Table 4-18. From the results of the Tukey test, it can be seen that $F_{x\,max}$ increases when changing feed rate from 0.10 to 0.20 mm/rev under both dry and semi-dry cutting conditions. The optimum cutting condition at a feed rate of 0.15 mm/rev under semi-dry cutting condition is selected in order to obtain low values for $F_{x\,max}$ when end milling 4340 steel blocks with advanced PVD TiAlN/TiN coated carbide cutting inserts.

5.1.2.2 Effect of feed on $F_{y\,max}$

It was observed that *feed* main effect has a significant effect on $F_{y\,max}$ as shown in Figure 4-5 (a). However, the results of the Tukey test showed that the difference in $F_{y\,max}$ means for the three different levels of feed were not statistically significant. Therefore for a higher material removal rate, the feed rate of 0.20 mm/rev is recommended to obtain low values of $F_{y\,max}$.

5.1.2.3 Effect of feed on $F_{z\,avg}$

Speed x feed x condition and *speed* x *feed* x *DOC* three way interactions have a significant effect on $F_{z\,avg}$ as shown in Figure 4-11 and 12 and Table 4-21 and 22. From the three way interactions, it can be seen that $F_{z\,avg}$ decreases with increase in feed rate from 0.10 to 0.15 mm/rev under semi-dry cutting condition at a cutting speed of 229 m/min. Also, $F_{z\ avg}$ decreases with an increase in feed rate from 0.10 to 0.15 mm/rev at a depth of cut of 2.54 mm and a cutting speed of 183 m/min. $F_{z\ avg}$ also decreases with an increase in feed rate from 0.10 to 0.15 mm/rev at a depth of cut of 3.81 mm and a cutting speed of 229 m/min.

From the *speed x feed x condition* interaction plot (Figure 4-11) and the Tukey comparison of means (Table 4-21), a cutting speed of 229 m/min with a feed rate of 0.20 mm/rev under dry cutting condition gives the highest material removal rate with low values of $F_{z\ avg}$.

From the *speed x feed x DOC* interaction plot (Figure 4-12) and the Tukey comparison of means (Table 4-22), a cutting speed of 229 m/min with a feed rate of 0.20 mm/rev and a depth of cut of 2.54 mm gives the highest material removal rate with low values of $F_{z\ avg}$.

5.1.2.4 Effect of feed on $F_{xy\ max}$

It was observed that *feed* main effect had a significant effect on $F_{xy\ max}$ as shown in Figure 4-14 (a). Tukey test showed that the difference in means of $F_{xy\ max}$ for the three levels of feed is statistically significant. $F_{xy\ max}$ increases with an increase in feed rate from 0.10 to 0.15 mm/rev and from 0.15 to 0.20 mm/rev respectively. Therefore in order to obtain low values of $F_{xy\ max}$, a lower feed rate of 0.10 mm/rev is recommended.

5.1.2.5 Effect of feed on $F_{xyz\ max}$

It was observed that *feed* main effect had a significant effect on $F_{xyz\ max}$ as shown in Figure 4-16 (a). Tukey test showed that the difference in $F_{xyz\ max}$ means for the three different levels of feed are statistically significant. $F_{xyz\ max}$ increases with an increase in feed rate from 0.10 to 0.15 mm/rev, and from 0.15 to 0.20 mm/rev respectively. Therefore, in order to obtain low values of $F_{xyz\ max}$, a lower feed rate of 0.10 mm/rev is recommended.

5.1.2.6 Effect of feed on P_{max}

Feed main effect had a significant effect on P_{max} as shown in Figure 4-18. Tukey test showed that the difference in P_{max} means were only statistically significant when feed rate was increased from 0.10 and 0.15 mm/rev.

There is no statistically significant difference between P_{max} means for feed rates of 0.15 and 0.20 mm/rev respectively. Therefore, in order to obtain a higher rate of material removal and low values of P_{max}, a feed rate of 0.20 mm/rev is recommended.

5.1.2.7 Effect of feed on P_{total}

Speed x feed x DOC and *speed* x *feed* x *condition* three way interactions have a significant effect on P_{total} as shown in Figure 4-21 and 22 and Table 4-24 and 25. From the three way interactions, it can be seen that P_{total} decreases with increase in feed rate from 0.10 to 0.15 mm/rev at a cutting speed of 229 m/min and a depth of cut of 3.81 mm. Also, P_{total} decreases with an increase in feed rate from 0.10 to 0.15 mm/rev at a cutting speed of 229 m/min under dry cutting condition.

From the *speed x feed x DOC* interaction plot (Figure 4-21) and the Tukey comparison of means (Table 4-24), a cutting speed of 229 m/min at a feed rate of 0.20 mm/rev and a depth of cut of 3.81 mm gives the highest material removal rate with low values of P_{total}.

From the *speed x feed x condition* interaction plot (Figure 4-22) and the Tukey comparison of means (Table 4-25), a cutting speed of 229 m/min with a feed rate of 0.20 mm/rev under semi-dry cutting conditions gives the highest material removal rate with low values of P_{total}.

5.1.2.8 Effect of feed R_a

Main effects plot shown in Figure 4-23 (b) shows the relationship between feed and surface finish (R_a) in μm. From Figure 4-23 (b), it can be seen that surface finish increases with an increase in feed level from 0.10 to 0.15 mm/rev, and from 0.15 to 0.20 mm/rev. There is a no statistically significant difference between R_a means obtained with feed rates of 0.10 and 0.15 mm/rev. However, there is a statistically significant difference between R_a means obtained for feed rates of 0.15 and 0.20 mm/rev. For maximum material removal rate and a higher surface finish, a feed rate of 0.15 mm/rev is recommended.

5.1.2.9 Effect of feed on T_{life}

It was observed that *speed* x *feed* x *condition* interaction had a significant effect on tool life (T_{life}) as shown in Figure 4-25 and Table 4-26. From Table 4-26, it can be seen that a change in feed rates from 0.10 to 0.15 mm/rev at a cutting speed of 183 m/min under dry cutting condition decreases tool life. Also, change in feed rate from 0.15 to 0.20 mm/rev at a cutting speed of 183 m/min under semi-dry cutting condition decreases tool life. Change in feed rate from 0.15 to 0.20 mm/rev at a cutting speed of 229 m/min under semi-dry cutting condition also lowers tool life.

In order to obtain the longest tool life and a high material removal rate, a cutting speed of 183 m/min at a feed rate of 0.15 mm/rev under semi-dry cutting condition is recommended when end milling 4340 steel with TiAlN/TiN coated carbide cutting tools.

5.1.3 Effect of depth of cut (*DOC*)

Independent variable *DOC* showed a significant effect on some of the dependant variables. The effect of this variable in some cases was not considered separately because of two and three way interactions of *DOC* showed a significant effect on some dependant variables.

5.1.3.1 Effect of *DOC* on $F_{x\ max}$

DOC had a significant effect on $F_{x\ max}$ as shown in Figure 4-1 (c). It was observed that maximum cutting force in X direction on the work piece ($F_{x\ max}$) increased with increase in *DOC* from 2.54 to 3.81 mm. The lowest value of $F_{x\ max}$ was obtained for a *DOC* level of 2.54 mm.

5.1.3.2 Effect of *DOC* on $F_{x\ avg}$

Speed x *DOC* x *condition* interaction effect has a significant effect on $F_{x\ avg}$ as shown in Figure 4-4 and Table 4-19. From Table 4-19, it can be seen that increasing depth of cut from 2.54 to 3.81 mm at a cutting speed of 183 m/min under semi-dry cutting condition increased $F_{x\ avg}$. Also, increasing depth of cut from 2.54 to 3.81 mm at a cutting speed of 229 m/min under dry cutting condition increased $F_{x\ avg}$.

From Figure 4-4 and Table 4-19, in order to obtain a high material removal rate and low values of $F_{x\,avg}$, a cutting speed of 229 m/min at a depth of cut of 3.81 mm under semi-dry cutting condition is recommended when end milling 4340 steel with PVD TiAlN/TiN coated carbide cutting tools.

5.1.3.3 Effect of *DOC* on $F_{y\,max}$

DOC had a significant effect on $F_{y\,max}$ as shown in Figure 4-5 (b). It was observed that maximum cutting force in Y direction on the work piece ($F_{y\,max}$) increases with an increase in *DOC* from 2.54 to 3.81 mm. The lower value of $F_{y\,max}$ was obtained for a DOC level of 2.54 mm.

5.1.3.4 Effect of DOC on $F_{z\,max}$

Speed x *DOC* x *condition* interaction effect has a significant effect on $F_{z\,max}$ as shown in Figure 4-8 and Table 4-20. From Table 4-20, it can be seen that increasing depth of cut from 2.54 to 3.81 mm at a cutting speed of 183 m/min under dry cutting condition increases $F_{z\,max}$. Also, increasing depth of cut from 2.54 to 3.81 mm at a cutting speed of 229 m/min under semi-dry cutting condition increases $F_{z\,max}$.

From Figure 4-8 and Table 4-20, in order to obtain a high material removal rate and low values of $F_{z\,max}$, a cutting speed of 229 m/min at a depth of cut of 3.81 mm under dry cutting condition is recommended when end milling 4340 steel with PVD TiAlN/TiN coated carbide cutting tools.

5.1.3.5 Effect of DOC on $F_{z\ avg}$

Speed x feed x DOC and *speed* x *DOC* x *condition* three way interactions have a significant effect on $F_{z\ avg}$ as shown in Figure 4-12 and 13 and Table 4-22 and 23. From the three way interactions, it can be seen that $F_{z\ avg}$ increases with an increase in depth of cut from 2.54 to 3.81 mm at a cutting speed of 183 m/min and a feed rate of 0.15 mm/rev. Also, $F_{z\ avg}$ increases with an increase in depth of cut from 2.54 to 3.81 mm at a cutting speed of 229 m/min under dry cutting condition. $F_{z\ avg}$ also increases with an increase in depth of cut from 2.54 to 3.81 mm at a cutting speed of 183 m/min under dry cutting condition.

From the *speed* x *feed* x *DOC* interaction plot (Figure 4-12) and the Tukey comparison of means (Table 4-22), a cutting speed of 229 m/min with a feed rate of 0.20 mm/rev at a depth of cut of 2.54 mm gives the highest material removal rate with low values of $F_{z\ avg}$.

From the *speed* x *DOC* x *condition* interaction plot (Figure 4-13) and the Tukey comparison of means (Table 4-23), a cutting speed of 229 m/min with a depth of cut of 3.81 mm under dry cutting conditions give the highest material removal rate with low values of $F_{z\ avg}$.

5.1.3.6 Effect of *DOC* on $F_{xy\ max}$

DOC had a significant effect on $F_{xy\ max}$ as shown in Figure 4-14 (b). It was observed that there is a statistically significant difference between $F_{xy\ max}$ means obtained for *DOC* levels of 2.54 and 3.81 mm respectively. Therefore, a *DOC* level of 2.54 mm is recommended in order to obtain low values of maximum 2 D cutting force ($F_{xy\ max}$).

5.1.3.7 Effect of ***DOC*** on $F_{xy\ avg}$

DOC had a significant effect on $F_{xy\ avg}$ as shown in Figure 4-15. It was observed that there is a statistically significant difference between $F_{xy\ avg}$ means obtained for *DOC* levels of 2.54 and 3.81 mm respectively. Therefore, a *DOC* level of 2.54 mm is recommended in order to obtain low values of $F_{xy\ avg}$.

5.1.3.8 Effect of ***DOC*** on $F_{xyz\ max}$

DOC had a significant effect on $F_{xyz\ max}$ as shown in Figure 4-16 (b). It was observed that there is a statistically significant difference between $F_{xyz\ max}$ means obtained for *DOC* levels of 2.54 and 3.81 mm respectively. A *DOC* level of 2.54 mm is recommended in order to obtain low values of $F_{xyz\ max}$.

5.1.3.9 Effect of ***DOC*** on $F_{xyz\ avg}$

DOC had a significant effect on $F_{xyz\ avg}$ as shown in Figure 4-17. It was observed that there is a statistically significant difference between $F_{xyz\ avg}$ means obtained for *DOC* levels of 2.54 and 3.81 mm respectively. Therefore, a *DOC* level of 2.54 mm is recommended in order to obtain low values of $F_{xyz\ avg}$.

5.1.3.10 Effect of DOC on P_{total}

Speed x *feed* x *DOC* interaction effect has a significant effect on P_{total} as shown in Figure 4-21 and Table 4-24. From Table 4-24, it can be seen that increasing depth of cut from 2.54 to 3.81 mm at a cutting speed of 229 m/min under a feed rate of 0.20 mm/rev decreases P_{total}.

From Figure 4-21 and Table 4-24, in order to obtain a high material removal rate and low values of P_{total}, a cutting speed of 229 m/min at a feed rate of 0.20 mm/rev and a depth of cut of 3.81 mm is recommended when end milling 4340 steel with PVD TiAlN/TiN coated carbide cutting tools.

5.1.3.11 Effect of *DOC* on R_a

DOC had a significant effect on R_a as shown in Figure 4-23 (c). It was observed that there is a statistically significant difference between R_a means obtained for *DOC* levels of 2.54 and 3.81 mm respectively. Therefore, a *DOC* level of 2.54 mm is recommended in order to obtain low values of R_a (i.e. a better surface finish).

5.1.3.12 Effect of *DOC* on T_{life}

It was observed that *speed* x *DOC* x *condition* interaction had a significant effect on T_{life} as shown in Figure 4-26 and Table 4-27. From Table 4-27, it can be seen that a cutting speed of 183 m/min and a *DOC* level of 3.81 mm under semi-dry cutting conditions gives the highest material removal rate with the longest tool life (T_{life}).

5.1.4 Effect of Cutting Condition

Independent variable cutting condition showed a significant effect on some of the dependant variables.

The effect of this variable in some cases was not considered separately because of two and three way interactions of condition showed a significant effect on some dependant variables.

5.1.4.1 Effect on $F_{x\ avg}$

Speed x *DOC* x *condition* interaction effect has a significant effect on $F_{x\ avg}$ as shown in Figure 4-4 and Table 4-19. From Table 4-19, it can be seen that changing cutting condition from semi-dry to dry under a cutting speed of 183 m/min and a depth of cut of 3.81 mm decreases $F_{x\ avg}$. From Figure 4-4 and Table 4-19, in order to obtain a high material removal rate and low values of $F_{x\ avg}$, a cutting speed of 229 m/min at a depth of cut of 3.81 mm under semi-dry cutting condition is recommended when end milling 4340 steel with PVD TiAlN/TiN coated carbide cutting tools.

5.1.4.2 Effect on $F_{z\ max}$

Speed x *DOC* x condition interaction effect has a significant effect on $F_{z\ max}$ as shown in Figure 4-8 and Table 4-20. From Table 4-20, it can be seen that changing cutting condition from semi-dry to dry under a cutting speed of 229 m/min and a depth of cut of 3.81 mm decreases $F_{z\ max}$. From Figure 4-8 and Table 4-20, in order to obtain a high material removal rate and low values of $F_{z\ max}$, a cutting speed of 229 m/min at a depth of cut of 3.81 mm under dry cutting condition is recommended when end milling 4340 steel with PVD TiAlN/TiN coated carbide cutting tools.

5.1.4.3 Effect on $F_{z\ avg}$

Speed x feed x condition and *speed* x *DOC* x *condition* three way interactions have a significant effect on $F_{z\ avg}$ as shown in Figure 4-11 and 13 and Table 4-21 and 23. From the three way interactions, it can be seen that $F_{z\ avg}$ increases with a change in cutting condition from semi-dry to dry at a cutting speed of 183 m/min and at a depth of cut of 3.81 mm. From the *speed* x *feed* x *condition* interaction plot (Figure 4-11) and the

Tukey comparison of means (Table 4-21), a cutting speed of 229 m/min with a feed rate of 0.20 mm/rev under dry cutting condition gives the highest material removal rate with low values of $F_{z\ avg}$.

From the *speed* x *DOC* x *condition* interaction plot (Figure 4-13) and the Tukey comparison of means (Table 4-23), a cutting speed of 229 m/min with a depth of cut of 3.81 mm under dry cutting conditions give the highest material removal rate with low values of $F_{z\ avg}$.

5.1.4.4 Effect on P_{total}

Speed x *feed* x *condition* three way interactions have a significant effect on P_{total} as shown in Figure 4-22 and Table 4-25. From the three way interactions, it can be seen that P_{total} increases with a change in cutting condition from semi-dry to dry at a cutting speed of 183 m/min under a feed rate of 0.15 mm/rev. Also, P_{total} decreases with a change in cutting condition from semi-dry to dry at a cutting speed of 229 m/min at a feed rate of 0.15 mm/rev.

From the *speed* x *feed* x *condition* interaction plot (Figure 4-22) and the Tukey comparison of means (Table 4-25), a cutting speed of 229 m/min with a feed rate of 0.20 mm/rev under semi-dry cutting conditions give the highest material removal rate with low values of $F_{z\ avg}$.

5.1.4.5 Effect of cutting condition on T_{life}

Speed x feed x *condition* interaction and s*peed* x *DOC* x *condition* interaction has a significant effect on T_{life} as shown in Figure 4-25 and 4-26, and Table 4-26 and 4-27 respectively. From the three way interaction plots, it can be seen that tool life decreases when changing cutting condition from semi-dry to dry for the following feed-speed combinations; feed rates of 0.15 and 0.20 mm/rev at a cutting speed of 183 m/min and a feed rate of 0.15 mm/rev at a cutting speed of 229 m/min.

From Figure 4-25 and Table 4-26, in order to obtain a longer tool life (T_{life}), the optimal condition is a speed level of 183 m/min and a feed level of 0.15 mm/rev under semi-dry cutting condition when end milling 4340 steel blocks with advanced PVD TiAlN/TiN coated cutting inserts.

From Figure 4-26 and Table 4-27, a cutting speed of 183 m/min and a DOC level of 3.81 mm under semi-dry cutting condition give the highest material removal rate with the longest tool life (T_{life}) when end milling 4340 steel blocks with advanced PVD TiN/TiAlN coated carbide cutting inserts.

Table 5-1 through 5-13 summarize recommended cutting conditions for the fourteen dependant variables that were studied for speed, feed, DOC and cutting condition main and interactions effects at a significance level of $\alpha = 0.05$ in the MANOVA analysis table shown in Table 4-2. When an interaction effect is present involving an independent variable, the main effect alone is not considered.

