PERFORMANCE OF DIAMOND TOOL IN MACHINING TITANIUM

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Thesis submitted in fulfillment of the requirements for the award of
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SUPERVISOR'S DECLARATION

I hereby declare that I have read this report and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering with Manufacturing Engineering.

Signature:	....
Name of Supervisor:	DR. THET THET MON
Position:	Supervisor/Lecturer
Date:	

STUDENT'S DECLARATION

I declare that this thesis entitled "*Performance of Diamond Tool in Machining Titanium*" is my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted for award of other degree.

Signature: ....

Name : AHMAD NAZMI BIN MOHD ROSE

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Date:

DEDICATION

To my beloved mother

Hafsah @ Fatimah Binti Haji Musa

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First and foremost, I wish to express my sincere appreciation to my project supervisor, Dr. Thet Thet Mon, for constantly guiding and encouraging me throughout this study. Thanks a lot for giving me a professional training, advice and suggestion to bring this thesis to its final form. Without her support and interest, this thesis would not have been the same as presented here. I am very grateful for her patience and her constructive comments that enriched this research project.

I would also like to acknowledge with much appreciation the crucial role of the staff in FKP Laboratory, for their valuable comments, sharing their time and knowledge on this research project during the project was carried out and giving a permission to use all the necessary tools in the laboratory. They have contributed towards my understanding and thoughts.

In particular, my sincere thankful is also extends to all my colleagues and others who have provided assistance at various occasions. Their views and tips are useful indeed. And last, but not least thanks to my family for their continuous support and confidence in my efforts.

ABSTRACT

Titanium and its alloys are attractive materials due to their unique high strength-weight ratio that is maintained at elevated temperatures and their exceptional corrosion resistance. PCD is known for its superior characteristics such as hardness, toughness and wear resistance. In this study, the perfomance of PCD has been investigated. The experiments were carried out on CNC turning centre. The cutting speeds selected in the experiments were 77.5736, 90, 120, 150 and 162.4264 m/min. The depth of cut was kept contstant at 0.5 mm. The feed rates used in the experiments were 0.029289, 0.05, 0.1, 0.15 and 0.170711 mm/rev. Tool wear was measured under OLYMPUS BX51M upright optical microscope with a magnification of 5X. All the data were analyzed by using Anova approach in the STATISTICA. The results have shown that the cutting speeds gave more affect on the tool wears compared to the feed rates. The diamond tool wear curve were also successfully developed in this study and compared with the previous study that used coated carbide as the cutting tool. From the data and visual analysis on the tool, it was shown that PCD has the greater performance over coated carbide.

ABSTRAK

Titanium dan aloinya merupakan bahan material yang menarik kerana unik nisbah kekuatan-bobot tinggi yang mampu kekal dalam suhu yang jauh tinggi dan ketahanan kakisan yang luar biasa. Mata pemotong PCD dikenali dengan ciri-ciri unggulnya seperti kekerasan, ketangguhan dan ketahanan haus. Dalam kajian ini, prestasi dari PCD telah diteliti. Eksperimen dilakukan dengan menggunakan mesin berputar. Kelajuan pemotongan yang dipilih adalah 77.5736, 90, 120, 150 dan 162.4264 m/min. Kedalaman untuk setiap pemotongan ditetapkan sebanyak 0.5 mm. Kadar suapan yang digunakan dalam percubaan ini adalah 0.029289, 0.05, 0.1, 0.15 dan 0.170711 mm/rev. Nilai kehausan pada mata pemotong dilihat dan diukur menggunakan mikroskop tegak OLYMPUS BX51M optik dengan perbesaran 5 kali ganda. Semua data dianalisis dengan menggunakan kaedah ANOVA dalam perisian STATISTICA. Kajian menunjukkan bahawa kadar kelajuan pemotongan lebih mempengaruhi berbanding dengan kadar suapan.Tahap kehausan pada mata pemotong PCD juga telah dibandingkan dengan mata pemotong karbide yang telah disadur yang dijalankan oleh pengkaji sebelum ini. Keputusan menunjukkan bahawa, mata pemotong jenis PCD lebih tahan berbanding mata pemotong karbide berdasarkan pada gambar dan nilai kehausan yang diukur.

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LIST OF SYMBOLS

lbf	-	Pound of force
mm	-	Millimeter
°	-	Degree
E	-	Young's modulus
g/cm^3	-	gram per centimeter cube
Gpa	-	Giga Pascal
J	-	Impact strentgh
kg/ cm^3	-	kilogram per centimeter cube
m/min	-	meter per minute
mm/rev	-	milimeter per revolution
Mpa	-	Mega Pascal
µm	-	micronmeter

LIST OF ABBREVIATIONS

CNC	-	Computer numerical control
DF	-	Degree of freedom
DOE	-	Design of experiment
FKM	-	Fakulti Kejuruteraan Mekanikal
FKP	-	Fakulti Kejuruteraan Pembuatan
IPM	-	Inches per minutes
ISO	-	International standard organization
MS	-	Mean square
PCBN	-	Polycrystalline diamond and cubic boron nitride
PCD	-	Polycrystalline diamond
SFM	-	Surface per minutes
SS	-	Sum of square
UMP	-	Universiti Malaysia Pahang

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

This chapter gives overview description of the project progress including approaches of method application. It includes project background, problem statement, objectives and scopes of the project of performance of diamond tool in machining titanium.

1.2 PROJECT BACKGROUND

Titanium and its alloys are being increasingly used in a wide variety of engineering and biomedical applications, their manufacturability,especially machining and grinding imposes lot of constraints. The major application of titanium has been in the aerospace industry. However, titanium and its alloys are notorious for their poor thermal properties and are classified as difficult-to-machine materials. Rapid tool wear encountered in machining of titanium alloys is a challenge that needs to be overcome.

In this project, the experiment will focus on progress of diamond tool in machining titanium using ROMI C420 CNC turning machine. Significant effect of process parameters on tool wear was identified using ANOVA approach in the STATISTICA. The independent variable are cutting speed and feed rate with range of 77.5736, 90, 120, 150, 162.4264 m/min and 0.029289, 0.05, 0.1, 0.15, 0.170711 mm/rev. The depth of cut is constantly set to 0.5 mm. In the end, the diamond tool wear graph is developed.

1.3 PROBLEM STATEMENT

Titanium and its alloys are regarded as extremely difficult-to-machine materials. The tool wear progresses rapidly because of high cutting temperature and strong adhesion between tool and work material resulted from their low thermal conductivity and high chemical reactivity.

1.4 PROJECT OBJECTIVE

The objectives of this study are:

i. To investigate the diamond tool wear during machining titanium
ii. To identify the machining parameters that effect on diamond tool wear based on statistical analysis
iii. To develop diamond tool wear curve in machining titanium

1.5 PROJECT SCOPE

The scopes of this project are:

i. Machining experiment will be designed in STATISTICA
ii. Machining parameters considered are cutting speed and feed rate
iii. The cutting speed range will be 90-150 m/min and feed rate 0.05-0.15 mm/rev
iv. Tool wear will be investigated with optical microscope
v. Experiment result will be analyzed in STATISTICA
vi. The tool wear curve will be plotted in EXCEL

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The main purpose of this literature review is to get the information from references, books, journals, technical papers and website to complete the project. For this chapter, some information from different sources will be discussed.

2.2 TITANIUM

Shane, et al. (2001) said that titanium is a relatively lightweight metal that provides excellent corrosion resistance, a high strength-to-weight ratio, and good high temperature properties. Pure titanium is allotropic, with an HCP crystal structure (α phase) at low temperatures and a BCC structure (β phase) above 882°C.

Ribeiro, M.V., et al. (2003) defined that, due to titanium's high relationship strength-to-weight and superior corrosion resistance, the titanium is used broadly in the production advanced industrial equipment, used in the generation of energy and in the transport.

Che Haron, C.H. (2001) stated that titanium and titanium alloys have low thermal conductivity and high chemical reactivity with many cutting tool materials. Its low thermal conductivity increases the temperature at the cutting edge of the tool. Hence, on machining, the cutting tools wear off rapidly due to high cutting temperature and strong adhesion between tool and workpiece material. Additionally, the low modulus of elasticity of titanium alloys and its high strength at elevated temperature further impair its machinability.

Kahles, et al. (1985) observed that when machining titanium alloys, the tool life is very sensitive to the changes in feed (*f*). Therefore, this parameter and the depth of cut (*a*p) were kept constant (*f* and *a*p were 0.1mm and 2mm, respectively), and only the cutting speed was varied so as to study its effect on the process.

Yang, X. and Liu, R.C. (1999) claimed that when machining titanium alloys, the combination of the two factors – the small contact area and low thermal conductivity – results in very high pressures and cutting temperatures; thus, the cutting speed for the titanium alloy must be low to avoid very short tool life. Figure 2.1 shows the construction of titanium at the Rolls Royce airplane engine.

Figure 2.1: Rolls Royce airplane engine

Source: Woodford, C. 2002

2.3 MACHINABILITY

Ribeiro, M.V., et al. (2001) said machining is an important manufacturing process because it is almost always involved if precision is required and is the most effective process for small volume production. Due to the low machinability of the alloys under study, selecting the machining conditions and parameters are crucial. The range of feeds and cutting speeds, which provide a satisfactory life, are very limited. On the other hand, adequate tool, coating, geometry and cutting flow materials should be used. Otherwise, the high wear of the tool, and the possible tolerance errors, would introduce unacceptable flaws in parts that require a high degree of precision.

Brunette, D.M. (2001) claimed that titanium is one of the more difficult metals to machine, but current in the industry metal working practices have advanced so that reasonable production rates with excellent surface finishes are possible, when taking the unique characteristics of this material into consideration. For example, the α-β titanium alloy Ti-6Al-4V (ASTM F136) has a low modulus elasticity, 15 msi. (104 GPa) versus 30 msi. (207 GPa) for steels and nickel grades. This lower modulus may cause greater "spring back" and deflection of the workpiece. Therefore, more rigid setups and greater clearances for tools are required. The following guidelines are suggested to machine titanium efficiently:

- **i.** Use low cutting speed
- **ii.** Maintain high feed rates
- **iii.** Use a generous quantity of cutting fluids
- **iv.** Use and maintain sharp tools
- **v.** Use rigid setups
- **vi.** Never interrupt a cut

2.4 POLYCRYSTALLINE DIAMOND

Lum Tso. P., et al. (2001) said that Polycrystalline diamonds, PCD is known for its superior characteristics such as hardness, toughness and wear resistance. Polycrystalline diamond, PCD is manufactured by a high pressure and high temperature process that yields direct diamond-to-diamond bonding within a matrix of cobalt metal. It is currently used in the industry for cutting tools of difficult-to-machine materials because of its superior characteristics. An important advantage of PCD cutting tools is that the crystals are randomly oriented so that the agglomerate does not have cleavage planes found in single diamond cutting tools. As a result, hardness and abrasion resistance are uniformly high in all directions. Hardness is about four times that of carbide and nearly equals that of single-crystal natural diamond. When PCD blanks are bonded to a tungsten or tungsten carbide substrate, cutting tools are produced that are not only high in hardness and abrasion resistance, but also greater in strength and shock resistance.

Zipperian, D. (2003) informed that Polycrystalline diamond is a synthetic diamond which provides better surface finishes and higher removal rates than monocrystalline diamond. Some of the more important features and advantages of polycrystalline diamond are listed below:

i. Higher cutting removal rates (selfsharpening abrasive)
ii. Very uniform surface finish
iii. More uniform particle size distribution
iv. Harder/ tougher particles
v. Blocky shaped particles
vi. Hexagonal microcrystallites (equally hard in all directions)
vii. Extremely rough surface (more cutting points)
viii. Surface area 300% greater than monocrystalline diamond

Venkatesh, V.C. and Izman, S. (2007) said that PCD consist of very small synthetic crystals. They are synthesized from graphite at a high temperature (3000 K) and a high pressure (125 kbars) in the presence of a molten solvent (Ni) to a thickness of about 0.5 to 1 mm. Diamond is sintered onto a carbide substrate with cobalt as a binder. Figure 2.2 illustrates the synthesis of PCD. PCD can be considered to be a composite material that combines the high thermal conductivity of diamond with the brazeability of WC. Both the PCD layer, by virtue of its cobalt content, and the WC substrate are electrically conducting. This allows machining by wire cut EDM as shown in figure 2.3.