Table 5-1 Summary of Cutting Conditions for Maximum Force in X direction of Work piece ($F_{x\ max}$)

Main effect or Interaction effect	Speed	Feed	DOC	Cutting condition
Speed	183 m/min	-	-	-
DOC	-	-	2.54 mm	-
Feed x condition	-	0.15 mm/rev	-	Semi-dry

Table 5-2 Summary of Cutting Conditions for Average Cutting Force in X direction of Work piece ($F_{x\ avg}$)

Main effect or Interaction effect	Speed	Feed	DOC	Cutting condition
Speed x DOC x condition	229 m/min	-	3.81 mm	Semi-dry

Table 5-3 Summary of Cutting Conditions for Maximum Cutting Force in Y direction of Work piece ($F_{y\ max}$)

Main effect or Interaction effect	Speed	Feed	DOC	Cutting condition
Feed	-	0.20 mm/rev	-	-
DOC	-	-	2.54 mm	-

Table 5-4 Summary of Cutting Conditions for Maximum Force in Z Direction of Work piece ($F_{z\ max}$)

Main effect or Interaction effect	Speed	Feed	DOC	Cutting condition
Speed x DOC x condition	229 m/min	-	3.81 mm	Dry

Table 5-5 Summary of Cutting Conditions for Average Cutting Force in Z Direction of Work piece ($F_{z\ avg}$)

Main effect or Interaction effect	Speed	Feed	DOC	Cutting condition
Speed x feed x condition	229 m/min	0.20 mm/rev	-	Dry
Speed x feed x DOC	229 m/min	0.20 mm/rev	2.54 mm	-
Speed x DOC x condition	229 m/min	-	3.81 mm	Dry

Table 5-6 Summary of Maximum 2 D Cutting Forces Acting on Work piece ($F_{xy\ max}$)

Main effect or Interaction effect	Speed	Feed	DOC	Cutting condition
Feed	-	0.10 mm/rev	-	-
DOC	-	-	2.54 mm	-

Table 5-7 Summary of Average 2D Cutting Force Acting on Work piece ($F_{xy\ avg}$)

Main effect or Interaction effect	Speed	Feed	DOC	Cutting condition
DOC	-	-	2.54 mm	-

Table 5-8 Summary of Maximum 3D Cutting Force Acting on Work piece ($F_{xyz\ max}$)

Main effect or Interaction effect	Speed	Feed	DOC	Cutting condition
Feed	-	0.10 mm/rev	-	-
DOC	-	-	2.54 mm	-

Table 5-9 Summary of Average 3D Cutting Force Acting on Work piece ($F_{xyz\ avg}$)

Main effect or Interaction effect	Speed	Feed	DOC	Cutting condition
DOC	-	-	2.54 mm	-

Table 5-10 Summary of Maximum Cutting Power Measured during a Cut (P_{max})

Main effect or Interaction effect	Speed	Feed	DOC	Cutting condition
Feed	-	0.20 mm/rev	-	-

Table 5-11 Summary of Total Cutting Power Measured during a Cut (P_{total})

Main effect or Interaction effect	Speed	Feed	DOC	Cutting condition
Speed x feed x DOC	229 m/min	0.20 mm/rev	3.81 mm	-
Speed x feed x condition	229 m/min	0.20 mm/rev	-	Semi-dry

Table 5-12 Summary of Surface Finish (R_a)

Main effect or Interaction effect	Speed	Feed	DOC	Cutting condition
Speed	229 m/min	-	-	-
Feed	-	0.15 mm/rev	-	-
DOC	-	-	2.54 mm	-

Table 5-13 Summary of Tool Life (T_{life})

Main effect or Interaction effect	Speed	Feed	DOC	Cutting condition
speed x feed x condition	183 m/min	0.15 mm/rev	-	Semi dry
speed x DOC x condition	183 m/min	-	3.81 mm	Semi dry

The summary of the results shown in Tables 5-1 through 5-13 are shown in Table 5-14.

Table 5-14 Summary of Results for Tables 5-1 through 13

Description	Symbol	Speed	Feed	DOC	Cutting condition
Maximum force in X direction of work piece (N)	$F_{x\ max}$	183 m/min	0.15 mm/rev	2.54 mm	Semi-dry
Avgerage force in X direction of work piece (N)	$F_{x\ avg}$	229 m/min	-	3.81 mm	Semi-dry
Maximum force in Y direction of work piece (N)	$F_{y\ max}$	-	0.20 mm/rev	2.54 mm	-
Maximum force in Z direction of work piece (N)	$F_{z\ max}$	229 m/min	-	3.81 mm	Dry
Avgerage force in Z direction of work piece	$F_{z\ avg}$	229 m/min	0.20 mm/rev	3.81 mm	Dry
Maximum 2 D force on the work piece (N)	$F_{xy\ max}$	-	0.10 mm/rev	2.54 mm	-
Average 2 D force on the work piece (N)	$F_{xy\ avg}$	-	-	2.54 mm	-
Maximum 3 D force on the work piece (N)	$F_{xyz\ max}$	-	0.10 mm/rev	2.54 mm	-
Average 3 D force on the work piece (N)	$F_{xyz\ avg}$	-	-	2.54 mm	-
Maximum cutting power during cuts (Watts)	P_{max}	-	0.20 mm/rev	-	-
Total cutting power during cuts (Watts)	P_{total}	229 m/min	0.20 mm/rev	3.81 mm	Semi-dry
Surface roughness (μm)	R_a	229 m/min	0.15 mm/rev	2.54 mm	-
Number of cuts to reach wear criterion	T_{life}	183 m/min	0.15 mm/rev	3.81 mm	Semi-dry

Table 5-15 was obtained from Table 5-14 by filling in the gaps with the corresponding independent variable at their highest levels in order to obtain the highest material removal rate and the best response.

Table 5-15 Summary of Speed, Feed, DOC, and Cutting Condition to Obtain the Best Response for the Dependant Variables (i.e. Highest Material Removal Rate with Low Values of Cutting Force, Cutting Power, High Surface Finish and Long Tool Life)

Description	Dependant variable	Speed	Feed	DOC	Cutting condition
Maximum force in X direction of work piece (N)	$F_{x\ max}$	183 m/min	0.15 mm/rev	2.54 mm	Semi-dry
Avgerage force in X direction of work piece (N)	$F_{x\ avg}$	229 m/min	0.20 mm/rev	3.81 mm	Semi-dry
Maximum force in Y direction of work piece (N)	$F_{y\ max}$	229 m/min	0.20 mm/rev	2.54 mm	Semi-dry or Dry
Maximum force in Z direction of work piece (N)	$F_{z\ max}$	229 m/min	0.20 mm/rev	3.81 mm	Dry
Avgerage force in Z direction of work piece	$F_{z\ avg}$	229 m/min	0.20 mm/rev	3.81 mm	Dry
Maximum 2 D force on the work piece (N)	$F_{xy\ max}$	229 m/min	0.10 mm/rev	2.54 mm	Semi-dry or Dry
Average 2 D force on the work piece (N)	$F_{xy\ avg}$	229 m/min	0.20 mm/rev	2.54 mm	Semi-dry or Dry
Maximum 3 D force on the work piece (N)	$F_{xyz\ max}$	229 m/min	0.10 mm/rev	2.54 mm	Semi-dry or Dry
Average 3 D force on the work piece (N)	$F_{xyz\ avg}$	229 m/min	0.20 mm/rev	2.54 mm	Semi-dry or Dry
Maximum cutting power during cuts (Watts)	P_{max}	229 m/min	0.20 mm/rev	3.81 mm	Semi-dry or Dry
Total cutting power during cuts (Watts)	P_{total}	229 m/min	0.20 mm/rev	3.81 mm	Semi-dry
Surface roughness (μm)	R_a	229 m/min	0.15 mm/rev	2.54 mm	Semi-dry or Dry
Number of cuts to reach wear criterion	T_{life}	183 m/min	0.15 mm/rev	3.81 mm	Semi-dry

From Table 5-15, it can be seen that longest tool life for the highest material removal rate is obtained with a cutting speed of 183 m/min, a feed rate of 0.15 mm/rev and a depth of cut of 3.81 mm under semi-dry cutting condition. The best surface finish with the highest material removal rate is obtained with a cutting speed of 229 m/min, a feed rate of 0.15 mm/rev and a depth of cut of 2.54 mm.

However, the Tukey test for comparison of surface finish (R_a) means between cutting speeds of 183 m/min and 229 m/min did not show any statistically significant difference at 95 % confidence level (Section 4.2.12.5 a). Also, the tool life (T_{life}) means did not show any statistically significant difference at 95 % confidence level for the following cutting conditions (Section 4.2.13.4 b);

1) Cutting speed of 183 m/min, depth of cut level of 2.54, semi-dry cutting condition
2) Cutting speed of 183 m/min, depth of cut level of 2.54, dry cutting condition
3) Cutting speed of 183 m/min, depth of cut level of 3.81 mm under semi-dry cutting condition

Therefore, in order to obtain the longest tool life and the best surface finish at the highest material removal rate, the recommended cutting condition is a cutting speed of 183 m/min, a feed rate of 0.15 mm/rev, a depth of cut of 2.54 mm under semi-dry cutting condition when end milling 4340 steel with PVD TiAlN/TiN multilayer coated carbide cutting inserts.

5.2 Conclusions

1. In this study, the effect of independent variables speed, feed, depth of cut and cutting condition and their interactions (two way and three way interaction) were studied in detail on 14 dependant variables, namely, maximum force in X direction of work piece ($F_{x\,max}$), average force in X direction of work piece ($F_{x\,avg}$), maximum force in Y direction of work piece ($F_{y\,max}$), average force in Y direction of work piece ($F_{y\,avg}$), maximum force in Z direction of work piece ($F_{z\,max}$), average force in Z direction of work piece ($F_{z\,avg}$), maximum 2 D forces acting on the work piece ($F_{xy\,max}$), average

2 D forces acting on the work piece ($F_{xy\ avg}$), maximum 3 D forces acting on the work piece ($F_{xyz\ max}$), average 3 D forces acting on the work piece ($F_{xyz\ avg}$), maximum power consumed during cuts (P_{max}), total power consumed during cuts (P_{total}), surface finish (R_a) and tool life (T_{life}). To our knowledge, this kind of comprehensive study does not exist in metal cutting literature for end milling 4340 steel (26 HRc) with advanced PVD TiAlN/TiN coated carbide inserts under dry and semi-dry cutting conditions. MANOVA, ANOVA and Tukey comparison of means were used to study the effect of independent variable speed, feed, depth of cut and cutting condition main and interaction effects on the fourteen response variables listed above. Main effect and interaction effect plots were plotted in Section 4.

2. Specific recommendations were given regarding levels of independent variables (namely, speed, feed, DOC and cutting condition) that would reduce cutting forces, reduce cutting power, improve surface finish and increase tool life when machining AISI 4340 steel blocks (26 HRc hardness) with TiAlN/TiN PVD coated carbide end mills under dry and semi-dry cutting conditions.
3. A multiple regression model for predicting tool life (cutting time in minutes) during end milling AISI 4340 steel blocks (26 HRc) using advanced PVD TiAlN/TiN coated carbide inserts in the following speed, feed, DOC, and cutting condition ranges (Cutting speed: 183 to 229 m/min, Feed: 0.10 to 0.20 mm/rev, Depth of cut: 2.54 to 3.81 mm, Cutting condition: semi-dry and dry) was developed.
4. A mixed effects model for progression of flank wear for semi-dry and dry end milling 4340 steel with PVD TiAlN/TiN coated carbides was developed. The model takes into account heterogeneity introduced due to hardness and machining variations.

5. A thorough discussion of advanced PVD coated carbide tools was done in the literature and the need for dry and semi-dry machining was explained. Through the experiment, recommendations on cutting conditions are given for machining 4340 steel with PVD TiAlN/TiN coated cutting tools under semi-dry and dry cutting conditions.
6. Energy dispersive X-ray analysis (EDX) and backscattered electron images of the worn out PVD TiAlN/TiN coated carbide inserts were analyzed in order to investigate the nature of wear that occurs on the tool crater face during dry and semi-dry machining of AISI 4340 medium carbon low alloy steel.

5.2.1 Merit and Impact of Research

To the best of our knowledge, this is the first time application of mixed effects modeling in metal cutting literature. The mixed effects modeling technique takes into account variations between blocks as well as within blocks that is captured by the random effect terms in the model. By allowing this subject-to-subject variability due to unobserved heterogeneity to be absorbed by the random effects and thus keeping them from being absorbed into random error, mixed effects models can provide substantially higher levels of power to detect significant factor effects.

This means that cutting tool manufacturers can cut down the number of repetitions of experiments typically conducted during tool degradation studies under various speed, feed, depth of cut and cutting conditions in order to reduce variations. This can lead to substantial savings in expenses in buying work pieces for experimentation. Also, the mixed effects modeling technique can be used for tool wear modeling in milling which is a complex machining process. The statistical technique can be extended to orthogonal machining also to in order to obtain accurate and better tool wear models.

Levels of speed, feed, depth of cut and cutting conditions that yield the lowest value for cutting force & cutting power, improve surface finish and increase tool life have been recommended for end milling 4340 medium carbon low alloy steel with new advanced PVD TiAlN/TiN multi-layer coated carbide inserts. Specific cutting conditions for obtaining the best surface finish with the longest tool life have also been recommended. This data will be useful to tool and dies manufacturers, machine tool structural parts manufacturers and the automotive industry.

Also, it has been shown through this study that under the cutting conditions selected, tool life was more than doubled during semi-dry versus compared to dry cutting conditions when end milling 4340 medium carbon low alloy steels with PVD TiAlN/TiN multi-layer coated carbide inserts. The nature of wear that occurs at the crater surface of the insert when end milling 4340 steel was determined to be diffusion wear as studied through the X ray EDS analysis. This is also useful information for the users of the insert.

5.3 Recommendations for Future Research

Further work is being proposed in the following areas:

1. Conduct the same experiment at more aggressive machining conditions on a bigger more powerful machine (greater than 15 HP nominal spindle power range) in order to cover a higher cutting speed, feed per tooth, and depth of cut range.

The Okuma vertical machining center (VMC) (Model- ESV-3016) has a 7.5 HP nominal horse power and a CAT 40 tapered shank that is not capable of withstanding cutting forces for feed levels above 0.20 mm/rev and cutting speeds above 330 m/min when machining 4340 alloy steel blocks (26 HRc hardness or higher).

2. Repeat experiment varying the mist parameters, for example, varying the air to coolant ratio.
3. Compare the effect of water based coolants versus that of oil based coolants on tool life, surface finish, cutting power and cutting forces.
4. Insert geometry could be varied to study the effect of different insert types. For example, varying rake angle and changing edge prep conditions (hone or T-land width).

Repeat study on different work piece material and cutting tool combinations during dry and semi-dry machining.

REFERENCES

1. Aizawa, T., Mitsuo, A., Yamamoto, S., Sumitomo, T., and Muraishi, S., “Self-Lubrication Mechanism via the in situ Formed Lubricious Oxide Tribofilm,” Wear, Vol. 259, Issues 1-6, July-Aug 2005, pp.708-718.

2. Alauddin, M., El Baradie, M.A., “Tool Life Model for End Milling Steel (190 BHN),” Journal of Materials Processing Technology, Vol.68, 1997, pp.50-59.

3. Alauddin, M., El Baradie, M.A., Hashmi, M.S.J., “Tool Life Testing in the End Milling of Inconel 718, Journal of Materials Processing Technology”, Vol.55, 1995, pp.321-330.

4. Alauddin, M., Mazid, M.A., El Baradi, M.A., Hashmi, M.S.J., “Cutting Forces in the End Milling of Inconel 718,” Journal of Materials Processing Technology, Vol.77, 1998, pp.153-159.

5. Autret, R., & Liang, S.Y., “Minimum Quantity Lubrication in Finish Hard Turning”, Proceedings of International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment, and Management (HNICEM), March 2003.

6. Bouzakis, K.D., Hadjiyiannis, S., Skordaris, G., Anastopoulos, J., Mirisidis, I., Michailidis, N., Efstathiou, K., Knotek, O., Erkens, G., Cremer, R., Rambadt, S., and Wirth, I, “The Influence of the Coating Thickness on its Strength Properties and on the Milling Performance of PVD Coated Inserts,” Surface and Coatings Technology, Vol.174-175, 2003, pp.393-401.

7. Bray, J.H., & Maxwell, S.E., “Multivariate Analysis of Variance: Quantitative Applications in the Social Sciences”, Second printing, A Sage University Paper, CA, 1986.

8. Bukkapatnam, S.T.S., Kumara, S.R.T., Lakhtakia, A., “Fractal Estimation of Flank Wear in Turning, Transactions of the ASME,” Vol.122, Issue 1, March 2000, pp.89-94.

9. Bull, S.J., Bhatt, D.G., and Staiac, M.H., “Properties and Performance of Commercial TiCN Coatings. Part 1: Coating Architecture and Hardness Modeling,” Surface and Coatings Technology, Vol.163-164, 2003, pp.499-506.

10. Carey, M.B., and Koenig, R.H., “Reliability Assessment Based on Accelerated Degradation: A Case Study,” IEEE Transactions on Reliability, Vol.40, 1991, pp.499-506.

11. D'Errico, G. E., Bugliosi, S., Calzavarini, R., and Cuppini, D., "Wear of Advanced Ceramics for Tool Materials," Wear, Vol. 225-229, Part 1, April 1999, pp.267-272.

12. D'Errico, G. E., Guglielmi, E., and Rutelli, G., "Study of Coatings for End Mills in High Speed Metal Cutting," Journal of Materials Processing Technology, Vol.92-93, Aug 1999, pp.251-256.

13. DeGarmo, E.P., Black, J.T., & Kohser, R.A., "Materials and Processes in Manufacturing," Eight Edition, Prentice Hall, NJ, 1997.

14. Deodhar, J., "Soluble cutting fluids: Chemistry, Management and Control," Proceedings of the International Conference on Industrial Tooling, Southampton, UK, Vol.12-13, Sept.1995, pp.151-158.

15. Derflinger, V., Brandle, H., and Zimmerman,H., "New Hardy Lubricant Coating for Dry Machining," Surface Coating Technology, Vol. 113, 1999, pp.286-292.

16. Dey, S.P., and Deevi, S.C., "Single Layer and Multi-Layer Wear Resistance Coatings of TiAlN: a Review," Material Science Engineering, Vol.A342, 2003, pp.58-79.

17. Doksum, K.A., and Holyland, A., "Models for Variable-Stress Accelerated Life Testing Experiment Based on Weiner Processes and the Inverse Gaussian Distribution," Technometrics, Vol. 34, 1992, pp.74-82.

18. Dos Santos, A.L.B, Duarte, M.A.V., Abrao, A.M., and Machado, A.R., "An Optimization Procedure to Determine the Coefficients of the Extended Taylor's Equation in Machining", International Journal of Machine Tools and Manufacture, Vol.39, 1999, pp.17-31.

19. Ducros, C., Benevent, V., and Sanchette, F., "Deposition, Characterization and Machining Performance of Multilayer PVD Coatings on Cemented Carbide Cutting Tools", Surface and Coatings Technology, Vol.163-164, Jan 2003, pp.681-688.

20. Dudzinski, D., Devillez, A., Moufki, A., Larrouque`re, D., Zerrouki, V., and Vigneau, J., "A Review of Developments Towards Dry and High Speed Machining of Inconel 718 alloy", International Journal of Machine Tools & Manufacture, Vol.44, 2004, pp.439-456.

21. Kountanya, R.K., and Endres, W.J., "Flank Wear of Edge-Radiused Cutting Tools Under Ideal Straight-Edged Orthogonal Conditions," Journal of Manufacturing Science and Engineering, Vol.126, Issue 3, August 2004, pp.496-505.

22. Ezugwu, E. O. and Okeke, C. I., "Tool Life and Wear Mechanisms of TiN Coated Tools in an Intermittent Cutting Operation," Journal of Material Processing Technology, Vol.116, No.1, Oct. 2001, pp.10-15.