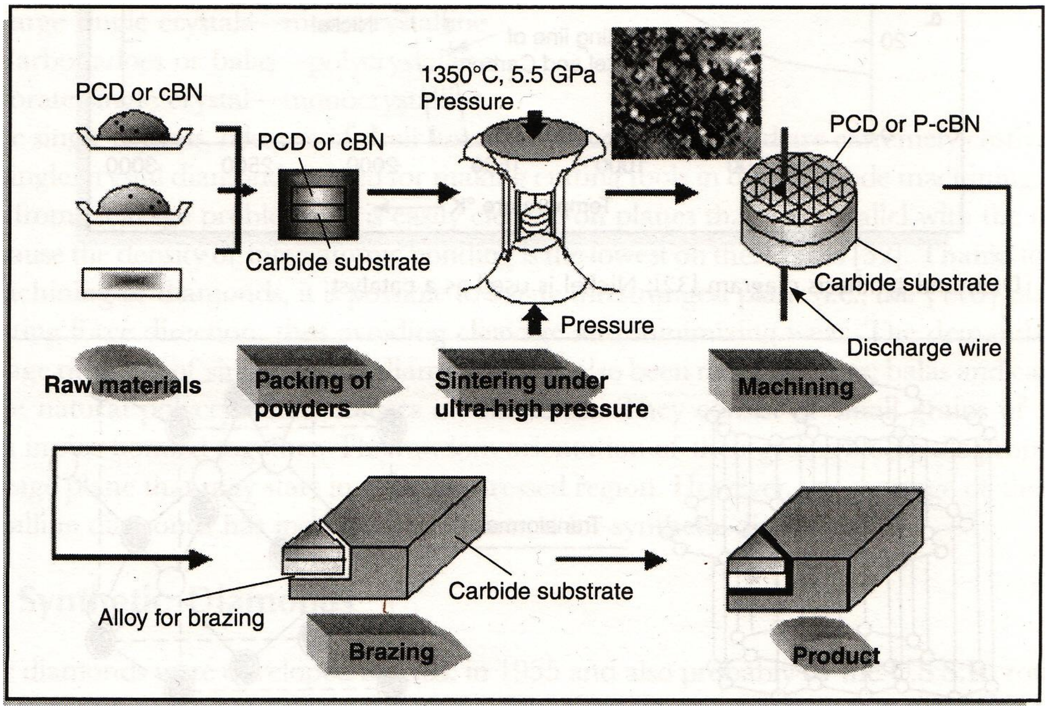


Figure 2.2: Synthesis of a polycrystalline diamond

Source: Clark 1993

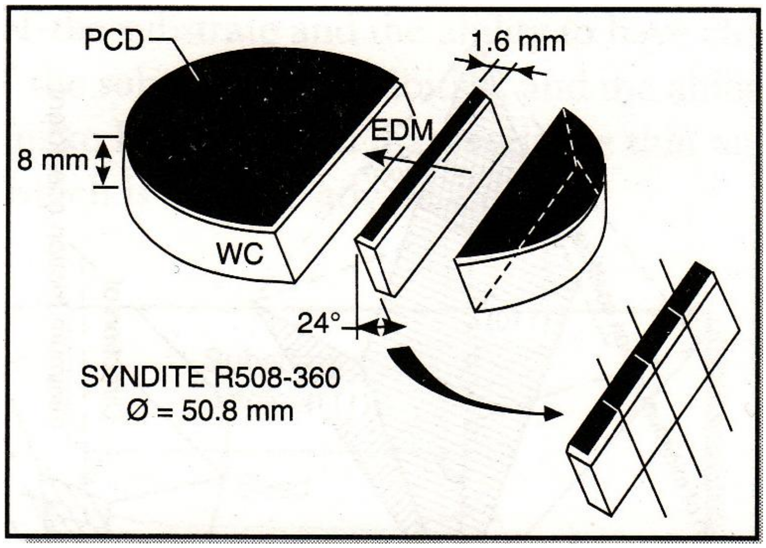


Figure 2.3: PCD inserts produced by EDM machining

Source: Venkatesh, V.C. and Izman, S. 2007

2.5 MACHINING-TURNING PROCESS

Venkatesh, V.C. and Izman, S. (2007) described that turning is metal cutting process used for the generation of cylindrical surfaces. Typically, the workpiece is rotated on a spindle, and tool is fed into it radically, axially or both ways simultaneously to give the required surface with a single-point tool. More specifically, it is often applied just to the generation of external cylindrical surfaces oriented primarily parallel to the workpiece axis. The generation of surfaces primarily perpendicular to the workpiece axis is called facing. In turning, the direction of the feeding motion is predominantly axial with respect to the machine spindle.

Boothroyd, G. (1981) stated that turning is characterized by steady conditions of metal cutting. Except at the beginning and the end of the cut, the forces on the cutting tool and the tool tip temperature are essentially constant. For the special cases of facing, the varying cutting speed will affect the tool tip temperature.

Higher temperatures will be encountered for larger diameters of the workpiece. However, since the cutting speed has only a small effect on cutting forces, the forces acting on a facing tool may be expected to remain almost constant during the cutting temperature.

Mattson, M. (2001) said that turning is a word used to describe a number of different machining operations that are performed on a machine called a lathe. Turning is fundamentally different from milling in that the tool is held stationary while the part is rotated-the resulting shape is cylindrical. The turning process is used to create shafts, bearings, fasteners, and many others machine components that require very precise cylindrical and conical features such as outside diameters, bores, and tapers. Turning can also produce flat faces, grooves, and threads. Figure 2.4 shows the cylindrical turning on an engine lathe.

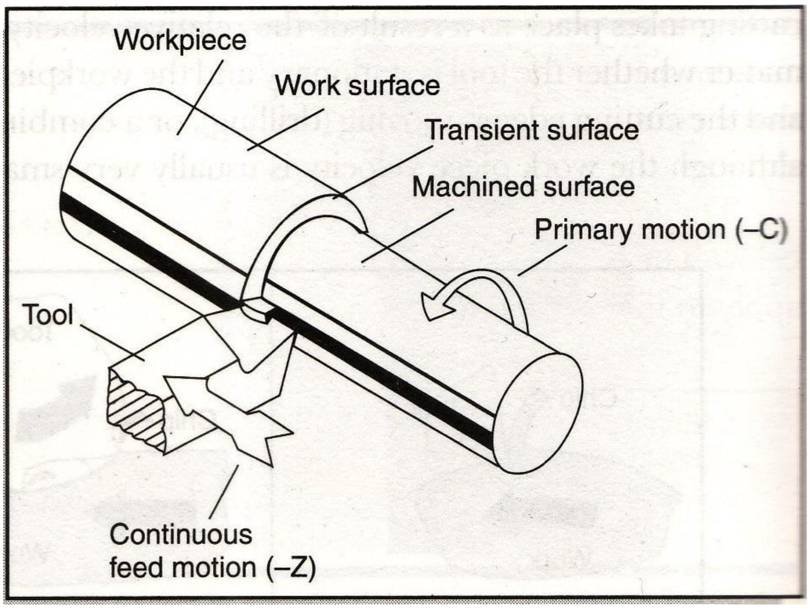


Figure 2.4: Cylindrical turning on an engine lathe

Source: Venkatesh, V.C., Izman, S. 2007

2.6 ADJUSTABLE CUTTING FACTORS IN TURNING

In the basic turning operation, there are three factors that need to be considering during machining which are cutting speed, feed rate and depth of cut. The type of tool and the kind material also have a large influence but these three are the ones the operator can change by adjusting the controls, right at the machine.

2.6.1 Cutting Speed

The speed of the workpiece surface relative to the edge of the cutting tool during a cut, measured in surface feet per minute (SFM). The formula is given below:

$$V = \pi D_o N \quad \text{(max. speed)}$$
$$= \pi D_{avg} N \text{ (min. speed) (m/min)} \qquad \textbf{(eq. 2.1)}$$

Whereas,

V= Cutting Speed (m/min)
D= Diameter (mm)
N= Spindle Speed (rpm)

2.6.2 Feed Rate

The speed of the cutting tool's movement relative to the workpiece as the tool makes a cut. The feed rate is measured in inches per minute (IPM) and is the product of the cutting feed (IPR) and the spindle speed (RPM).

$$\breve{U} = fN \text{ (mm/min)} \qquad \textbf{(eq. 2.2)}$$

Whereas,

Ŭ= Feed rate (mm/min)
f= freed (mm/rev)
N= Spindle Speed (rpm)

2.6.3 Depth of cut

The thickness of the layer being removed from the workpiece or the distance from the uncut surface of the work to the cut surface. It is important to note, though, that the diameter of the workpiece is reduced by two times the depth of cut because this layer is being removed from both sides of the work.

$$d = (D_0 + D_f)/2 \text{ (mm)} \qquad \textbf{(eq. 2.3)}$$

Whereas,

d = Depth of Cut (mm)
D_0 = Initial Diameter (mm)
D_f = Final Diameter (mm)

2.7 TOOL CHARACTERISTIC

Tool characteristic will be discussed briefly in this section and also the type of wear that usually occurred during machining.

2.7.1 Tool Geometry

Kalpakjian, S., et al. (2006) describe that the various angles in a single-point cutting tool have important functions in machining operations. These angles are measured in a coordinate system consisting of the three major axes of the tool shank. These angles may be different, with respect to the workpiece, after the tool is installed in the tool holder. The terminology used to designate the surfaces, angles and radii of single-point tools is shown in figure 2.5 and figure 2.6. Some of the common terms in single-point cutting tools are as follows:

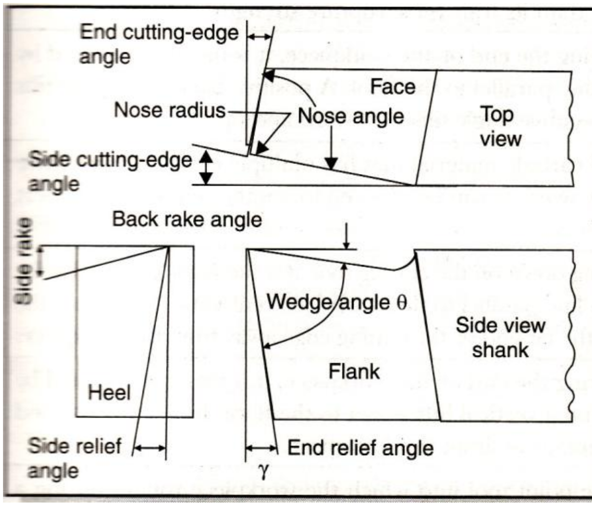
a) Rake angle is important in controlling both the direction of chip flow and the strength of the tool tip. Positive rake angles improve the cutting operation by reducing forces and temperature. Positive angles also result in a small included angle of the tool tip which may lead to premature tool chipping and failure, depending on the toughness of the tool material.

b) Side rake angle is more important than the back rake angle, although the latter usually control the direction of chip flow. For machining metals and using carbide inserts, these angles typically are in range of -5° to 5°.

c) Cutting-edge angle affects chip formation, tool strength, and cutting forces to various degrees. Typically they are around 15°.

d) Relief angle controls interference and rubbing at the tool-workpiece interface. If it is too large, the tool tip may chip off; if it is too small, flank wear may be excessive. Relief angles typically are 5°.

e) Nose radius affects surface finish and tool-tip strength. The smaller the nose radius (sharp tool), the rougher the surfaces finish of the workpiece and the lower the strength of the tool. Large nose radius can lead to tool chatter.



Tool Signature	Dimensions	Abbreviation
8	Back Rake Angle	BR
14	Side Rake Angle	SR
6	End Relief Angle	ER
12	End Clearance Angle	……
6	Side Relief Angle	SRF
12	Side Clearance Angle	……
20	End Cutting-Edge Angle	ECEA
15	Side Cutting-Edge Angle	SCEA
3/4	Nose Radius	NR

Figure 2.5: Three views of a typical HSS (High Speed Steel Tool) showing the various angles and their values with abbreviations

Source: Venkatesh, V.C, Izman, S 2007

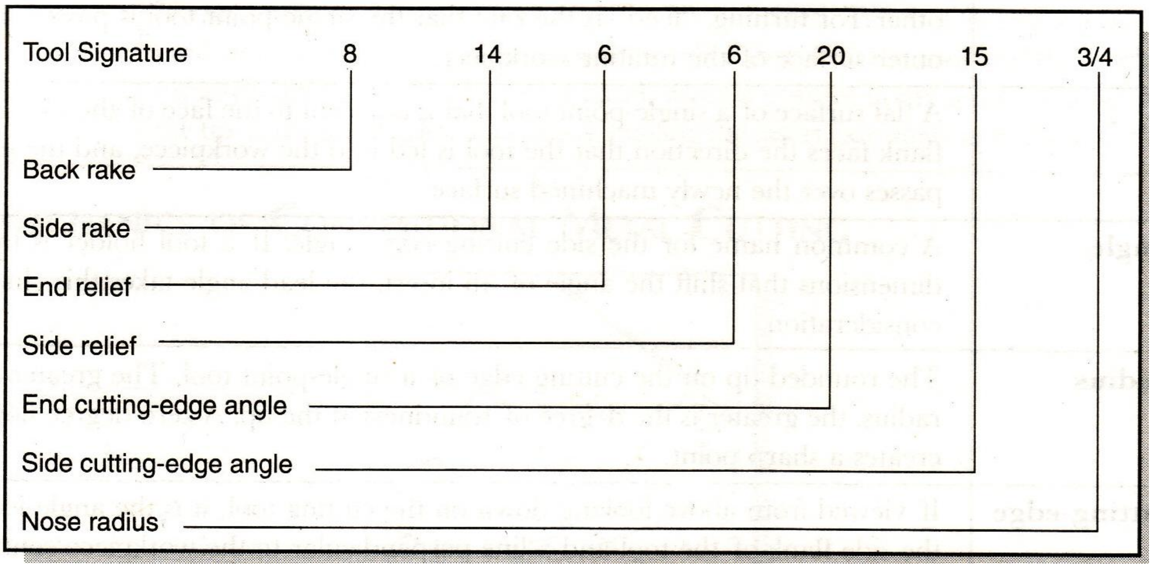


Figure 2.6: Designations and symbols for the right-hand cutting tool with the tool signature

Source: Venkatesh, V.C, Izman, S. 2007

2.7.2 Tool Material

Venkatesh, V.C. and Izman, S. (2007) claimed that cutting tool materials are required to have several properties that enhance the efficiency of the material removal process. The main requirements for cutting tool materials are as follows:

i. High hot hardness
ii. High wear resistance
iii. High-temperature physical and chemical stability
iv. Toughness or high resistance to brittle fracture

Figure 2.7 illustrates the major classes of tool materials. A comparison between hot hardness, wear resistance and toughness is shown in table 2.1. It indicates that single-crystal diamond which is widely used for ultra-precision applications has the highest hot hardness and wear resistance, but it lacks toughness in terms of which it is quite surprising that this earliest tool material still holds an edge over the materials. Carbon steels and high-speed steels are of excellent toughness. Table 2.2 shows that the relative values of several properties for each cutting tool materials. Certain tool materials are very limited in their application due to the reactive nature of the material or element in the cutting tool. Diamond for instance cannot used to machine carbon steel through the properties of diamond are very much desirable. Figure 2.8 shows a few type of cutting insert while table 2.3 shows the comparison of properties of diamond cutting tool materials.

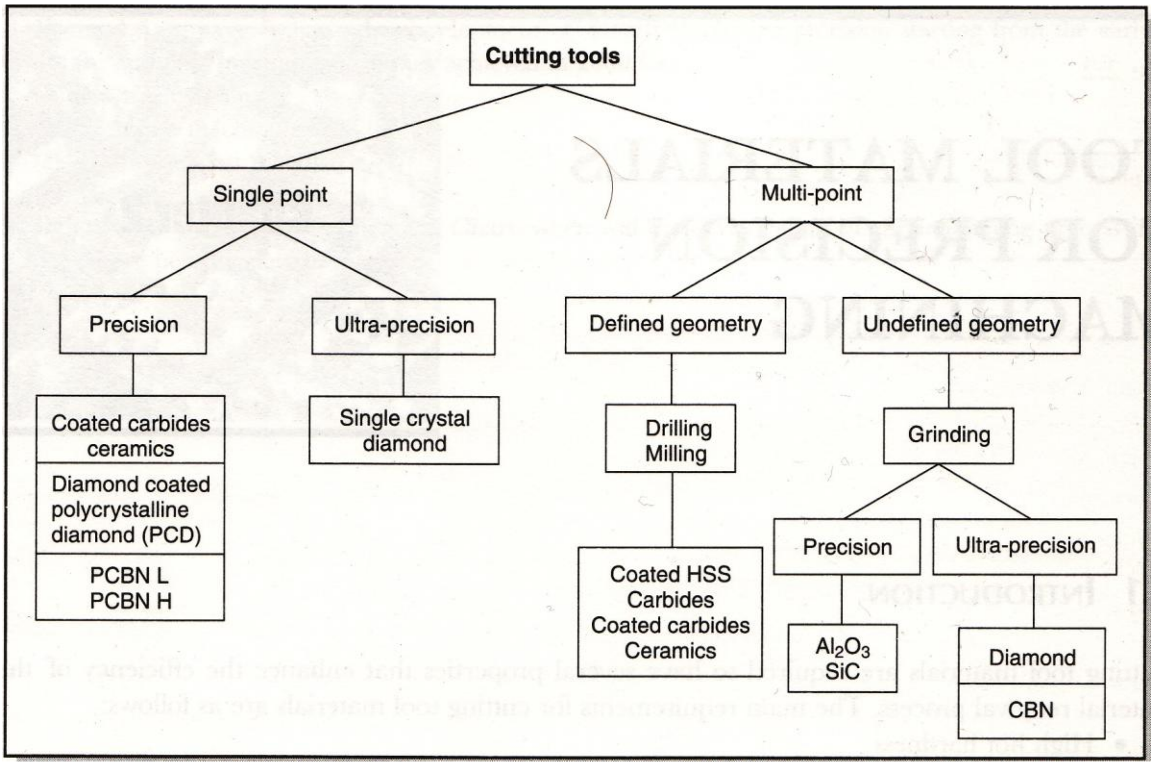


Figure 2.7: Relevance tree for cutting tools

Source: Venkatesh, V.C., Izman, S. 2007

Table 2.1: Comparison between the major classes of cutting tool materials.