23. Fallboehmer, P., Rodriguez, C.A., Ozel, T., Altan, T., “High-speed Machining of Cast Iron and Alloy Steels for Die and Mold Manufacturing,” Journal of Materials Processing Technology, Vol.98, 2000, pp.104-115.

24. Fox, V., Jones, A., Renevier, N.M., Teer, D.G., “Hard Lubricating Coatings for Cutting and Forming Tools and Mechanical Components,” Surface and Coatings Technology, Vol.125, 2000, pp.347-353.

25. French, A. & Poulsen, J., “Multivariate Analysis of Variance (MANOVA),” MANOVA online, 2000.
[http://userwww.sfsu.edu/~efc/classess/biol710/manova/manova.htm]

26. Ghani, J.A., “Application of Taguchi Method in the Optimization of End Milling Parameters,” Journal of Materials Processing Technology, Vol.145, 2004, pp.84-92.

27. Grzesik, W., “The Role of Coatings in Controlling the Cutting Next Term Process when Turning with Coated Indexable Inserts,” Journal of Materials Processing Technology, Vol.79, Issues 1-3, July 1998, pp.133-143.

28 a) Harris, S. G., Doyle, E. D., Vlasveld, A.C., Audy, J., Long, J. M., and Quick, D., “Influence of Chromium Content on the Dry Machining Next Term Performance of Cathodic Arc Evaporated TiAlN Coatings,” Wear, Volume 254, Issues 1-2 , Jan 2003, pp.185-194.

28 b) Harris, S. G., Doyle, E. D., Vlasveld, A. C., Audy, J., and Quick, D., “A Study of the Wear Mechanisms of $Ti_{1-x}Al_xN$ and $Ti_{1-x-y}Al_xCr_yN$ Coated High-speed Steel Twist Drills under Dry Machining Conditions,” Wear, Vol.254, Issues 7-8, April 2003, pp.723-734.

29. Harris, S.G., Doyle, E.D., Vlasveld, A.C., and Dolder, P.J., “Dry Cutting Performance of Partially Filtered Arc Deposited Titanium Aluminum Nitride Coatings with Various Metal Nitride Base Coatings,” Surface Coating Technology, Vol.146-147, 2001, pp.305–311.

30. Harris, S. G., Vlasveld, A. C., Doyle, E. D., and Dolder, P. J., “Dry Machining - Commercial Viability through Filtered Arc Vapour Deposited Coatings,” Surface and Coatings Technology, Vol.133-134, Nov 2000, pp.383-388.

31. Hassan, A., and Yao, Z.K., “Minimum Lubrication Milling of Titanium Alloys,” Material Science Forum, Vol. 471-472, 2004, pp.87-91.

32. Hedenqvist, P., Jacobson, S., Hogmark, S., “Tribological PVD Coatings - Characterization of Mechanical Properties,” Surface and Coatings Technology, 1997, pp.212-217.

33. Heidenreich, E., “Cutting Fluids: a Practical Approach to Productivity,” Cutting Tool Engineering October, 1985, pp.28-33.

34. Huang, Y., Liang, S.Y., “Modeling of CBN Tool Flank Wear Progression in Finish Hard Turning,” Journal of Material Science and Engineering, Vol.126, Feb 2004, pp.98-106.

35. Itakura, K., Kuroda, M., Omokawa, H., Itani, H., Yamamoto, K., Ariura, Y., “Wear Mechanism of Coated Cemented Carbide Tool in Coated Tool in Cutting of Inconel 718 Super-heat Resisting Alloy,” International Journal of Japanese Society for Precision Engineering, Vol.33, No.4, Dec 1999, pp.326–333.

36. Jindal, P. C., Santhanam, A. T., Schleinkofer, U., and Shuster, A. F., “Performance of PVD TiN, TiCN, and TiAlN Coated Cemented Carbide Tools in Turning,” International Journal of Refractory Metals and Hard Materials, Vol.17, Issues 1-3 , May 1999, pp.163-170.

37. Kalidas,S., Richard E. DeVor, R.E., and Kapoor,S.G., “Experimental Investigation of the Effect of Drill Coatings on Hole Quality under Dry and Wet Drilling Conditions,” Surface and Coatings Technology, Vol. 148, Issues 2-3, Dec 2001, pp.117-128.

38. Kathrein, M., Michotte, C., Penoy, M., Polcik, P., and Mitterer, C., “Multifunctional Multi-component PVD Coatings for Cutting Tools,” Surface & Coatings Technology, Vol.200, 2005, pp.1867–1871.

39. Kelly, J. F., and Cotterell, M. G., “Minimal Lubrication Machining of Aluminum Alloys,” Journal of Materials Processing Technology, Vol. 120, Issues 1-3, Jan 2002, pp.327-334.

40. Kim, S.W., Lee, D.W., Kang, M.C., Kim, J.S., “Evaluation of Machinability by Cutting Environments in High Speed Milling of Difficult to Cut Materials,” Journal of Materials Processing Technology, Vol.111, 2001, pp.256-260.

41. Klocke, F., and Eisenblatter, G., “Machinability Investigation of the Drilling Process using Minimal Cooling Lubrication Techniques,” Production Engineering, Vol.4, No.1, 1997, pp.19-24.

42. Koshy, P., Dewes, R.C., Aspinwall, D.K., “High Speed End Milling of Hardened AISI D2 tool steel (~58 HRC),” Journal of Materials Processing Technology, Vol.127, 2002, pp.266-273.

43. Kwam, P. and Bae, S. J., “A Non-linear Random Coefficients Model for Degradation Testing,” Technometrics, Vol.46, No.4, 2004, pp.460-469.

44. Lacalle, L.N.L., Lamikiz, A., Sa´nchez, J.A., Arana, J.L., “Improving the Surface Finish in High Speed Milling of Stamping Dies,” Journal of Materials Processing Technology, Vol.123, 2002, pp.292-302.

45. Laird, N.M., and Ware, J.H., “Random-Effects Models for Longitudinal Data,” Biometrics, Vol.38, 1982, pp.963-974.

46. Lawless, J., Hu, J., and Cao, J., “Methods for the Estimation of Failure Distributions and Rates from Automobile Warranty Data,” Lifetime Data Analysis, Vol.1, 1995, pp.227-240.

47. Lee, C.M., and Hwang, Y.K., “A Study on the Effect of Cutting Conditions on the Surface Roughness in MQL Turning,” The IASTED Conference on Applied Simulation and Modeling, June 2006.

48. List, G., Nouari, M., Géhin, D., Gomez, S., Manaud, J.P., Petitcorps, Y.L., and Girot, F., “Wear Behavior of Cemented Carbide Tools in Dry Machining of Aluminum Alloy,” Wear, Vol. 259, Issues 7-12 , July-Aug 2005, pg.1177-1189.

49. Liu, N., Han, C., Yang, H., Xua,Y., Shia, M., Chaoa, S., and Xie, F., “The Milling Performances of TiC-based Cermet Tools with TiN Nanopowders Addition Against Normalized Medium Carbon Steel AISI1045,” Wear, Vol.258, Issues 11-12 , June 2005, pp.1688-1695.

50. Liu, Z.Q., Ali, X., Zhang, H., Wang, Z.T., and Wan, Y., “Wear Patterns and Mechanisms of Cutting Tools in High Speed Face Milling,” Journal of Materials Processing, 2002, pp.222-226.

51. Machado, A.R., and Wallbank, J., “The Effect of Extremely Low Lubricant Volumes in Machining,” Wear, Vol.210, 1997, pp.76-82.

52. Makiyama, T., “Advanced near dry machining system,” 4rth Annual NCMS Fall Workshop Series, Oct. 2000.

53. Meeker, W.Q., and Escobar, L.A., “Statistical Methods for Reliability Data,” John Wiley and Sons, 1998, New York.

54. Ng, E.G., Aspinwall, D.K., “Modeling of Hard Part Machining,” Journal of Materials Processing Technology, Vol. 127, 2002, pp.222-229.

55. Neter, J., Kutner, M.H., Nachtsheim, C.J., Wasserman, W., “Applied Linear Regression Models,” Third Edition, Irwin Publishers, 1996, pp.98-102.

56. Nouari, M., List, G., Girot, F., and Coupard, D., "Experimental Analysis and Optimization of Tool Wear in Dry Machining of Aluminum Alloys," Wear, Vol. 255, Issues 7-12, Aug-Sept 2003, pp.1359-1368.

57. Onar, A., Thomas, F., Choubane, B., and Byron, T., "Statistical Mixed Effects Models for Evaluation and Predication of Accelerated Pavement Testing Results," Transportation Engineering, Accepted 2005 (to appear).

58. Ozel, T., Altan, T., "Process Simulation using Finite Element Method - Prediction of Cutting Forces, Tool Stresses and Temperatures in High Speed Flat End Milling," International Journal of Machine Tools & Manufacture, Vol.40, 2000, pp.713-738.

59. Navinsek, B., Panjan, P., Cekada, M., Quinto, D.T., "Interface Characterization of Combination Hardy Solid Lubricant Coatings by Specific Methods," Surface and Coatings Technology, Vol.154, 2002, pp.194-203.

60. Ning, Y., Rahman, M., Wong, Y.S., "Investigation of Chip Formation in High Speed End Milling," Journal of Materials Processing Technology, Vol.113, 2001, pp.360-367.

61. Olson, C.L., "On Choosing a Test Statistic in Multivariate Analysis of Variance," Psychological Bulletin, Vol.83, 1976, pp.579-586.

62. Prengel, H.G., Jindal, P.C., Wendt, K.H., Santhanam, A.T., Hegde, P.L., and Penich, R.M., "A New Class of High Performance PVD Coatings for Carbide Cutting Tools," Surface and Coatings Technology, Vol.13, 2001, pp.25-34.

63. Rahman, M., Kumar, A.S., and Salam, M.U., "Experimental Evaluation on the Effect of Minimal Quantities of Lubricant in Milling," International Journal of Machine Tools & Manufacture, Vol.42, 2002, pp.539–547.

64. Rech, J., "Influence of Cutting Edge Preparation on the Wear Resistance in High Speed Dry next Term Gear Hobbing," Wear, Jan 2006 (Article in Press-accepted).

65. Renevier, N.M., Lobiondo, N., Fox, V.C., Teer, D.G., and Hampshire, J., "Performance of MoS2/Metal Composite Coatings used for Dry Machining and other Industrial Applications," Surface and Coatings Technology, Vol.123, 2000, pp.84–91.

66. Santhanam, A.T., Quinto, D.T., & Grab, G.P., "Comparison of the Steel Milling Performance of Carbide Inserts with MTCVD and PVD TiCN Coatings," International Journal of Refractory Metal & Hard Materials, Vol. 14, 1996, pp.31-40.

67. Schramm, B.C., Scheerer, H., Hoche, H., Broszeit, E., Abelea, E., and Bergerb,C., "Tribological Properties and Dry Machining Characteristics of PVD-Coated Carbide Inserts," Surface and Coating Technology, Vol. 188-189, 2004, pp.623– 629.

68. Schulz, H., Moriwaki, T., "High-Speed Machining," Annals of the CIRP, Vol.41, No.2, 1992, pp.637-643.

69. Shao, H., Wang, H.L., and Zhao, X.M., "A Cutting Power Model for Tool Wear Monitoring in Milling," International Journal of Machine Tools and Manufacture Vol.44, Issue 14, Nov 2004, pp.1503-1509.

70. Sharma, S., "Applied Multivariate Techniques," First edition, John Wiley & Sons, NY, 1996.

71. Sharman, A., Dewes, R.C., and Aspinwall, D.K., "Tool life when High Speed Ball Nose End Milling Inconel 718," Journal of Materials Processing Technology, Vol.118, Issues 1-3, Dec 2001, pp. 29-35.

72. Smith, G.T., "Cutting Tool Technology," Advanced Machining; The Handbook of Cutting Technology", 1989, pp.9.

73. Smith, I.J., Gillibrand, D., Brooks, J.S., Münz, W.D., Harvey, S., and Goodwin, R., "Dry Cutting Performance of HSS Twist Drills Coated with Improved TiAlN," Surface Coating Technology, Vol.90, 1997, pp.164-171.

74. Su, Y., He, N., Li, L., and Li, X.L., "An Experimental Investigation of Effects of Cooling/Lubrication Conditions on Tool Wear in High-speed End Milling of Ti-6Al-4V," Wear, Feb 2006 (Article in Press).

75. Sunkhapong, A., "Effects of some Machining Variables on Tool Wear, Surface Finish, Dimensional Error, and Cutting Power in Turning Gray Cast Iron using CBN and Ceramic Tools," Dissertation, University of Miami, 2000.

76. Trent, E.M., Metal Cutting, 3rd Edition, Butterworth Heinmann, London, 1991.

77. Verbeke, G., and Molenberghs, G., "Linear Mixed Models on Longitudinal Data with Application to SAS," 1999, pp.1-485.

78. Vieira, J. M., Machado, A. R., and Ezugwu, E. O., "Performance of Cutting Fluids during Face Milling of Steels," Journal of Materials Processing Technology Vol.116, No.2, Oct 2001, pp.244-251.

79. Wakabayashi, T., Sato, H., Inasaki, I., "Turning Using Extremely Small Amounts of Cutting Fluids," JSME International Journal, Series C 41 (1), 1998, pp.143-148.

80. Zelinski, P., "The Cost Impact of Coated Tools," Modern Machine Shop, May 2003 [http://www.findarticles.com/p/articles/mi_m3101/is_12_75/ai_101533065]

81. Zheng, H.Q., Li, X.P., Wong, Y.S., Nee, A.Y.C., "Theoretical Modeling and Simulation of Cutting Forces in Face Milling with Cutter Run Out," International Journal of Machine Tools & Manufacture, Vol.39, 1999, pp.2003-2018.

82. "4340 Alloy Steel Material Property Data Sheet", Metal Suppliers Online, March 2006. [http://www.suppliersonline.com/propertypages/4340.asp]

83. "Artis GmbH, Visualization & Diagnostic System (ViDi)," ViDi User's Guide for STM and MTC systems for ViDi version V3.01, 1997.

84. "Box Cox Transformation," [http://www-stat.stanford.edu/~olshen/manuscripts/selenite/node6.html]

85. "Dry Up," Seco Carboloy Online Article, [http://www.secotools.com/template/start.asp?id=6652]

86. European Commission - Research: Industrial technologies - Cutting Edge Technology, Sept 2005. [http://europa.eu.int/comm/research/industrial_technologies/impacts/article_3020_en.html]

87. http://www.corrosion-doctors.org/MetalCoatings/chemical.htm

88. Kennametal Milling Tooling Catalog 3050, 2005, pp. M20

89. Metalworking Fluids, Safety and Health Best Practices Manual, 1999.

90. Metal Working: Safety and Health Best Practices Manual, U.S. Department of Labor, Occupational Safety & Health Administration, 1998.

91. "Robust Box-Cox Response Transformations based on Optimal Prediction," [http://www.stat.uiuc.edu/icors04/abstracts/Alfio%20Marazzi%20abstract.pdf]

92. "Surface Coating by Physical Vapor Deposition," [http://p2library.nfesc.navy.mil/P2_Opportunity_Handbook/1_5.html]

93. "Using Cermets to Make Brazed Tools," Northwest Research Institute, Inc. / Carbide Processors, Inc., 1998. [http://www.carbideprocessors.com/Brazing/book/40.htm]

94. "Tool Life Testing in Milling- Part 2: End milling," International Standard, Reference number - ISO 8688-2: 1989 (E).

95. “What You Need to Know About Occupational Exposure to Metal Working Fluids,” National Institute for Occupational Safety and Health, March 1998.

APPENDIX A

Plots of Residuals and Anderson Darling test for Normality for all Dependant Variables

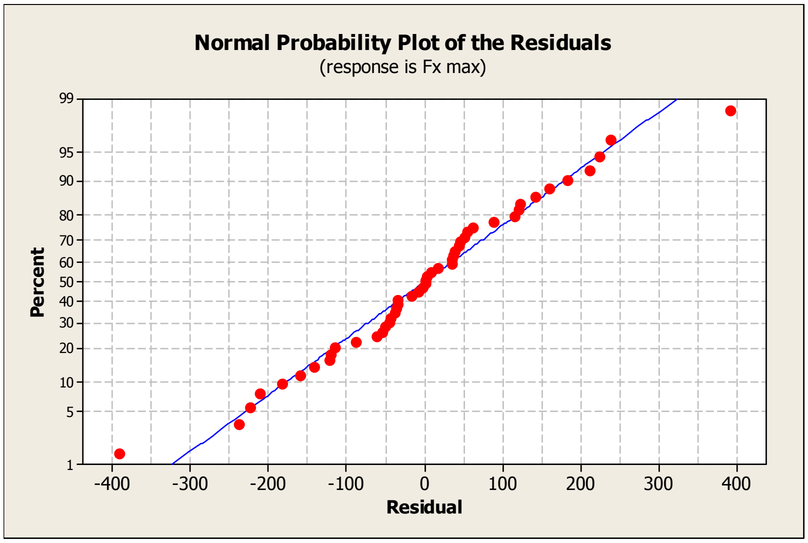


Figure A-1 Residual versus fitted values for $F_{x\ max}$

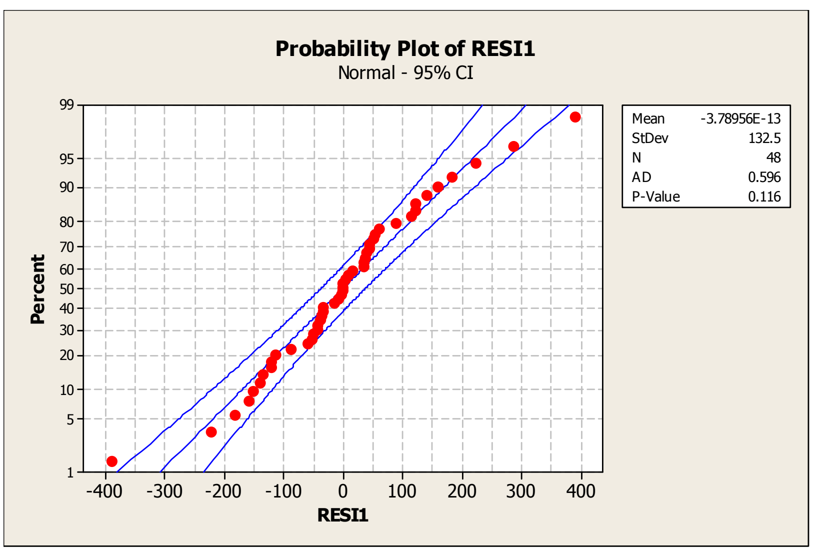


Figure A-2 Anderson Darling test for normality for $F_{x\ max}$ residual

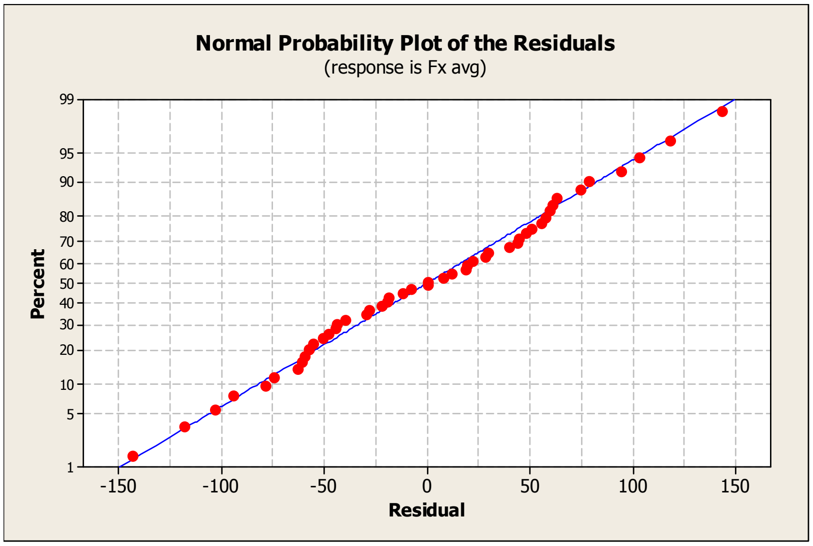


Figure A-3 Residual versus fitted values for $F_{x\ avg}$

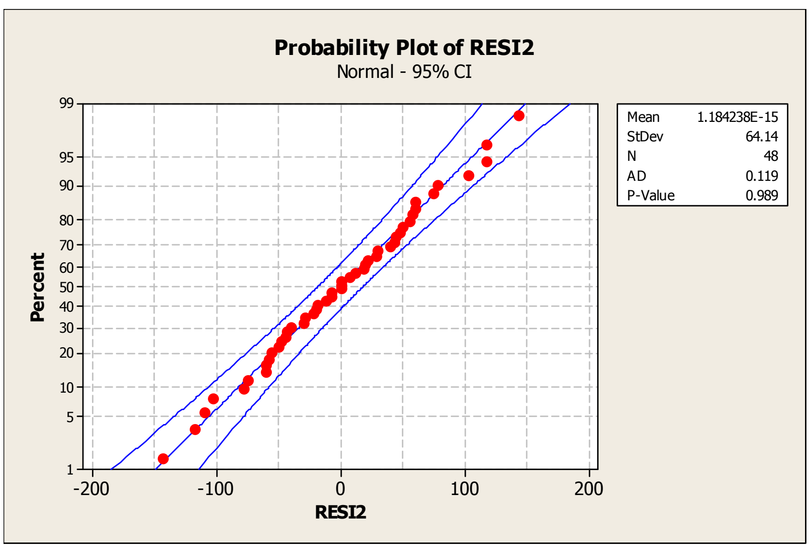


Figure A-4 Anderson Darling test for normality for $F_{x\ avg}$ residual

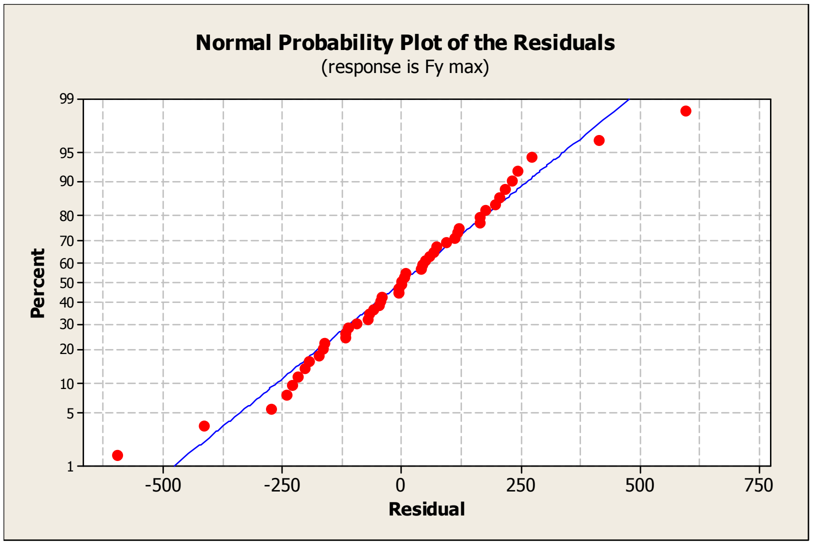


Figure A-5 Residual versus fitted values for $F_{y\ max}$

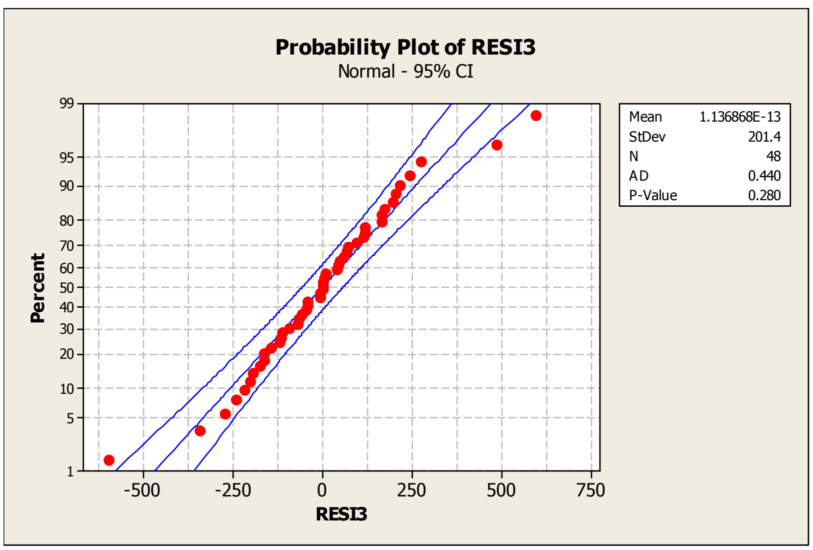


Figure A-6 Anderson Darling test for normality for $F_{y\ max}$ residual

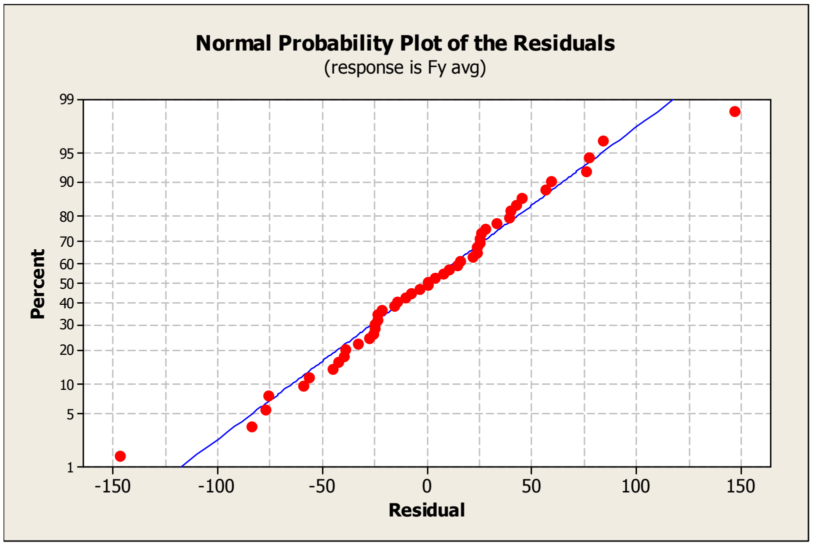


Figure A-7 Residual versus fitted values for $F_{y\ avg}$

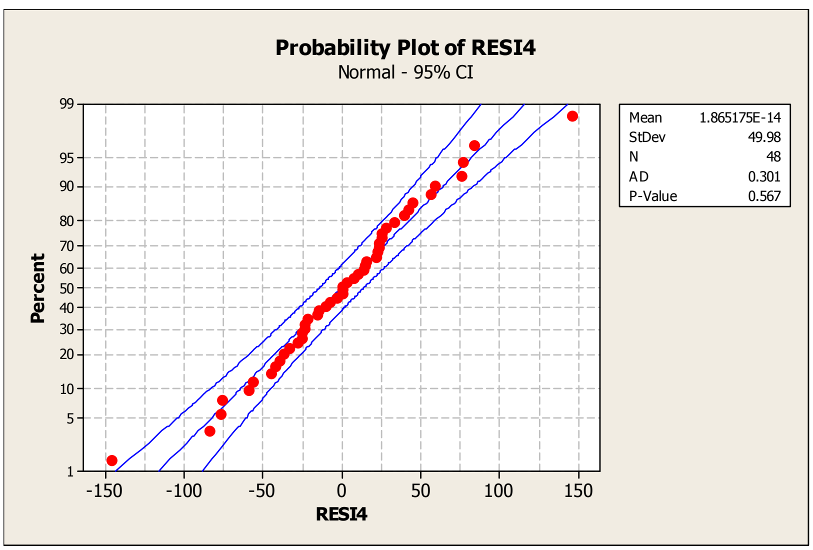


Figure A-8 Anderson Darling test for normality for $F_{y\ avg}$ residual

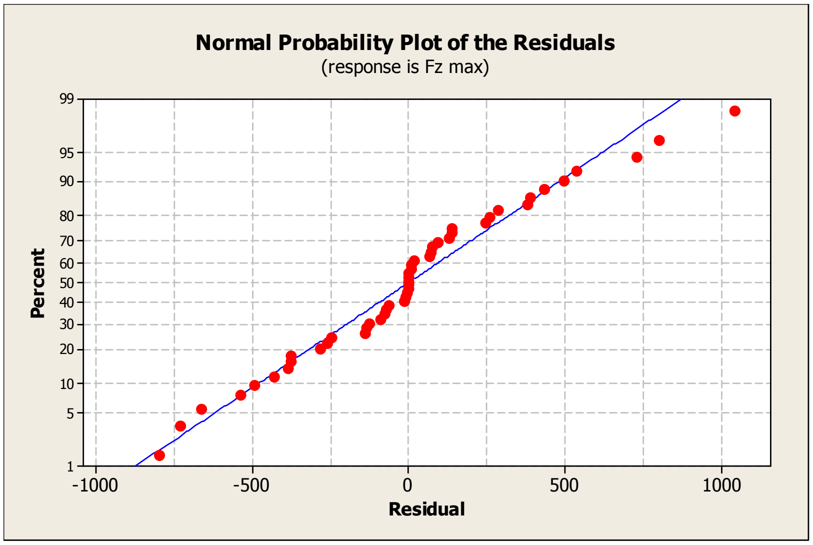


Figure A-9 Residual versus fitted values for $F_{z\ max}$

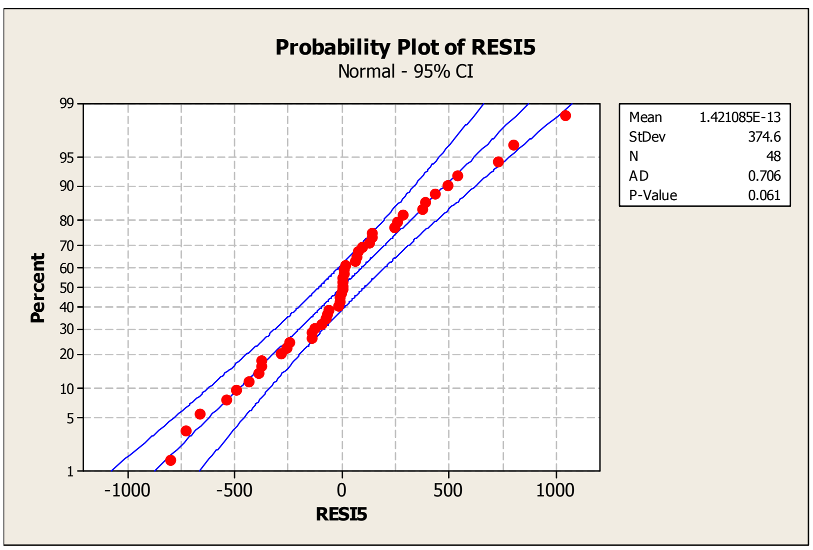


Figure A-10 Anderson Darling test for normality for $F_{z\ max}$ residual

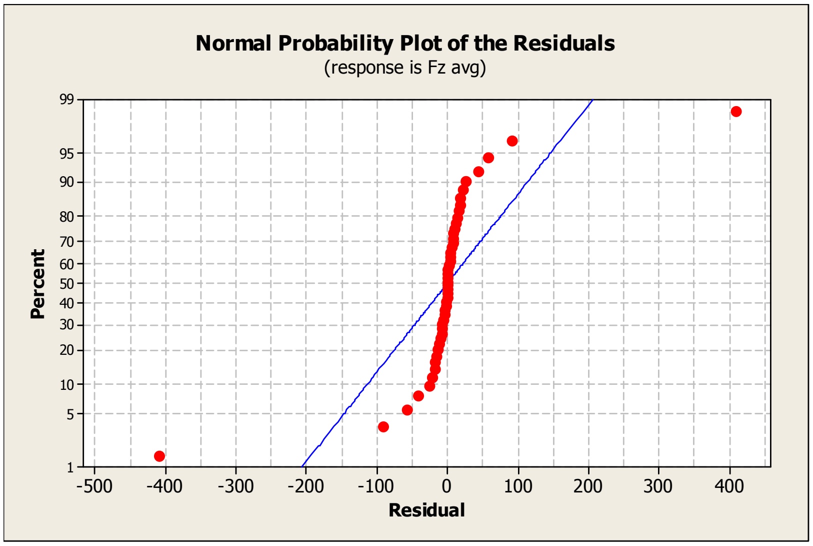


Figure A-11 Residual versus fitted values for $F_{z\ avg}$ (before transformation)

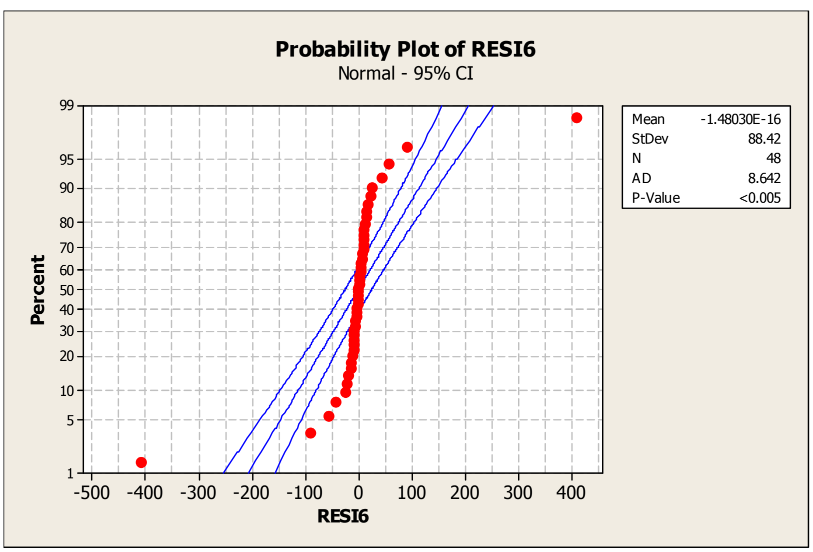


Figure A-12 Anderson Darling test for normality for $F_{z\ avg}$ (before transformation)

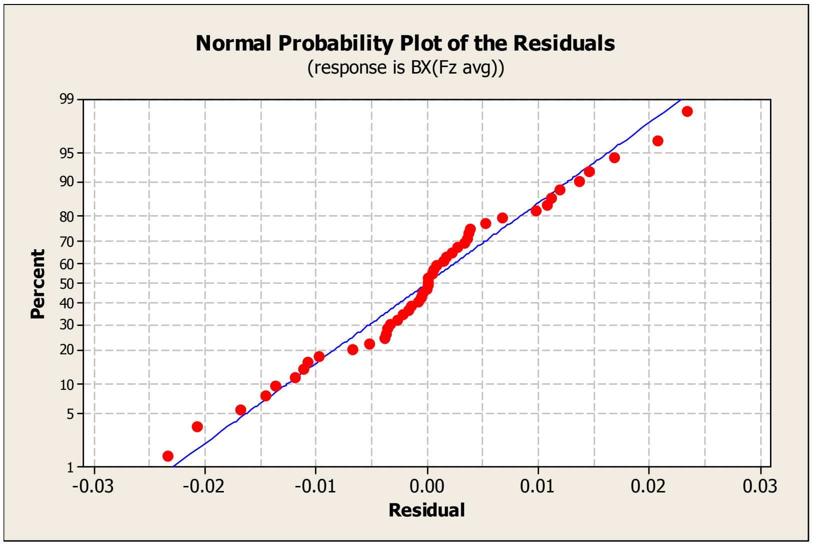


Figure A-13 Residual versus fitted values for $F_{z\ avg}$ (after Box Cox transformation - $1/\sqrt{F_{z\ avg}}$)

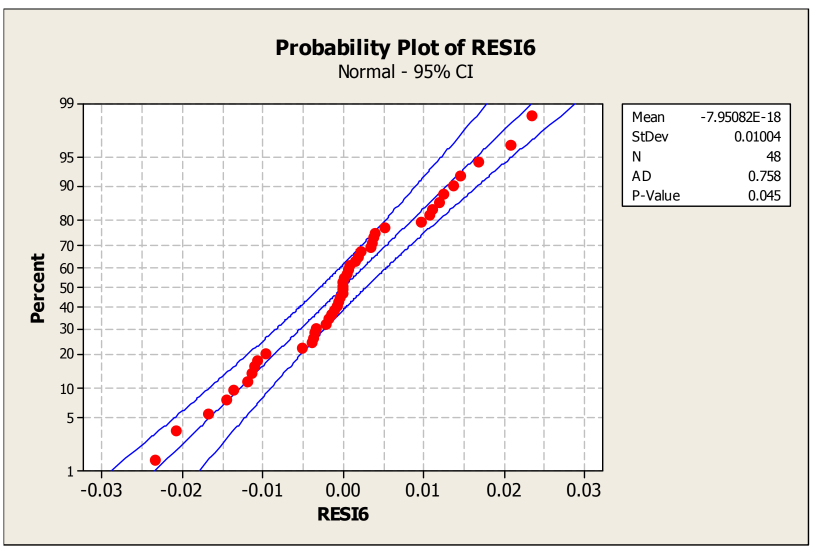


Figure A-14 Anderson Darling test for normality for $F_{z\ avg}$ (after transformation)