Hot hardness ↓	Wear resistance ↓	Material	Toughness ↑
		1. Carbon steels	
		2. High-speed steels	
		3. Cast alloys	
		4. Tungsten Carbides	
		5. Cermets	
		6. Titanium carbides	
		7. Ceramics	
		8. Polycrystalline diamond and cubic boron nitride	
		9. Single-crystal diamond	

Source : Boothroyd, G. 1989

Table 2.2: Properties of cutting tool materials

Property	High-speed steel	Cast alloys	Tungsten carbides	Titanium carbide	Ceramics	Cubic boron nitride	Single-crystal diamond
Hardness	83–86 HRA	82–84 HRA	90–95 HRA	91–93 HRA	91–95 HRA	4000–5000 HK	7000–8000 HK
Compressive strength, MPa	4100–4500	1500–2300	4100–5850	3100–3850	2750–4500	6900	6900
Transverse rupture strength, MPa	2400–4800	1380–2050	1050–2600	1380–1900	345–950	700	1350
Impact strength, J	1.35–8	0.34–1.25	0.34–1.35	0.79–1.24	< 0.1	< 0.5	< 0.2
Modulus of elasticity, GPa	200	–	520–690	310–450	310–410	850	820–1050
Density, kg/m³	8600	8000–8700	10,000–15,000	5500–5800	4000–4500	3500	3500
Volume of hard phase (%)	7–15	10–20	70–90	–	100	95	95
Melting of decomposition temperature, °C	1300	–	1400	1400	2000	1300	700
Thermal conductivity, W/mK	30–50	–	42–125	17	29	13	500–2000
Coefficient of thermal expansion, × 10^{-6}/°C	12	–	4–6.5	7.5–9	6–8.5	4.8	1.5–4.8

Source : Kalpakjian, S. and Schmid, S.R. 2003

Figure 2.8: Variable of cutting tool material

Source: Catalog 4010 GB, Kennamatel

Table 2.3: Comparison of properties of PCD and other tool materials.

Properties	Carbide WC + 6% Co	PCD	PCBN	Natural Diamond
Density, g/cm³	14.8	3.43	3.12	3.52
Knoop's Hardness, Gpa	13	50	28	57-104
Young's Modulus, E, Gpa	620	925	680	1141
Modulus of Rigidity, G Gpa	250	426	279	553
Poisson's Ratio,υ	0.22	0.086	0.22	0.07
Transverse Rupture Strength, Mpa	2300	>2800	600-800	700-1700
Compressive Strength, Mpa	5900	4740	3800	8580
Fracuture Toughness, K_{ic}, MN/$m^{3/2}$	12	6.89	10	3.4
Thermal expansion coefficient, $_e$, 10^{-6}/K	5	3.8	4.9	3.5
Thermal conductivity, W/mK	95	120	100	500-200

Source: Harris et al. 2004

2.7.3 Tool Wear

Kalpakjian, S., et al. (2001) said that wear is a gradual process, much like the wear of the tip of an ordinary pencil. The rate of tool wear depends on tool and workpiece materials, tool geometry, process parameters, cutting fluids, and the characteristics of the machine tool. Tool wear and the changes in tool geometry during cutting themselves in different ways, generally classified as flank wear, crater wear, nose wear, notching, plastic deformation of the tool tip, chipping, and gross fracture. Figure 2.11 shows the tool-wear rate progression.

2.7.3.1 Flank Wear

Flank wear occurs on the relief (flank) face of the tool. It generally is attributed to rubbing of the tool along the machined surface, causing adhesive or abrasive wear and high temperature, which adversely affect tool-material properties. Figure 2.9 shows the visual of flank wear from the side of cutting tool.

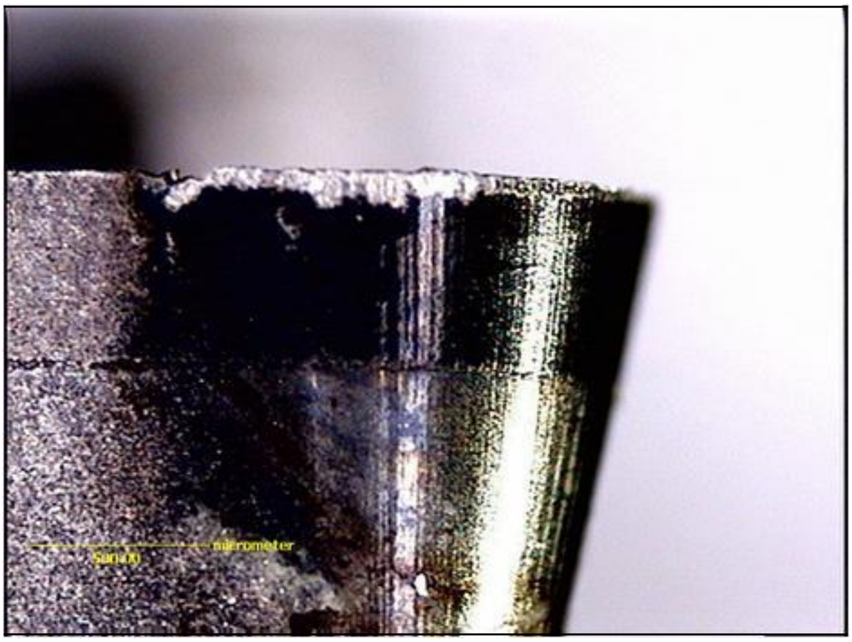


Figure 2.9: Visual of flank wear.

2.7.3.2 Crater Wear

Crater wear occurs on the rake face. It readily can be seen that crater wear changes the tool-chip interface contact geometry. The most significant factors influencing crater wear are temperature at the tool-chip interface and the chemical affinity between the tool and workpiece material. The factors influencing flank wear also may influence crater wear. Figure 2.10 shows the wear occurred on the top surface of the cutting tool.