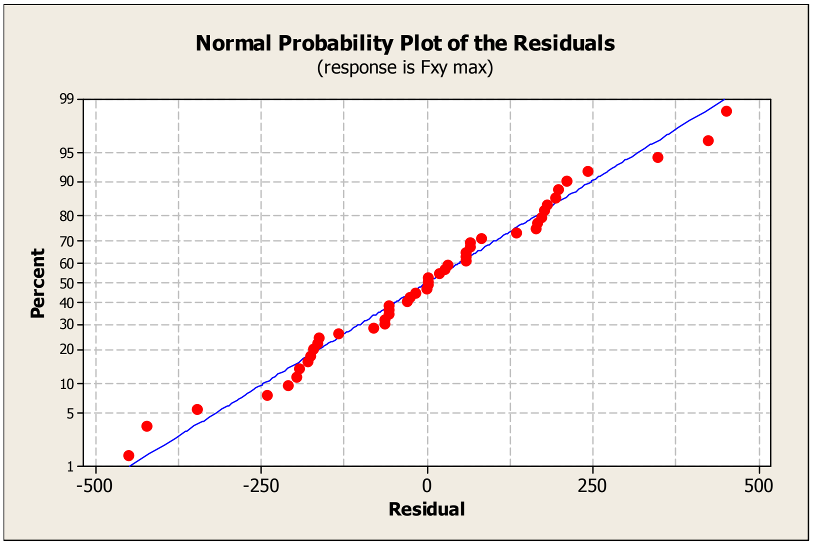


Figure A-15 Residual versus fitted values for $F_{xy\ max}$

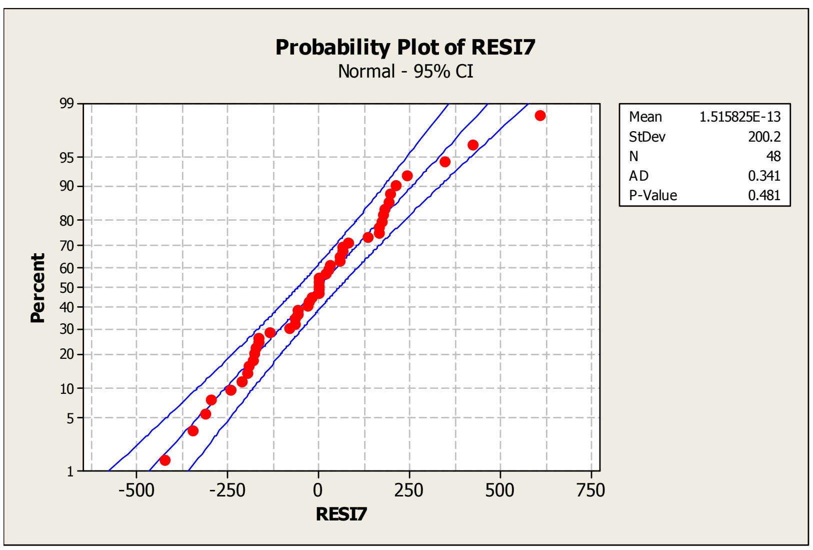


Figure A-16 Anderson Darling test for normality for $F_{xy\ max}$

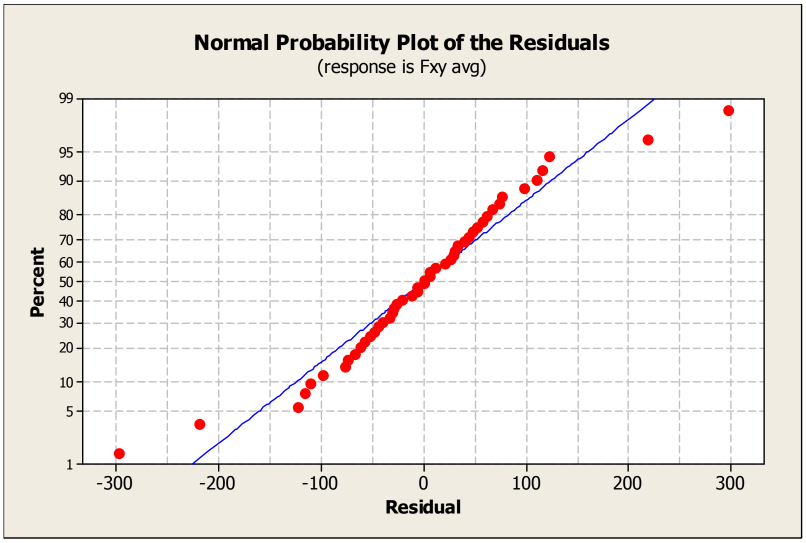


Figure A-17 Residual versus fitted values for $F_{xy\ avg}$

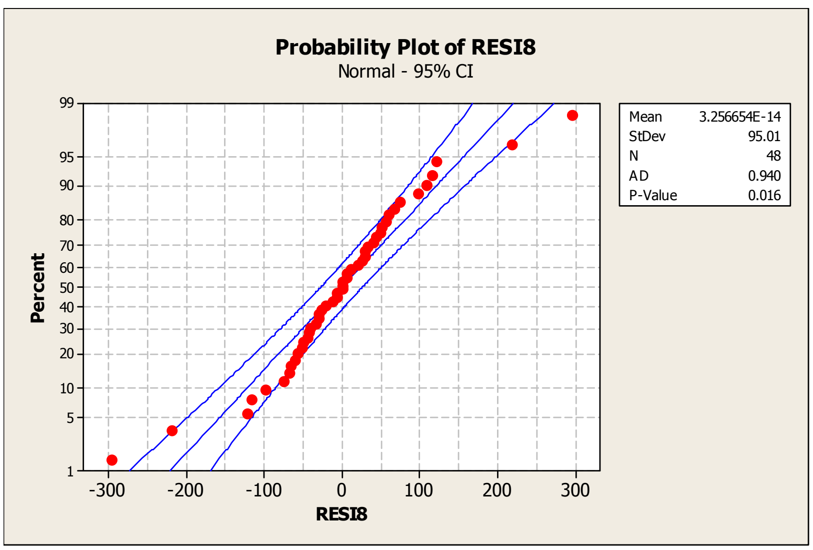


Figure A-18 Anderson Darling test for normality for $F_{xy\ avg}$

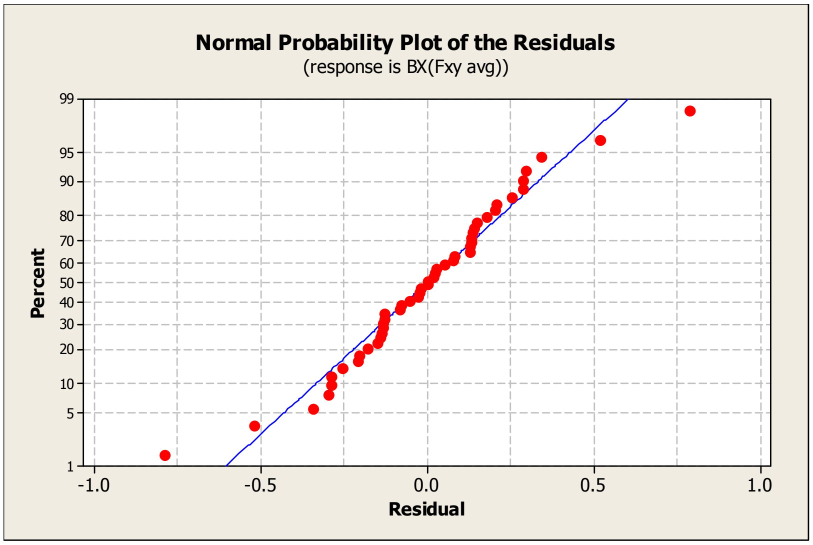


Figure A-19 Residual versus fitted value plot for $F_{xy\ avg}$ (after Box Cox transformation – Log_e ($F_{xy\ avg}$)

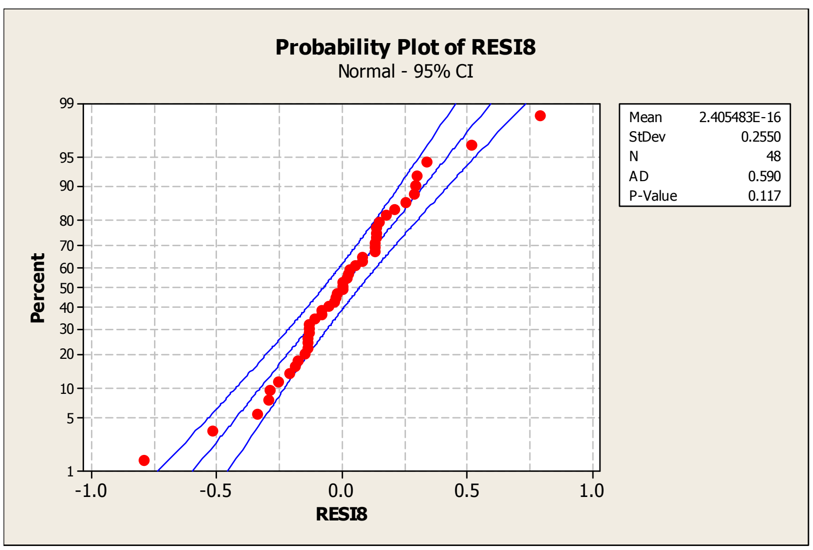


Figure A-20 Anderson Darling test for normality for $F_{xy\ avg}$ (after transformation)

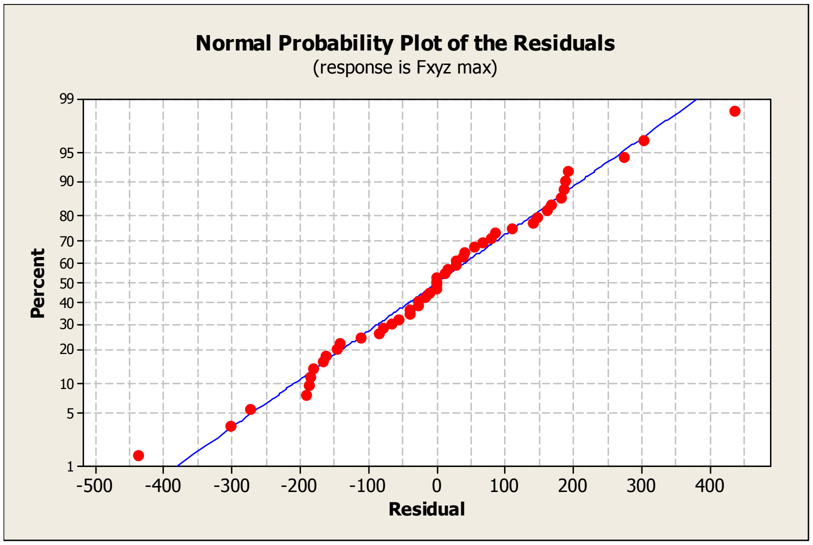


Figure A-21 Residual versus fitted value plot for $F_{xyz\ max}$

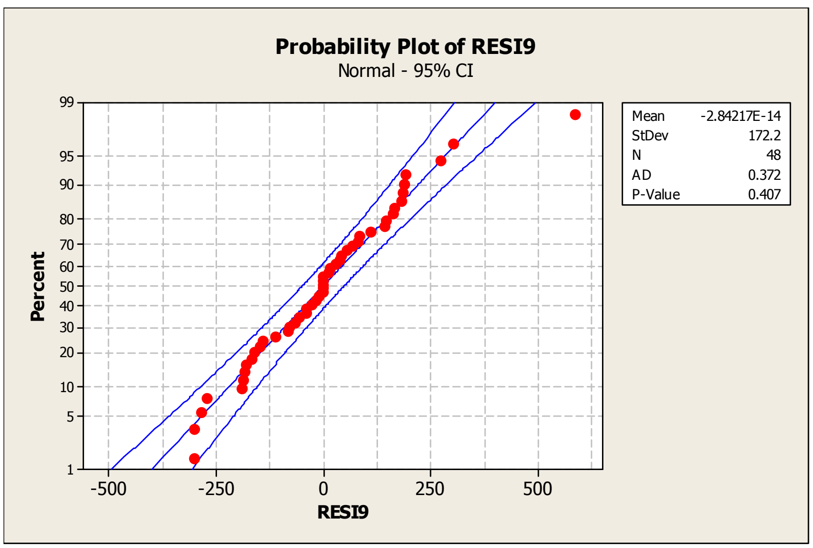


Figure A-22 Anderson Darling test for normality for $F_{xyz\ max}$

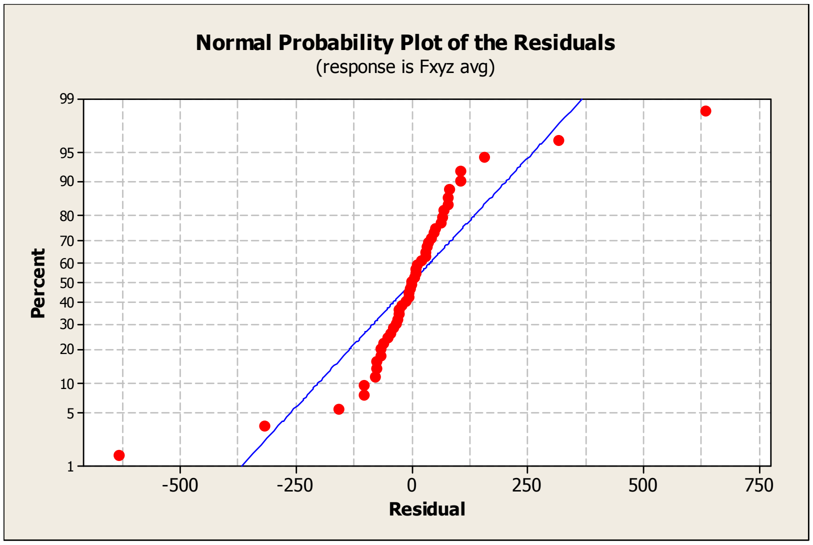


Figure A-23 Residual versus fitted value plot for $F_{xyz\ avg}$

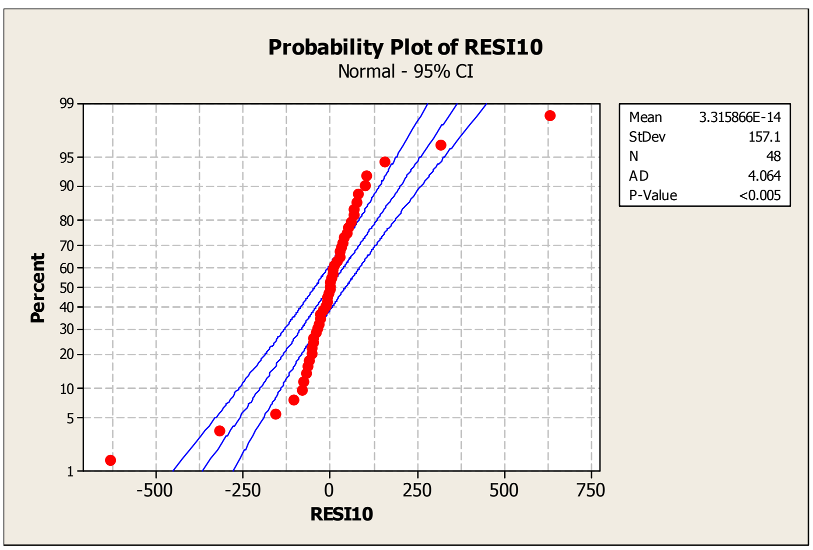


Figure A-24 Anderson Darling test for normality for $F_{xyz\ avg}$

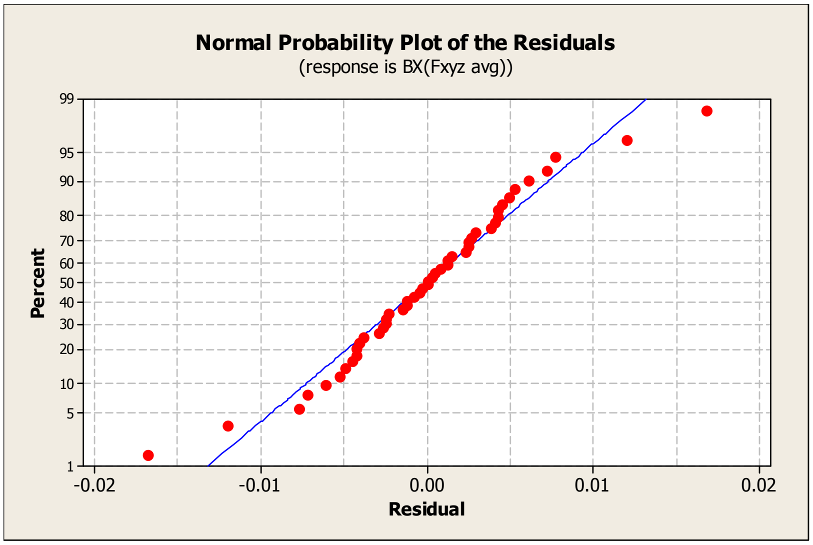


Figure A-25 Residual versus fitted value plot for $F_{xyz\ avg}$ (after Box Cox transformation – $1/\sqrt{F_{xyz\ avg}}$)

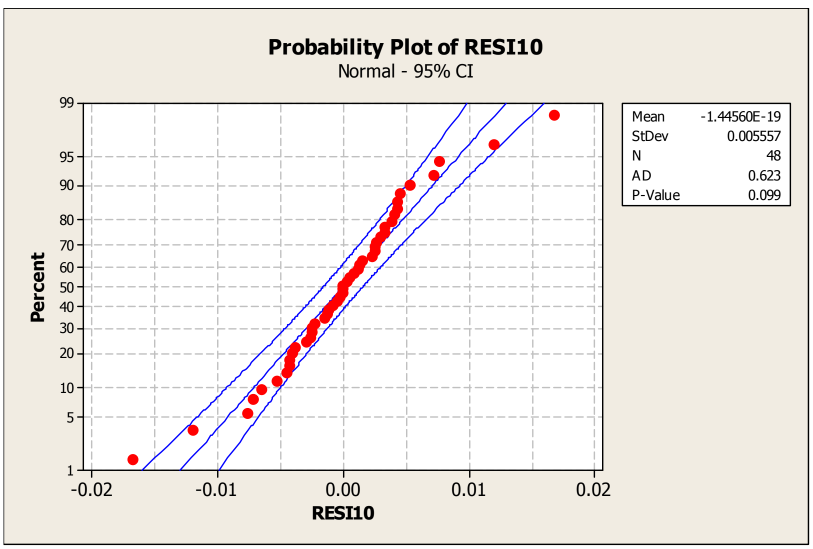


Figure A-26 Anderson Darling test for normality for $F_{xyz\ avg}$ (after transformation)

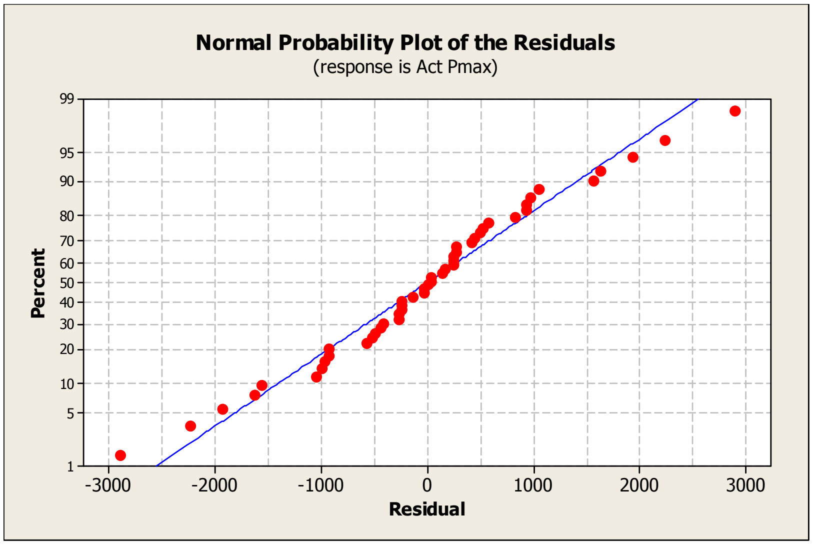


Figure A-27 Residual versus fitted value plot for P_{max}

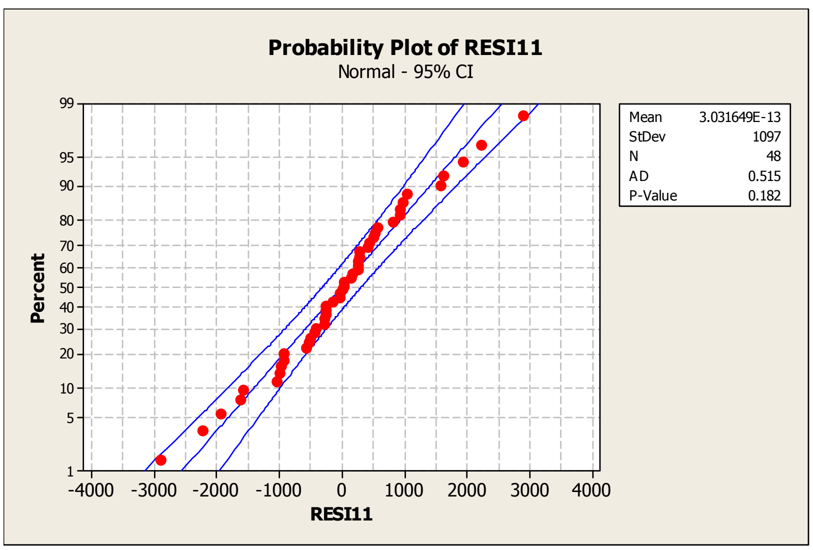


Figure A-28 Anderson Darling test for normality for P_{max}

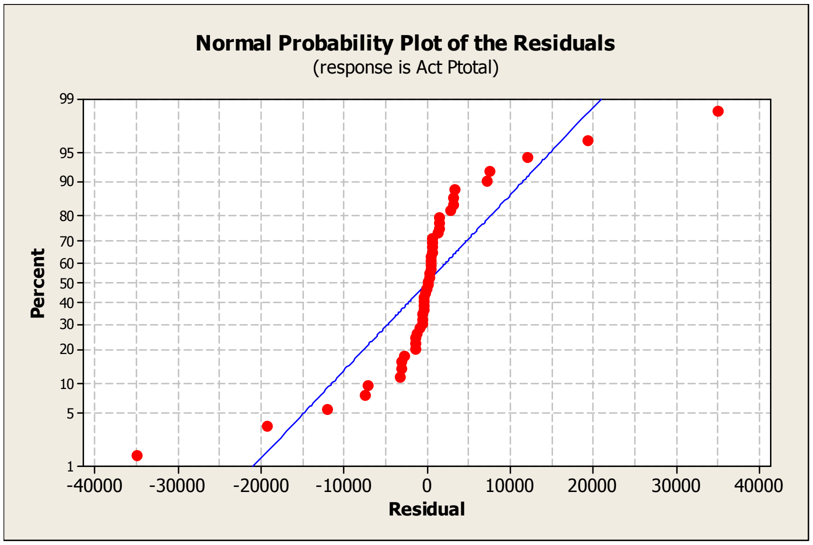


Figure A-29 Residual versus fitted value plot for P_{total}

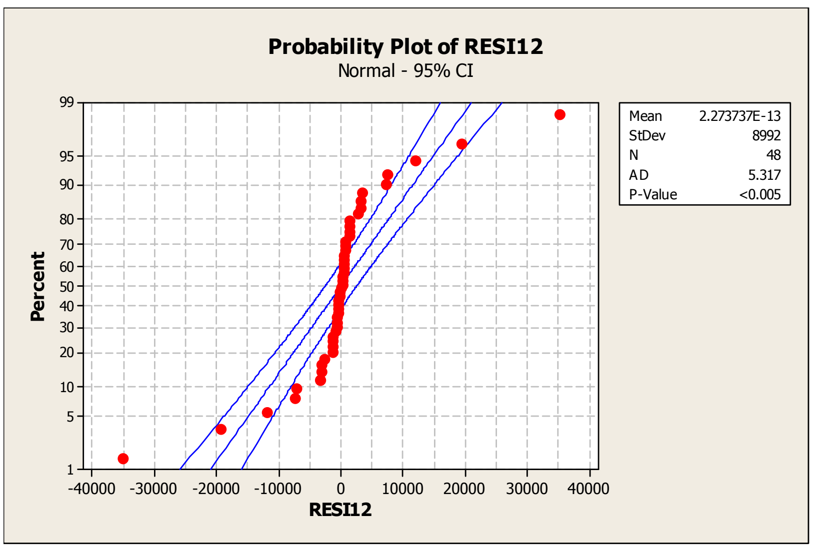


Figure A-30 Anderson Darling test for normality for P_{total}

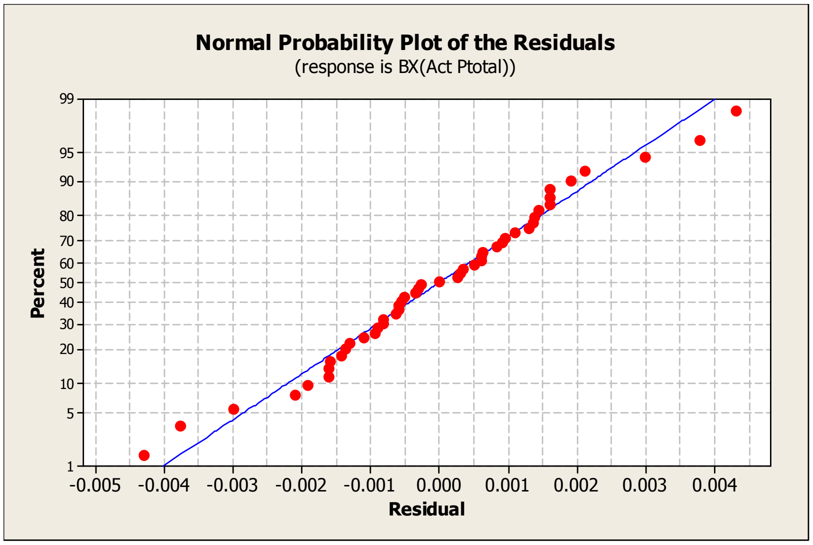


Figure A-31 Residual versus fitted value plot for P_{total} (after Box Cox transformation – $1/\sqrt{P_{total}}$)

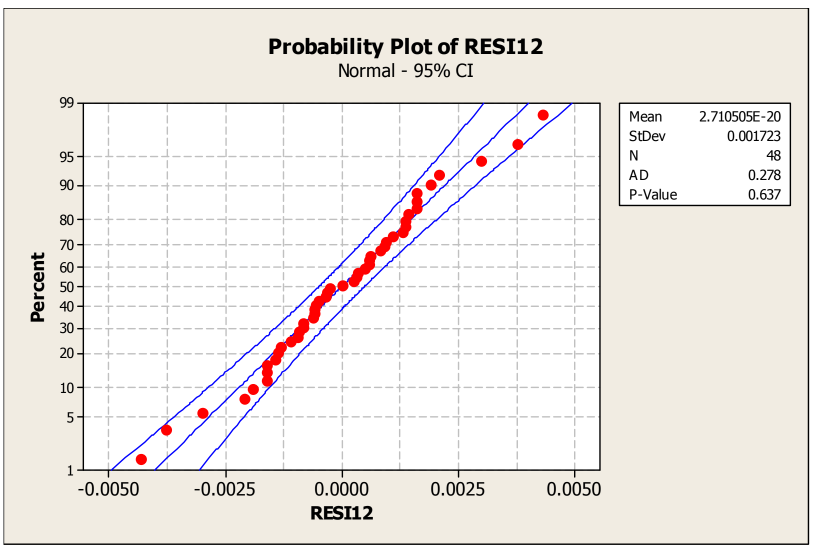


Figure A-32 Anderson Darling test for normality for P_{total} (after transformation)

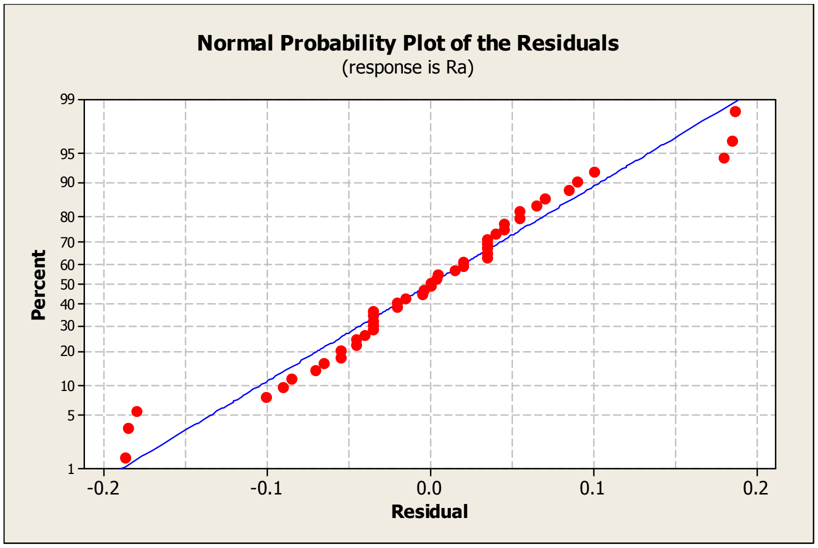


Figure A-33 Residual versus fitted value plot for surface roughness, R*a*

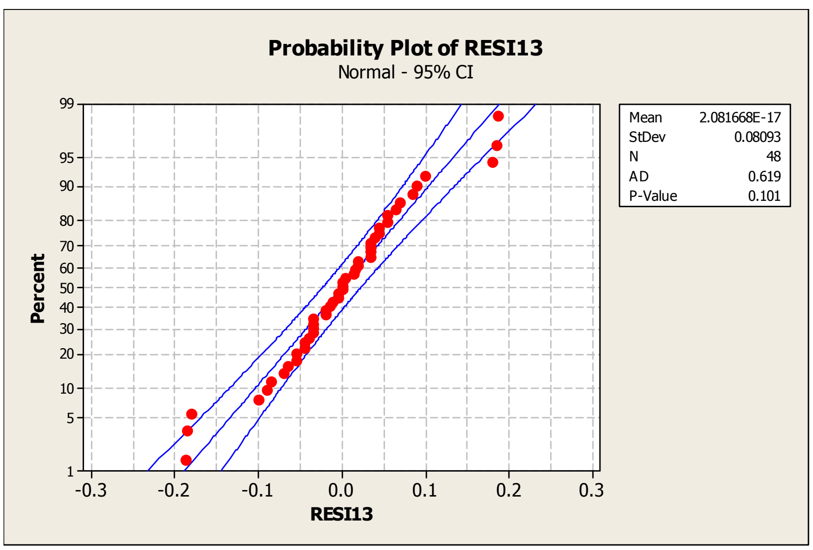


Figure A-34 Anderson Darling test for normality for surface roughness, R*a*

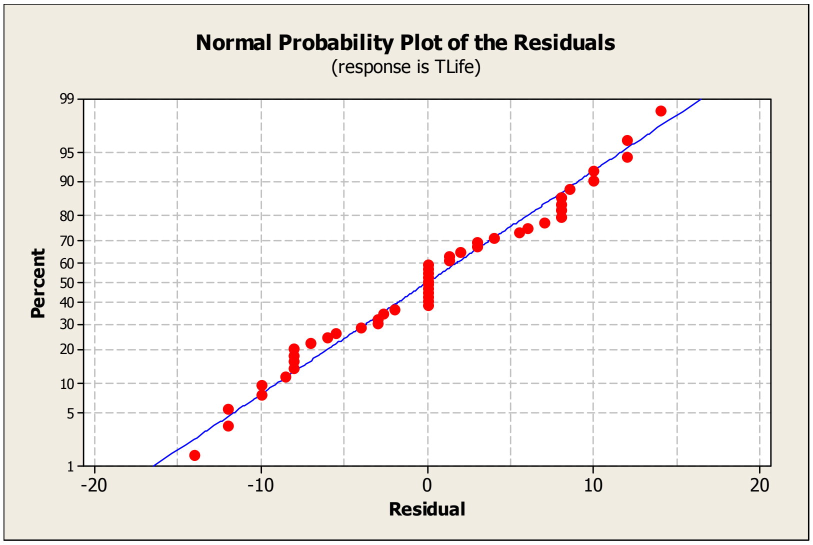


Figure A-35 Residual versus fitted value plot for T*life*

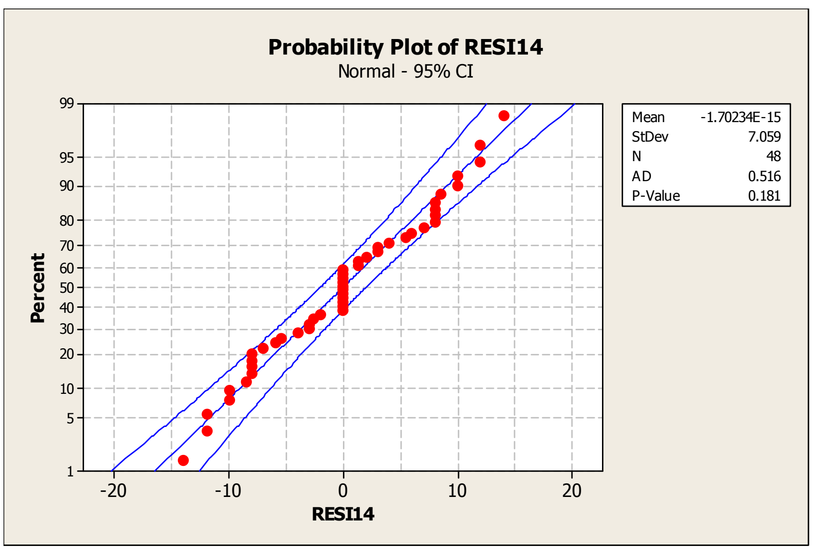


Figure A-36 Anderson Darling test for normality for T*life*

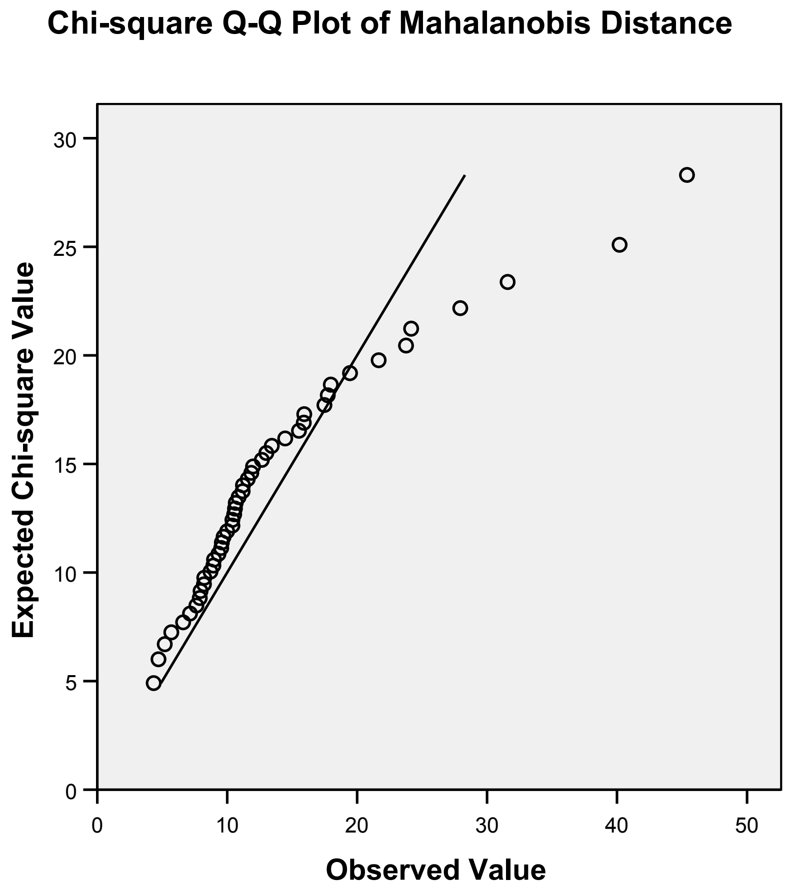


Figure A-37 Chi-Square plot of Mahalanobis distance for multivariate normality testing (before transforming data)

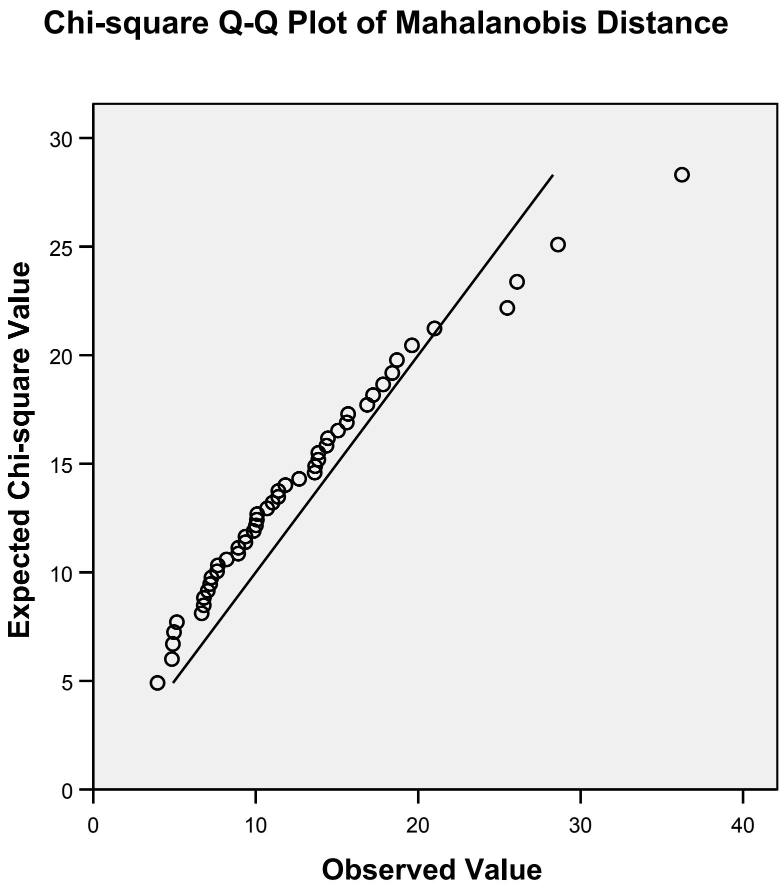


Figure A-38 Chi-Square plot of Mahalanobis distance for multivariate normality testing (after data transform)