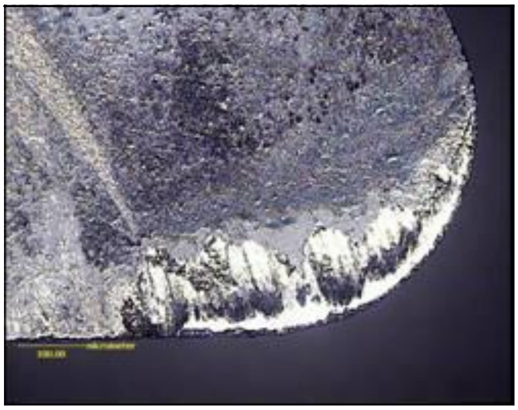


Figure 2.10: Crater wear

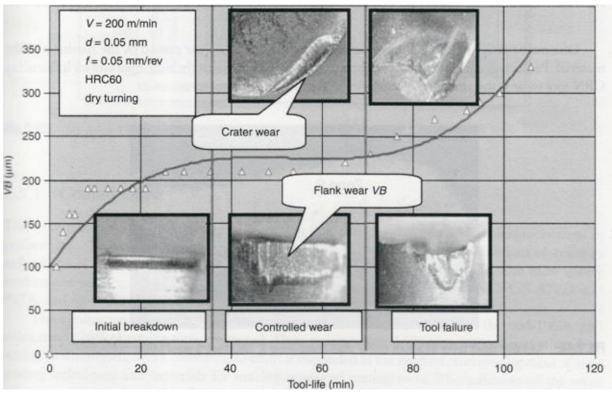


Figure 2.11: Tool-wear rate progression

Source: Poulachon, G., et al. 2004

2.8 RELATED STUDIES

Table 2.4: Summarizes previous study of machining of titanium and its alloys using various types of cutting tools

AUTHOR, YEAR, PAPER	***FINDING***
[1] Ezugwu, E.O *, Wang, Z.M (1997), Titanium alloys and their machinability, Journal of Materials Processing Technology 68 (1997) 262-274.	The straight tungsten carbide (WC/Co) cutting tools continue to maintain their superiority in almost all machining processes of titanium alloys, whilst CVD coated carbides and ceramics have not replaced cemented carbides due to their reactivity with titanium and their relatively low fracture toughness as well as the poor thermal conductivity of most ceramics.
[2] Farhad Nabhani, (2001), Machining of aerospace titanium alloys, Robotics and Computer Integrated Manufacturing 17 (2001) 99-106	The performance of PCBN and PCD has been compared with the coated tungsten carbide tool. Tests confirm that PCD gives better surface finish, longer tool life and more manageable than other tools.

AUTHOR, YEAR, PAPER	***FINDING***
[3] Hooper a, R.M*, Henshall b, J.L, Klopfer a, A, (1999), The wear of polycrystalline diamond tools used in the cutting of metal matrix composites, International Journal of Refractory Metals & Hard Materials 17 (1999) 103-109.	The results indicate that polycrystalline diamond tooling offers superior performance over carbide, both in wear resistance and the quality of the surface finish produced. Observations of the morphology of the wear scars on the tools indicate that the wear process involves both adhesive wear and of the buildup of defects within the diamond particles leading to eventual micro- and macro-fracture in a fatigue-like process.
[4] Norihiko Narutaki and Akio Murakoshi, (1983), Study on Machining of Titanium Alloys, CIRP Annals - Manufacturing Technology, Volume 32, Issue 1, 1983, Pages 65-69.	In this experiment, a natural diamond tool characterized by the highest thermal conductivity of all the tool materials available was utilized by applying abundant water-soluble coolant. It was found that the natural diamond tool exhibits an excellent cutting performance in machining titanium alloys, and the cutting speed could be increased up to 3.33 m/s when applying abundant coolant. In addition, the quality of surface machined with the natural diamond tool was found to be better than those with the other tools.

AUTHOR, YEAR, PAPER	***FINDING***
[5] Bhaumik, S.K, Divakar, C, Singh, A.K, (1995), Machining Ti -6AI-4V alloy with a wBN-cBN composite tool, Materials & Design, Volume 16, Issue 4, 1995, Pages 221-226	An attempt has been made in this work to machine Ti-6AI-4V alloy with wurtzite boron nitride (wBN) based cutting tools. The mechanisms controlling the wear of the cutting tool have been found to be similar to those observed in polycrystalline diamond (PCD) and polycrystalline cubic boron nitride (PCBN) tools. The results indicate that the wBN-cBN composite tools can be used economically to machine titanium alloys.
[6] Jawaid, A., et. al, (1999), Tool wear characteristics in turning titanium alloy Ti-6246, Elsevier, Journal of Materials Processing Technology, Pages 329-334	Research work has been carried out to determine the behaviour of titanium alloys during the processes of turning. The experiments were carried out under dry cutting conditions. The effects of different types of chip-breaker geometry and grain size of the tool were observed. SEM analysis has been carried out on the worn tools to determine the tools wear mechanisms. The results have shown that inserts with fine grain size and a honed edge have a longer tool life. At higher cutting speeds the tool failure was due to maximum flank face wear and excessive chipping on the flank edge.

2.9 DESIGN OF EXPERIMENT

Ramachandran, K.M., et al. (2009) said that statistics concerned with the analysis of data generated from an experiment. It is desirable to take the necessary time and effort to organize the experiment appropriately so that the right type of data and sufficient amount of data to answer the questions of interest as clearly and efficiently as possible. This is called experimental design. Dr. Genichi Taguchi pioneered the use of design of experiments (DOE) in designing robust products-those relatively incentive to change in the parameters. DOE is used as an essential tool for improving the quality of goods and services. It is important to note that, unless a sound design is employed, it may be very difficult or even impossible to obtain valid conclusions from the resulting data. Also, properly designed experiments will generate more precise data while using substantially fewer experiments runs than ad hoc approaches. In industrial manufacturing, some of the major benefits of DOE are lower costs, simultaneous optimization of several factors, fast generation and organization of quantitative information, and overall quality improvement.

2.9.1 STATISTICA SOFTWARE

STATISTICA is a comprehensive, integrated data analysis, graphics, database management, and custom application development system featuring a wide selection of basic and advanced analytic procedures for business, data mining, science, and engineering applications. Common software used for DOE and statistical analyses are:

i. Statistica
ii. Minitab
iii. SPSS

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This chapter generally discusses methodology of the project, with a focus on growth of tool wear during turning process of pure titanium using PCD as a cutting tool. Relevant data collection is done in order for further research analysis in subsequent chapter.

3.2 METHODOLOGY FLOW CHART

Methodology flow chart is developed as a guideline to finish the project. Figure 3.1 illustrates a simple flow chart shows the flow processes of this project. As illustrated, the first step is literature study on related topic followed by design of experiment in STATISTICA. The next step is running the experiment using CNC machine. After that, diamond tool wear is investigated under optimal microscope. The result will be analysis in STATISTICA and finally the tool wear curved will be developed.

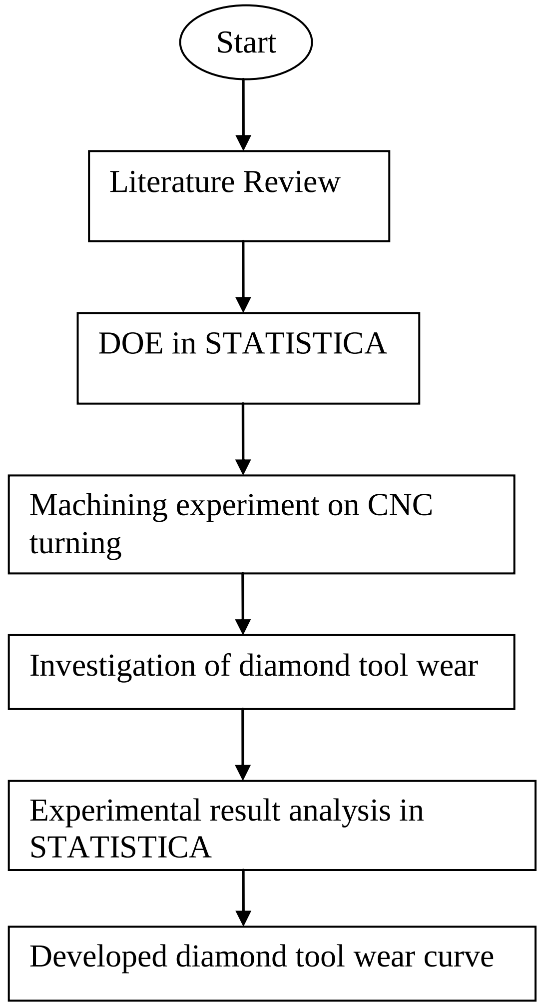


Figure 3.1: Simple Flow Chart

3.3 TURNING EXPERIMENT

Polycrystalline diamond tool of grade KD100 (ISO designation TG 323) with holder (CTGPR – 2020K16) produced by Kennametel was tested for tool wear study. This insert-holder combination provide rake angle of 5° and clearance angle of 6° respectively. Detail description of ISO designation is given in the appendix. Tooling, workpiece and also the set-up for turning is shown in figure 3.2, figure 3.3, figure 3.4 and figure 3.5.