APPENDIX B

Data Sample for Tool Life Model

Table B-1 Data used to generate regression equation for T_{life}

Speed	Feed	DOC	Condition	Tlife	Log(Tlife)	Log(S)	Log(F)	Log(D)
183	0.1	2.54	1	52.0	1.72	2.26	-1.00	0.40
183	0.1	2.54	1	52.0	1.72	2.26	-1.00	0.40
183	0.15	2.54	1	29.5	1.47	2.26	-0.82	0.40
183	0.15	2.54	1	34.7	1.54	2.26	-0.82	0.40
183	0.2	2.54	1	18.2	1.26	2.26	-0.70	0.40
183	0.2	2.54	1	17.2	1.24	2.26	-0.70	0.40
183	0.1	3.81	1	34.4	1.54	2.26	-1.00	0.58
183	0.1	3.81	1	44.2	1.65	2.26	-1.00	0.58
183	0.15	3.81	1	24.9	1.40	2.26	-0.82	0.58
183	0.15	3.81	1	29.5	1.47	2.26	-0.82	0.58
183	0.2	3.81	1	18.2	1.26	2.26	-0.70	0.58
183	0.2	3.81	1	12.3	1.09	2.26	-0.70	0.58
229	0.1	2.54	1	14.9	1.17	2.36	-1.00	0.40
229	0.1	2.54	1	21.2	1.33	2.36	-1.00	0.40
229	0.15	2.54	1	14.1	1.15	2.36	-0.82	0.40
229	0.15	2.54	1	8.9	0.95	2.36	-0.82	0.40
229	0.2	2.54	1	5.1	0.71	2.36	-0.70	0.40
229	0.2	2.54	1	5.1	0.71	2.36	-0.70	0.40
229	0.1	3.81	1	32.2	1.51	2.36	-1.00	0.58
229	0.1	3.81	1	25.9	1.41	2.36	-1.00	0.58
229	0.15	3.81	1	11.0	1.04	2.36	-0.82	0.58
229	0.15	3.81	1	11.0	1.04	2.36	-0.82	0.58
229	0.2	3.81	1	4.1	0.62	2.36	-0.70	0.58
229	0.2	3.81	1	3.5	0.55	2.36	-0.70	0.58
183	0.1	2.54	2	44.2	1.65	2.26	-1.00	0.40
183	0.1	2.54	2	57.9	1.76	2.26	-1.00	0.40
183	0.15	2.54	2	19.0	1.28	2.26	-0.82	0.40
183	0.15	2.54	2	24.2	1.38	2.26	-0.82	0.40
183	0.2	2.54	2	8.6	0.93	2.26	-0.70	0.40
183	0.2	2.54	2	11.3	1.05	2.26	-0.70	0.40
183	0.1	3.81	2	44.2	1.65	2.26	-1.00	0.58
183	0.1	3.81	2	44.2	1.65	2.26	-1.00	0.58
183	0.15	3.81	2	15.1	1.18	2.26	-0.82	0.58
183	0.15	3.81	2	17.0	1.23	2.26	-0.82	0.58
183	0.2	3.81	2	12.3	1.09	2.26	-0.70	0.58
183	0.2	3.81	2	9.3	0.97	2.26	-0.70	0.58
229	0.1	2.54	2	14.9	1.17	2.36	-1.00	0.40
229	0.1	2.54	2	24.3	1.39	2.36	-1.00	0.40
229	0.15	2.54	2	7.3	0.87	2.36	-0.82	0.40
229	0.15	2.54	2	5.8	0.76	2.36	-0.82	0.40
229	0.2	2.54	2	4.3	0.64	2.36	-0.70	0.40
229	0.2	2.54	2	5.9	0.77	2.36	-0.70	0.40
229	0.1	3.81	2	7.1	0.85	2.36	-1.00	0.58
229	0.1	3.81	2	13.7	1.14	2.36	-1.00	0.58
229	0.15	3.81	2	7.9	0.90	2.36	-0.82	0.58
229	0.15	3.81	2	7.9	0.90	2.36	-0.82	0.58
229	0.2	3.81	2	3.5	0.55	2.36	-0.70	0.58
229	0.2	3.81	2	2.7	0.44	2.36	-0.70	0.58

Table B-1 Data used to generate regression equation for T_{life} (contd.)

C1	C2	C1*Log(S)	C2*Log(S)	C1*Log(F)	C2*Log(F)	C1*Log(D)	C2*Log(D)
1	0	2.26	0.00	-1.00	0.00	0.40	0.00
1	0	2.26	0.00	-1.00	0.00	0.40	0.00
1	0	2.26	0.00	-0.82	0.00	0.40	0.00
1	0	2.26	0.00	-0.82	0.00	0.40	0.00
1	0	2.26	0.00	-0.70	0.00	0.40	0.00
1	0	2.26	0.00	-0.70	0.00	0.40	0.00
1	0	2.26	0.00	-1.00	0.00	0.58	0.00
1	0	2.26	0.00	-1.00	0.00	0.58	0.00
1	0	2.26	0.00	-0.82	0.00	0.58	0.00
1	0	2.26	0.00	-0.82	0.00	0.58	0.00
1	0	2.26	0.00	-0.70	0.00	0.58	0.00
1	0	2.26	0.00	-0.70	0.00	0.58	0.00
1	0	2.36	0.00	-1.00	0.00	0.40	0.00
1	0	2.36	0.00	-1.00	0.00	0.40	0.00
1	0	2.36	0.00	-0.82	0.00	0.40	0.00
1	0	2.36	0.00	-0.82	0.00	0.40	0.00
1	0	2.36	0.00	-0.70	0.00	0.40	0.00
1	0	2.36	0.00	-0.70	0.00	0.40	0.00
1	0	2.36	0.00	-1.00	0.00	0.58	0.00
1	0	2.36	0.00	-1.00	0.00	0.58	0.00
1	0	2.36	0.00	-0.82	0.00	0.58	0.00
1	0	2.36	0.00	-0.82	0.00	0.58	0.00
1	0	2.36	0.00	-0.70	0.00	0.58	0.00
1	0	2.36	0.00	-0.70	0.00	0.58	0.00
0	1	0.00	2.26	0.00	-1.00	0.00	0.40
0	1	0.00	2.26	0.00	-1.00	0.00	0.40
0	1	0.00	2.26	0.00	-0.82	0.00	0.40
0	1	0.00	2.26	0.00	-0.82	0.00	0.40
0	1	0.00	2.26	0.00	-0.70	0.00	0.40
0	1	0.00	2.26	0.00	-0.70	0.00	0.40
0	1	0.00	2.26	0.00	-1.00	0.00	0.58
0	1	0.00	2.26	0.00	-1.00	0.00	0.58
0	1	0.00	2.26	0.00	-0.82	0.00	0.58
0	1	0.00	2.26	0.00	-0.82	0.00	0.58
0	1	0.00	2.26	0.00	-0.70	0.00	0.58
0	1	0.00	2.26	0.00	-0.70	0.00	0.58
0	1	0.00	2.36	0.00	-1.00	0.00	0.40
0	1	0.00	2.36	0.00	-1.00	0.00	0.40
0	1	0.00	2.36	0.00	-0.82	0.00	0.40
0	1	0.00	2.36	0.00	-0.82	0.00	0.40
0	1	0.00	2.36	0.00	-0.70	0.00	0.40
0	1	0.00	2.36	0.00	-0.70	0.00	0.40
0	1	0.00	2.36	0.00	-1.00	0.00	0.58
0	1	0.00	2.36	0.00	-1.00	0.00	0.58
0	1	0.00	2.36	0.00	-0.82	0.00	0.58
0	1	0.00	2.36	0.00	-0.82	0.00	0.58
0	1	0.00	2.36	0.00	-0.70	0.00	0.58
0	1	0.00	2.36	0.00	-0.70	0.00	0.58

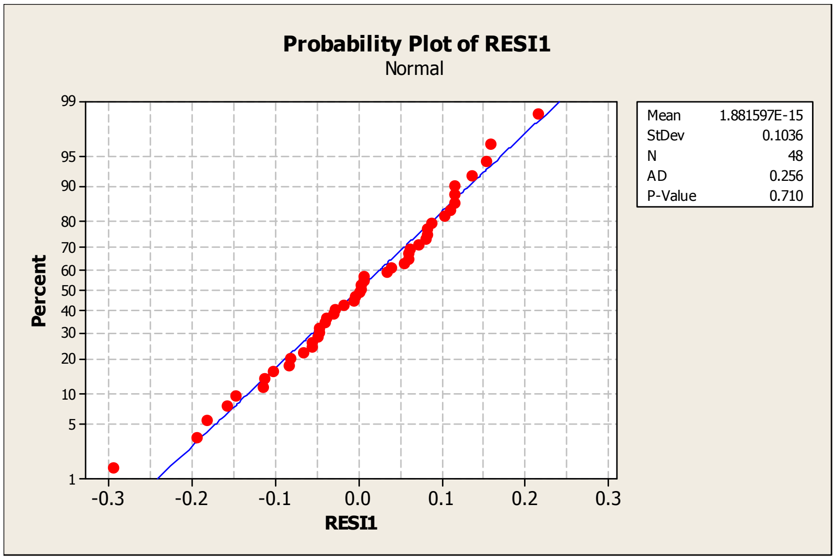


Figure B-1 Normal probability plot for residuals for tool life regression model

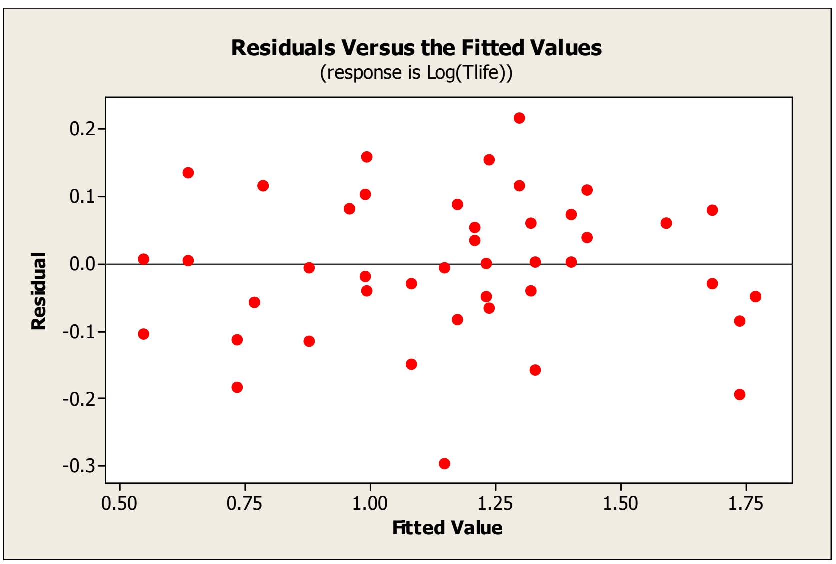


Figure B-2 Residual versus fitted plot for tool life regression model

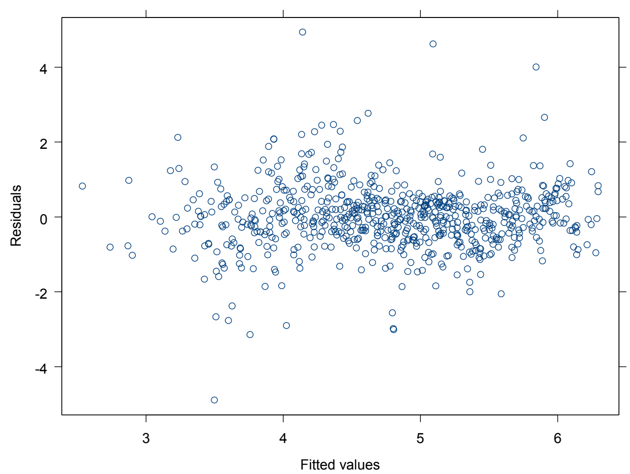
APPENDIX C

S Plus and Minitab Output for Mixed Effects Model

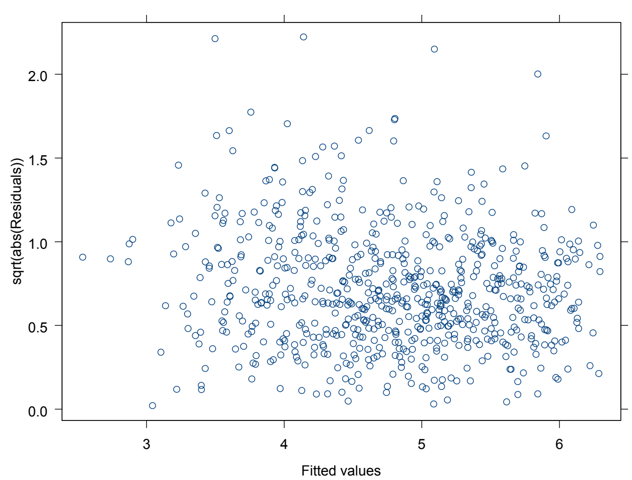
Model 4-13

Random effects:
Formula: ~ CutNo + CutNo^2 + CutNo^3 | Block

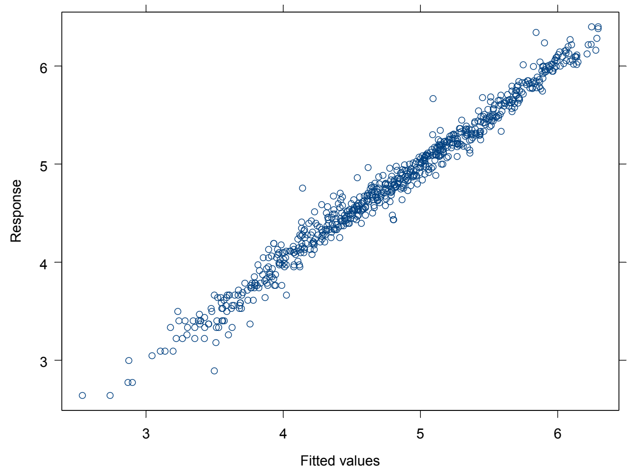
Fixed effects: LnWear = SpeedI + Feeed0.15 + ConditionI + Feed0.2 + CutNo + CutNo^2 + CutNo^3 + SpeedI x Feed0.15 + SpeedI x ConditionI + Feed0.15 x ConditionI + SpeedI x Feed0.2 + Feed0.2 x ConditionI + SpeedI x CutNo + SpeedI x CutNo^2 + SpeedI x CutNo^3 + SpeedI x Feed0.15 x ConditionI + SpeedI x Feed0.2 x ConditionI



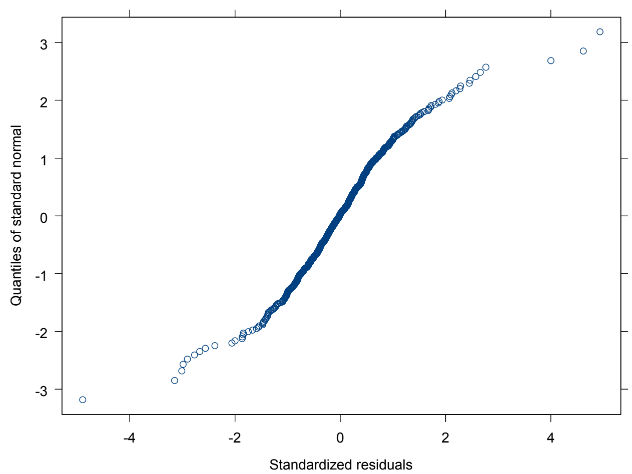
Residual versus fitted plots



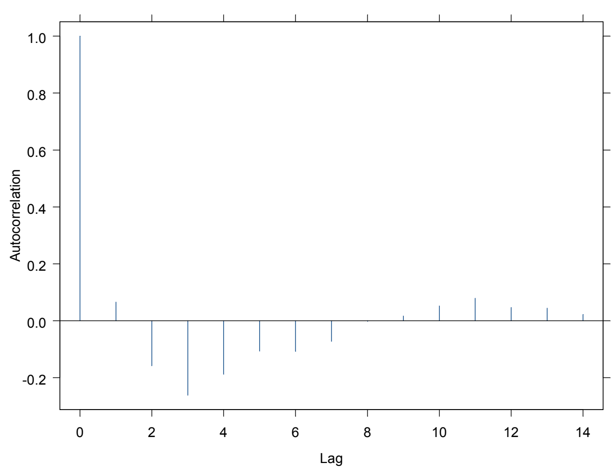
Square root of absolute residual versus fitted plots