Figure 3.2: Holder

Figure 3.3: Titanium bar

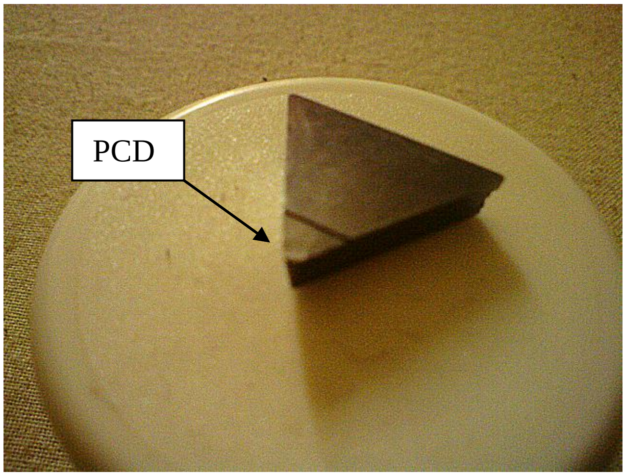


Figure 3.4: PCD

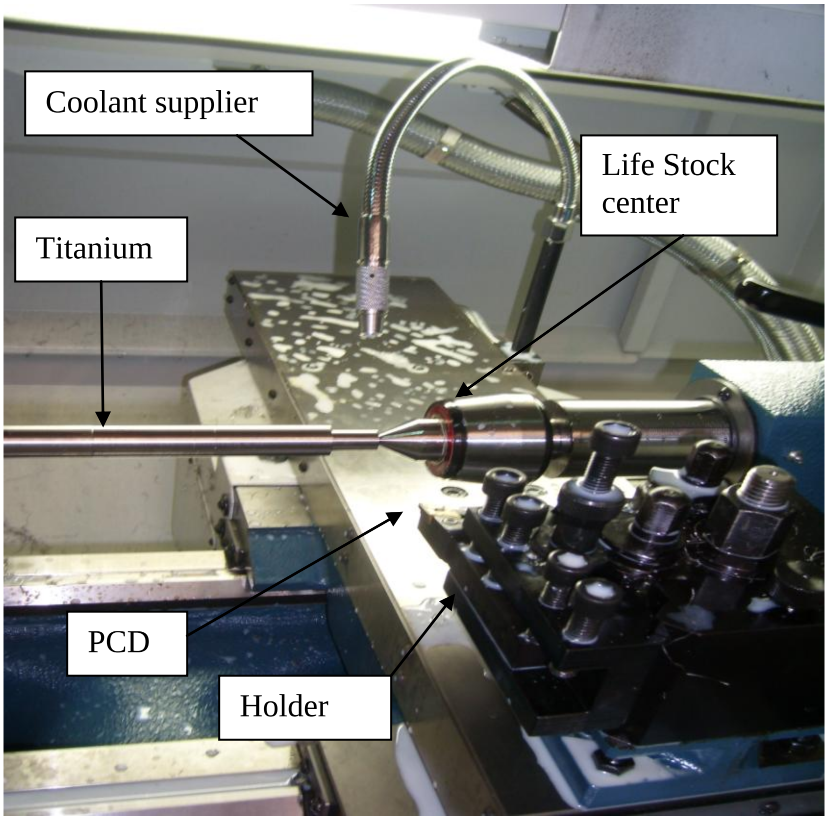


Figure 3.5: Experimental setup

3.4 EXPERIMENTAL DESIGN AND CONDITIONS.

The design of experiments has an effect on the number of experiments required. Therefore, it is essential to have a well-design experiment so that the number of experiments required can be minimized. A small central composite design consisting of 20 experiments used in this experiment is shown in the table below.

Table 3.1: DOE developed using STATISTICA

2**(2) central composite, nc=4 ns=4 n0=2 Runs=10 (Spreadsheet17)
+ 1 replications

Standard Run	Replicate	v	f
14	2	150	0.15
20c	2	120	0.1
1	1	90	0.05
11	2	90	0.05
9c	1	120	0.1
7	1	120	0.029289
2	1	90	0.15
16	2	162.4264	0.1
17	2	120	0.029289
13	2	150	0.05
3	1	150	0.05
5	1	77.5736	0.1
10c	1	120	0.1
8	1	120	0.170711
6	1	162.4264	0.1
15	2	77.5736	0.1
12	2	90	0.15
19c	2	120	0.1
18	2	120	0.170711
4	1	150	0.15

3.5 WEAR MEASUREMENT

The tool is examined after completing each pre-determined cutting time until the last experiment. The average for maximum flank and crater wear are measured by OLYMPUS BX51M upright optical microscope in figure 3.6 with a magnification of 5X. All the data then will be use to develop the diamond tool wear curve and also to be analyzed in STATISTICA to see the relationship between the independent variable and dependent variable which is the relation between machining parameter and the average flank wear and crater wear. STATISTICA analysis is adopted to identify the significant parameters that affect diamond tool wear. Finally diamond tool wear is compared with carbide tool wear reported in literature.

Figure 3.6: OLYMPUS BX51M upright optical microscope

CHAPTER 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

This chapter will present the result from the experiment. The data then will analyzed using STATISTICA.

4.2 WEAR MEASUREMENT

The wear progress of diamond tool during turning of titanium was investigated. Although there are more type of wears, only the flank wear and crater wear were observed because these wears form were more significant compared to others. Figure 4.1 and figure 4.2 show the condition of both wear after running a few of experiments. Both wears were measured using 5X under OLYMPUS BX51M upright optical microscope. Wear values were entered in DOE table 3.1 for statistical analysis in STATISTICA. However since only one insert was used throughout the experiments and the other half of DOE was replication, only the experimental runs without replication were analyzed for statistical significant. The following section presents results from STATISTICA. Table 4.1 is shown the experimental results for both wears.