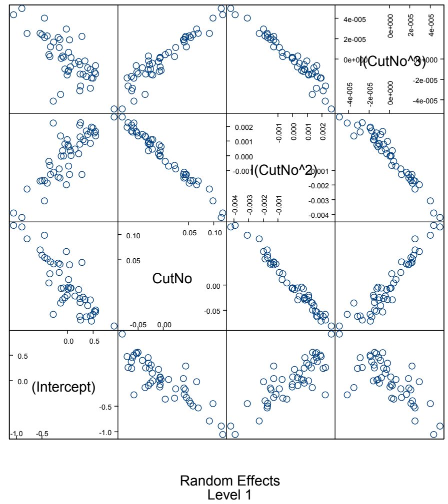
Response versus fitted plot



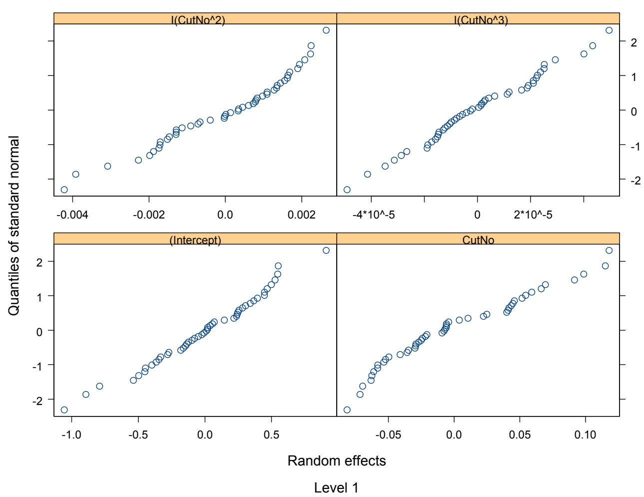
QQ plot of residuals



Auto-correlation plot of residuals



Scatter plot of random effects



QQ plot of random effects

```
*** Linear Mixed Effects Model - Full model ***

Linear mixed-effects model fit by REML
 Data: WearDataWithIndicators
       AIC       BIC  logLik
  -149.686 -18.97492 103.843

Random effects:
 Formula:  ~ CutNo + CutNo^2 + CutNo^3 | Block
 Structure: General positive-definite
                StdDev    Corr
(Intercept) 0.4421998178 (Intr) CutNo  I(CN^2)
      CutNo 0.0553573620 -0.816
 I(CutNo^2) 0.0018130175  0.782 -0.977
 I(CutNo^3) 0.0000241241 -0.666  0.910 -0.952
   Residual 0.1242017669
```

```
Fixed effects: LNWear ~ SpeedI * Feed0.15 * ConditionI + SpeedI * Feed0.2 *
ConditionI +  SpeedI * (CutNo + CutNo^2 + CutNo^3)
                               Value Std.Error  DF   t-value p-value
               (Intercept)  2.793556 0.1460276 634  19.13033  <.0001
                    SpeedI -0.169965 0.2086849  36  -0.81446  0.4207
                  Feed0.15  0.065649 0.1733734  36   0.37865  0.7072
                ConditionI  0.584323 0.1733273  36   3.37121  0.0018
                   Feed0.2  0.383269 0.1736924  36   2.20660  0.0338
                     CutNo  0.093071 0.0116852 634   7.96485  <.0001
                I(CutNo^2) -0.002188 0.0003875 634  -5.64694  <.0001
                I(CutNo^3)  0.000021 0.0000051 634   4.18553  <.0001
           SpeedI:Feed0.15  0.361818 0.2466279  36   1.46706  0.1510
         SpeedI:ConditionI  0.276316 0.2477171  36   1.11545  0.2720
       Feed0.15:ConditionI  0.438458 0.2455002  36   1.78598  0.0825
            SpeedI:Feed0.2  0.595798 0.2516326  36   2.36773  0.0234
        Feed0.2:ConditionI  0.237607 0.2463095  36   0.96467  0.3411
              SpeedI:CutNo  0.065860 0.0171600 634   3.83799  0.0001
         SpeedI:I(CutNo^2) -0.002444 0.0006099 634  -4.00782  0.0001
         SpeedI:I(CutNo^3)  0.000045 0.0000086 634   5.27395  <.0001
SpeedI:Feed0.15:ConditionI -0.720437 0.3521165  36  -2.04602  0.0481
 SpeedI:Feed0.2:ConditionI -0.656587 0.3556770  36  -1.84602  0.0731
 Correlation:
                           (Intr) SpeedI Fd0.15 CndtnI Fed0.2  CutNo
                    SpeedI -0.700
                  Feed0.15 -0.594  0.415
                ConditionI -0.593  0.415  0.500
                   Feed0.2 -0.595  0.417  0.499  0.499
                     CutNo -0.526  0.368  0.000 -0.001  0.005
                I(CutNo^2)  0.497 -0.348  0.000  0.001 -0.006 -0.973
                I(CutNo^3) -0.420  0.294  0.000 -0.001  0.005  0.901
           SpeedI:Feed0.15  0.417 -0.591 -0.703 -0.352 -0.351  0.000
         SpeedI:ConditionI  0.415 -0.591 -0.350 -0.700 -0.349  0.001
       Feed0.15:ConditionI  0.416 -0.291 -0.706 -0.706 -0.352  0.006
            SpeedI:Feed0.2  0.411 -0.593 -0.345 -0.345 -0.690 -0.003
        Feed0.2:ConditionI  0.415 -0.290 -0.352 -0.704 -0.705  0.003
              SpeedI:CutNo  0.358 -0.524  0.000  0.001 -0.003 -0.681
         SpeedI:I(CutNo^2) -0.316  0.467  0.000 -0.001  0.004  0.618
         SpeedI:I(CutNo^3)  0.251 -0.357  0.000  0.001 -0.003 -0.539
SpeedI:Feed0.15:ConditionI -0.290  0.407  0.492  0.492  0.246 -0.004
 SpeedI:Feed0.2:ConditionI -0.287  0.410  0.244  0.487  0.488 -0.002
                           I(CN^2) I(CN^3) SI:F015 SpI:CI F015:CI
                    SpeedI
                  Feed0.15
                ConditionI
                   Feed0.2
                     CutNo
                I(CutNo^2)
                I(CutNo^3) -0.952
           SpeedI:Feed0.15  0.000   0.000
         SpeedI:ConditionI -0.001   0.001   0.496
       Feed0.15:ConditionI -0.008   0.007   0.496   0.494
            SpeedI:Feed0.2  0.004  -0.003   0.489   0.490  0.243
        Feed0.2:ConditionI -0.002  -0.002   0.247   0.492  0.497
              SpeedI:CutNo  0.663  -0.614   0.000  -0.001 -0.004
         SpeedI:I(CutNo^2) -0.635   0.605   0.002   0.006  0.005
         SpeedI:I(CutNo^3)  0.569  -0.598  -0.005  -0.016 -0.004
SpeedI:Feed0.15:ConditionI  0.005  -0.005  -0.700  -0.702 -0.697
 SpeedI:Feed0.2:ConditionI  0.001   0.001  -0.346  -0.697 -0.344
                           SI:F02 F02:CI SpI:CN SI:I(CN^2) SI:I(CN^3)
                    SpeedI
                  Feed0.15
                ConditionI
                   Feed0.2
                     CutNo
                I(CutNo^2)
                I(CutNo^3)
           SpeedI:Feed0.15
```

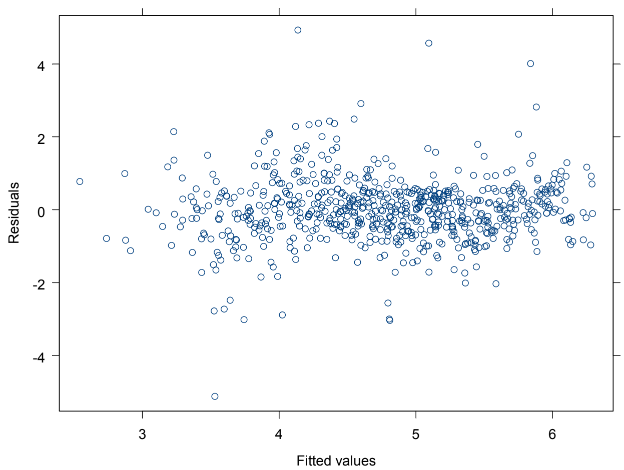
```
         SpeedI:ConditionI
       Feed0.15:ConditionI
            SpeedI:Feed0.2
        Feed0.2:ConditionI  0.487
              SpeedI:CutNo  0.005 -0.002
         SpeedI:I(CutNo^2)  0.005  0.001 -0.955
         SpeedI:I(CutNo^3) -0.033  0.001  0.850 -0.942
SpeedI:Feed0.15:ConditionI -0.339 -0.346  0.003  0.000      -0.007
 SpeedI:Feed0.2:ConditionI -0.703 -0.693  0.002 -0.004       0.011
                           SI:F015:CI
                    SpeedI
                  Feed0.15
                ConditionI
                   Feed0.2
                     CutNo
                I(CutNo^2)
                I(CutNo^3)
           SpeedI:Feed0.15
         SpeedI:ConditionI
       Feed0.15:ConditionI
            SpeedI:Feed0.2
        Feed0.2:ConditionI
              SpeedI:CutNo
         SpeedI:I(CutNo^2)
         SpeedI:I(CutNo^3)
SpeedI:Feed0.15:ConditionI
 SpeedI:Feed0.2:ConditionI  0.489

Standardized Within-Group Residuals:
       Min         Q1         Med        Q3      Max
 -4.892385 -0.4653517 -0.01457191 0.4360401 4.935876

Number of Observations: 688
Number of Groups: 48


Analysis of Variance Table
                           numDF denDF  F-value p-value
               (Intercept)     1   634 13523.75  <.0001
                    SpeedI     1    36    22.38  <.0001
                  Feed0.15     1    36     0.16  0.6953
                ConditionI     1    36   104.80  <.0001
                   Feed0.2     1    36    56.70  <.0001
                     CutNo     1   634   248.87  <.0001
                I(CutNo^2)     1   634    29.49  <.0001
                I(CutNo^3)     1   634    95.02  <.0001
           SpeedI:Feed0.15     1    36     0.78  0.3821
         SpeedI:ConditionI     1    36     0.87  0.3564
       Feed0.15:ConditionI     1    36     1.00  0.3235
            SpeedI:Feed0.2     1    36     4.00  0.0531
        Feed0.2:ConditionI     1    36     0.34  0.5639
              SpeedI:CutNo     1   634     6.57  0.0106
         SpeedI:I(CutNo^2)     1   634     8.05  0.0047
         SpeedI:I(CutNo^3)     1   634    27.83  <.0001
SpeedI:Feed0.15:ConditionI     1    36     1.72  0.1981
 SpeedI:Feed0.2:ConditionI     1    36     3.41  0.0731


Approximate 95% confidence intervals

 Fixed effects:
                                 lower           est.
               (Intercept)  2.50680006175  2.79355634197
                    SpeedI -0.59319798337 -0.16996543330
                  Feed0.15 -0.28596892958  0.06564868304
                ConditionI  0.23279868764  0.58432275338
                   Feed0.2  0.03100460067  0.38326904986
```

```
                     CutNo  0.07012467270  0.09307111118
                I(CutNo^2) -0.00294917788 -0.00218822616
                I(CutNo^3)  0.00001139170  0.00002146006
           SpeedI:Feed0.15 -0.13836624843  0.36181838579
         SpeedI:ConditionI -0.22607790896  0.27631557234
       Feed0.15:ConditionI -0.05943898733  0.43845848571
            SpeedI:Feed0.2  0.08546395532  0.59579845062
        Feed0.2:ConditionI -0.26193231778  0.23760654197
              SpeedI:CutNo  0.03216261058  0.06585998734
         SpeedI:I(CutNo^2) -0.00364184194 -0.00244423802
         SpeedI:I(CutNo^3)  0.00002837556  0.00004520862
SpeedI:Feed0.15:ConditionI -1.43456244233 -0.72043701777
 SpeedI:Feed0.2:ConditionI -1.37793316903 -0.65658682553
                                    upper
               (Intercept)  3.08031262220
                    SpeedI  0.25326711676
                  Feed0.15  0.41726629566
                ConditionI  0.93584681911
                   Feed0.2  0.73553349906
                     CutNo  0.11601754966
                I(CutNo^2) -0.00142727444
                I(CutNo^3)  0.00003152842
           SpeedI:Feed0.15  0.86200302001
         SpeedI:ConditionI  0.77870905365
       Feed0.15:ConditionI  0.93635595874
            SpeedI:Feed0.2  1.10613294593
        Feed0.2:ConditionI  0.73714540173
              SpeedI:CutNo  0.09955736409
         SpeedI:I(CutNo^2) -0.00124663409
         SpeedI:I(CutNo^3)  0.00006204168
SpeedI:Feed0.15:ConditionI -0.00631159321
 SpeedI:Feed0.2:ConditionI  0.06475951796

 Random Effects:
  Level: Block
                                    lower          est.          upper
            sd((Intercept))  0.2987821418  0.4421998178  0.65445905722
                 sd(CutNo)  0.0384749010  0.0553573620  0.07964770401
             sd(I(CutNo^2))  0.0011067210  0.0018130175  0.00297006425
             sd(I(CutNo^3))  0.0000131254  0.0000241241  0.00004433942
     cor((Intercept),CutNo) -0.9382637025 -0.8160146705 -0.51256728848
cor((Intercept),I(CutNo^2))  0.3877208584  0.7818300691  0.93427536640
cor((Intercept),I(CutNo^3)) -0.8993075226 -0.6655229508 -0.13589349168
      cor(CutNo,I(CutNo^2)) -0.9947052056 -0.9772878155 -0.90529562809
      cor(CutNo,I(CutNo^3))  0.6846110276  0.9096625016  0.97637642188
 cor(I(CutNo^2),I(CutNo^3)) -0.9876060776 -0.9521051845 -0.82392448164

 Within-group standard error:
     lower      est.     upper
 0.1130724 0.1242018 0.1364265
```

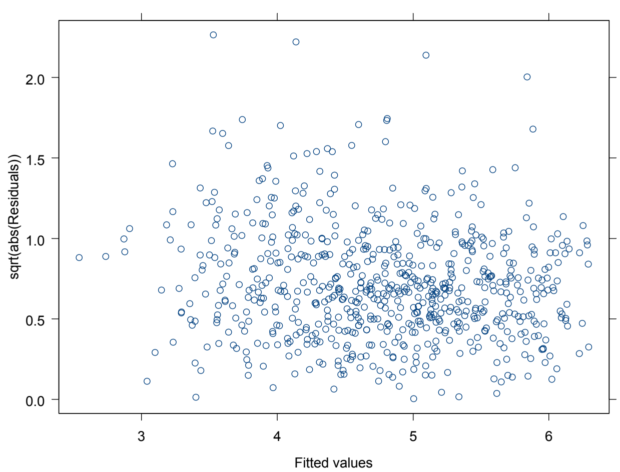
Model 4-14

Random effects:
Formula: ~ CutNo + CutNo^2 + CutNo^3 | Block

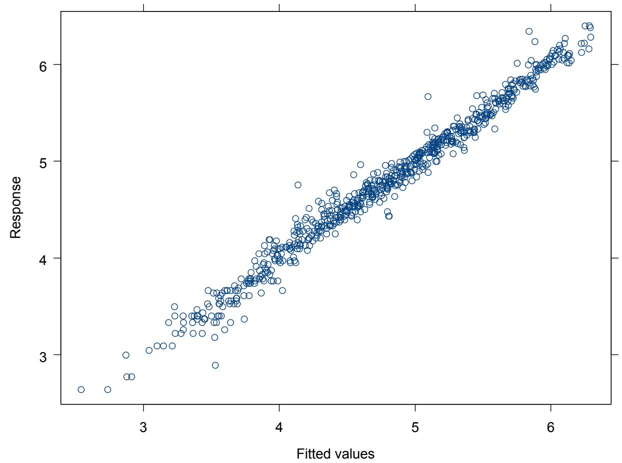
Fixed effects: LNWear ~ SpeedI + Feed0.15 + CondI + Feed0.2 + CutNo + CutNo^2 + CutNo^3 + SpeedI * CutNo + SpeedI * CutNo^2 + SpeedI * CutNo^3



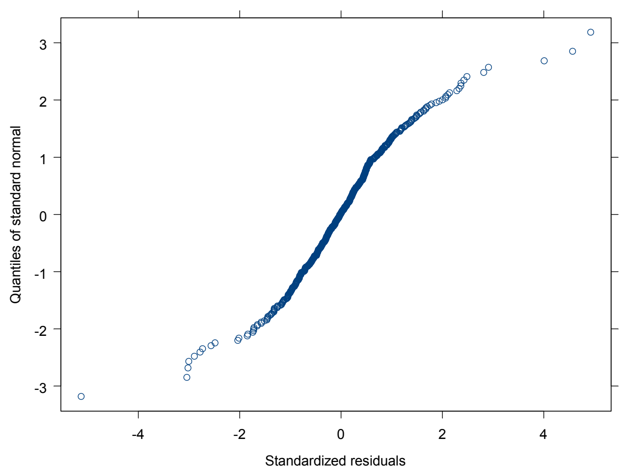
Residual versus fitted plots



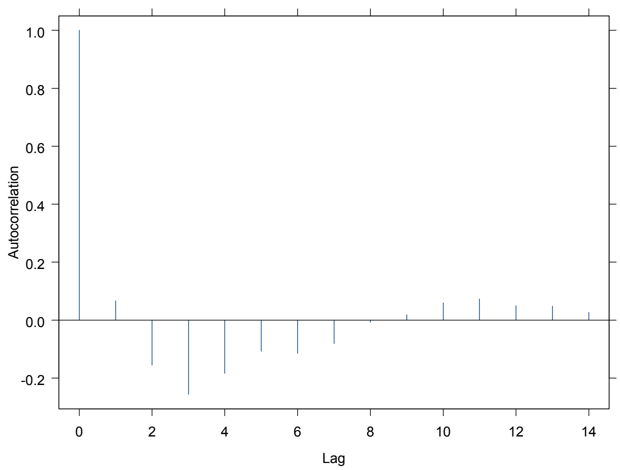
Square root of absolute residual versus fitted plots



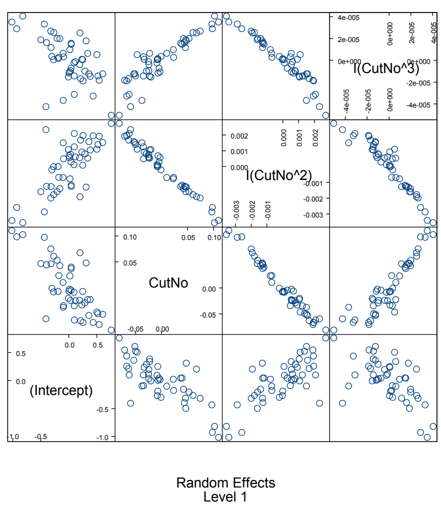
Response versus fitted plot



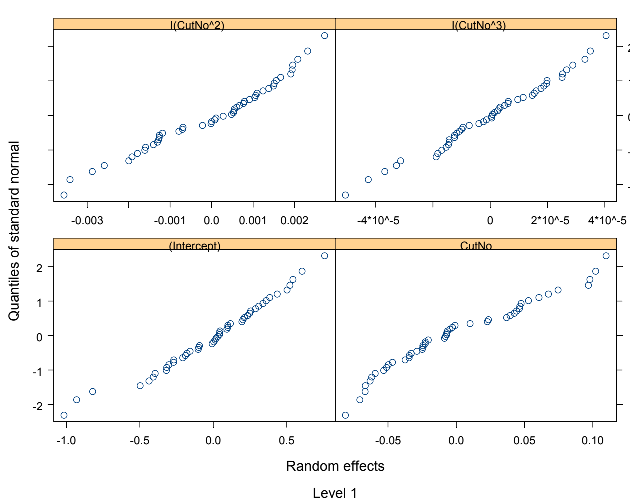
QQ plot of residuals



Auto-correlation plot of residuals



Scatter plot of random effects



QQ plot of random effects

```
*** Linear Mixed Effects Model- Simplified model ***

Linear mixed-effects model fit by REML
 Data: AllWearDataCoded
        AIC       BIC   logLik
  -159.5529 -60.16414 101.7765

Random effects:
 Formula:  ~ CutNo + CutNo^2 + CutNo^3 | Block
 Structure: General positive-definite
                   StdDev   Corr
(Intercept) 0.40772743632 (Intr) CutNo  I(CN^2)
      CutNo 0.05388482331 -0.757
 I(CutNo^2) 0.00167926364  0.733 -0.975
 I(CutNo^3) 0.00002238862 -0.581  0.841 -0.920
   Residual 0.12484468916

Fixed effects: LNWear ~ SpeedI + Feed0.15 + CondI + Feed0.2 + CutNo + CutNo^2 +
CutNo^3 + SpeedI * CutNo + SpeedI * CutNo^2 + SpeedI * CutNo^3
                      Value Std.Error  DF   t-value p-value
      (Intercept)  2.709441 0.1098880 634  24.65638  <.0001
           SpeedI  0.045327 0.1235976  43   0.36673  0.7156
         Feed0.15  0.313842 0.0950245  43   3.30275  0.0019
            CondI  0.678739 0.0778535  43   8.71816  <.0001
          Feed0.2  0.595547 0.0955489  43   6.23290  <.0001
            CutNo  0.092218 0.0113641 634   8.11486  <.0001
       I(CutNo^2) -0.002151 0.0003590 634  -5.98998  <.0001
       I(CutNo^3)  0.000021 0.0000048 634   4.42299  <.0001
     SpeedI:CutNo  0.069427 0.0166875 634   4.16041  <.0001
SpeedI:I(CutNo^2) -0.002645 0.0005721 634  -4.62236  <.0001
SpeedI:I(CutNo^3)  0.000048 0.0000082 634   5.77437  <.0001

Standardized Within-Group Residuals:
      Min         Q1         Med        Q3      Max
 -5.12524 -0.4680503 -0.01230348 0.4523409 4.928867

Number of Observations: 688
Number of Groups: 48


Analysis of Variance Table
                  numDF denDF  F-value p-value
      (Intercept)     1   634 10960.26  <.0001
           SpeedI     1    43    25.22  <.0001
         Feed0.15     1    43     0.01  0.9197
            CondI     1    43    81.08  <.0001
          Feed0.2     1    43    45.98  <.0001
            CutNo     1   634   246.12  <.0001
       I(CutNo^2)     1   634    39.26  <.0001
       I(CutNo^3)     1   634   106.75  <.0001
     SpeedI:CutNo     1   634     7.01  0.0083
SpeedI:I(CutNo^2)     1   634     2.66  0.1031
SpeedI:I(CutNo^3)     1   634    33.34  <.0001
```