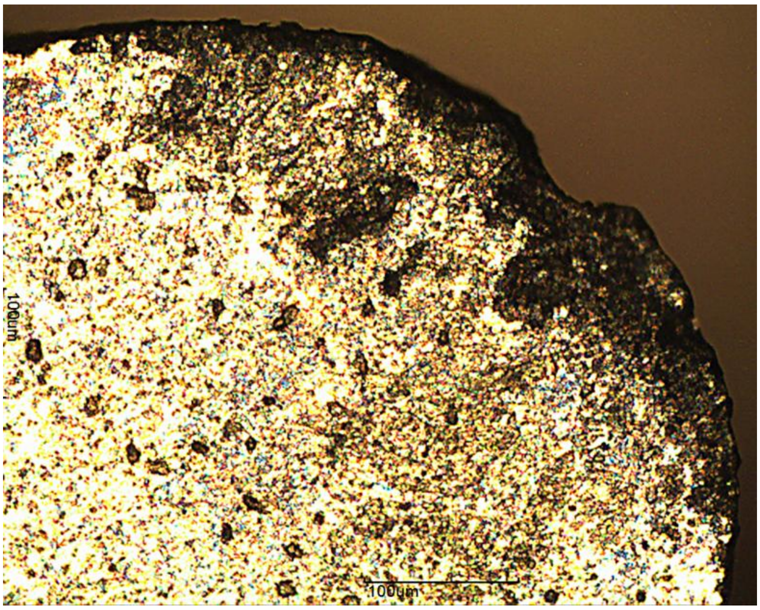


Figure 4.1: Crater wear

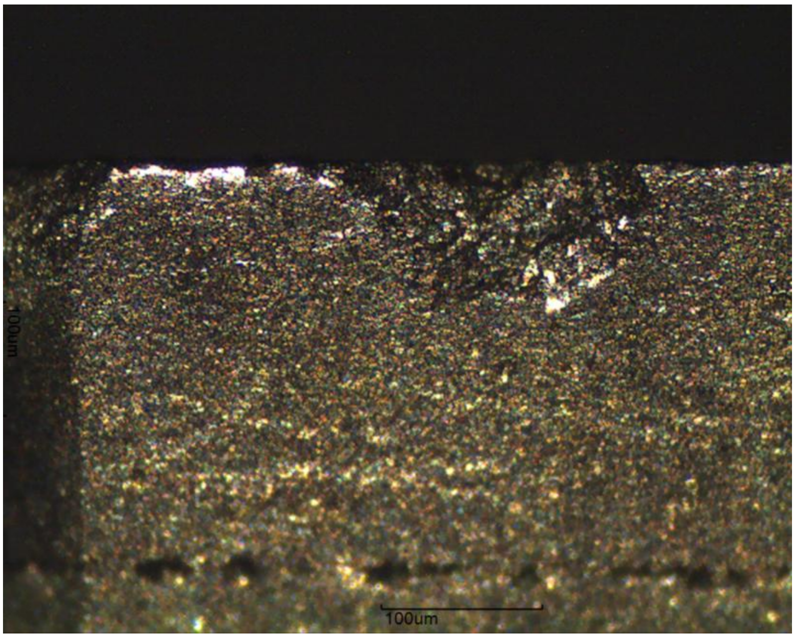


Figure 4.2: Flank wear

Table 4.1: Experimental results

V (m/min)	f (mm/rev)	fw (μm)	cw (μm)
90	0.05	3.7975	68.3544
77.5736	0.1	15.1899	69.6203
90	0.15	35.443	73.4177
120	0.1	46.8354	83.5443
120	0.1	55.6962	87.3418
150	0.15	68.3544	93.6709
120	0.02929	77.2152	96.2025
120	0.17071	87.3418	97.4684
162.426	0.1	91.1392	101.266
150	0.05	92.7342	105.861

Legend:

V = Cutting Speed (m/min)

f = Feed rate (mm/rev)

fw= Flank wear (μm)

cw= Crater wear (μm)

4.3 CUTTING SPEED AND FEED RATE AGAINST FLANK WEAR

Table 4.2 shows the anova result for the flank wear. According to Anova, the parameter cutting speed for the linear term affects flank wear significantly as P-value less than 0.05 while for the quadratic term, it has less significant cause P-value is higher than 0.05. For the feed rate, both linear and quadratic terms have less significant. So it is shown that feed rate not give more effect for the both wears in this experiment. The amount of experimental error was found to be 7.67% which is accpetable for CNC turning centre.

Table 4.2: Anova for flank wear

	Anova ; Var.:FW; R-sqr=.92331; Adj:.82746 (Spreadsheet47) 2 Factors, 1 Blocks, 10 Runs; MS Residual=173.4552 DV: FW				
Factor	SS	df	MS	F	p
(1)CS (L)	6569.25	1	6569.83	37.8762	0.003537
CS (Q)	54.739	1	54.739	0.31558	0.604259
(2)FR (L)	58.249	1	58.249	0.33582	0.593325
FR (Q)	562.901	1	562.901	3.24523	0.145992
1L by 2L	784.709	1	784.709	4.52398	0.100551
Error	693.821	4	173.445		
Total SS	9047.529	9			

The normality plot is a graphical technique for assesing wheter or not a data set is approximately normal distributed. The data are plotted against a thereotical normal distribution in such a way that the point should form an approximate straight line. Departures from this straight line indicate departures from normality. Normal distribution assumption was vertied in figure 4.3. As shown in the figure, residual values are scattered near by normal value which indicated that normal assumption is valid.

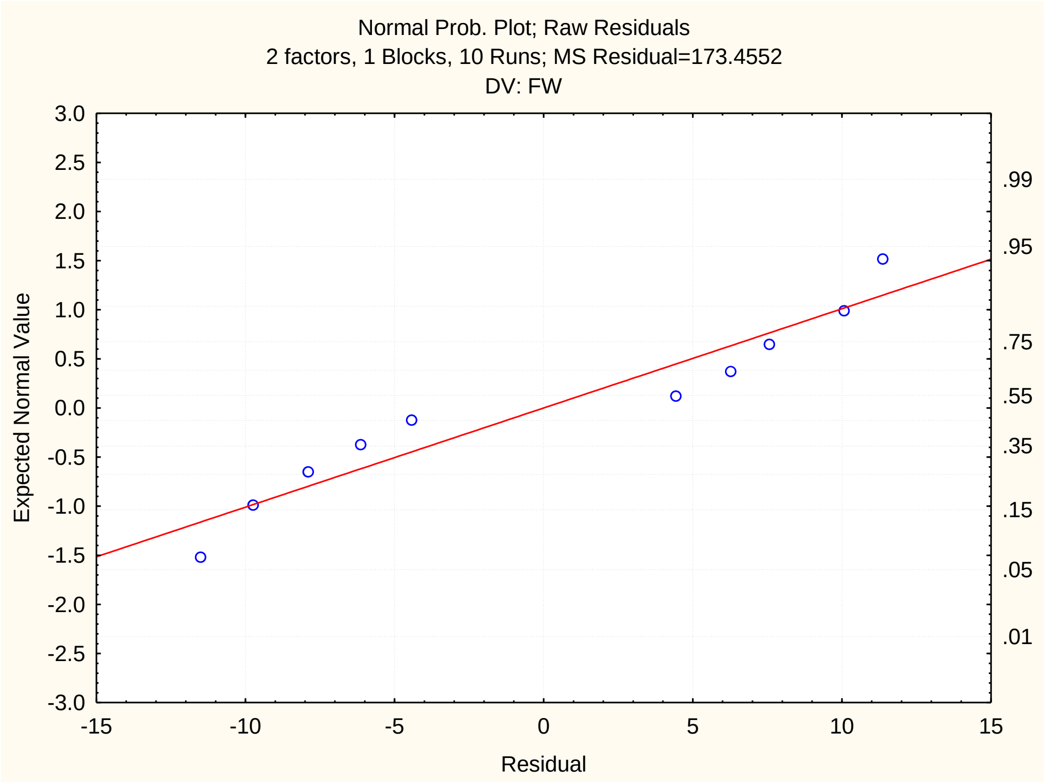


Figure 4.3: Normality plot for flank wear

The model for statistical analysis was linear main effect + 2 ways set by default. The approximation of the model was examined in figure 4.4 which shows the choosen best model data and experimental data. As seen in figure 4.4, almost all experimental points scatters near by predicted values and it is still acceptable as a good choice since the R-square is more than 80%.

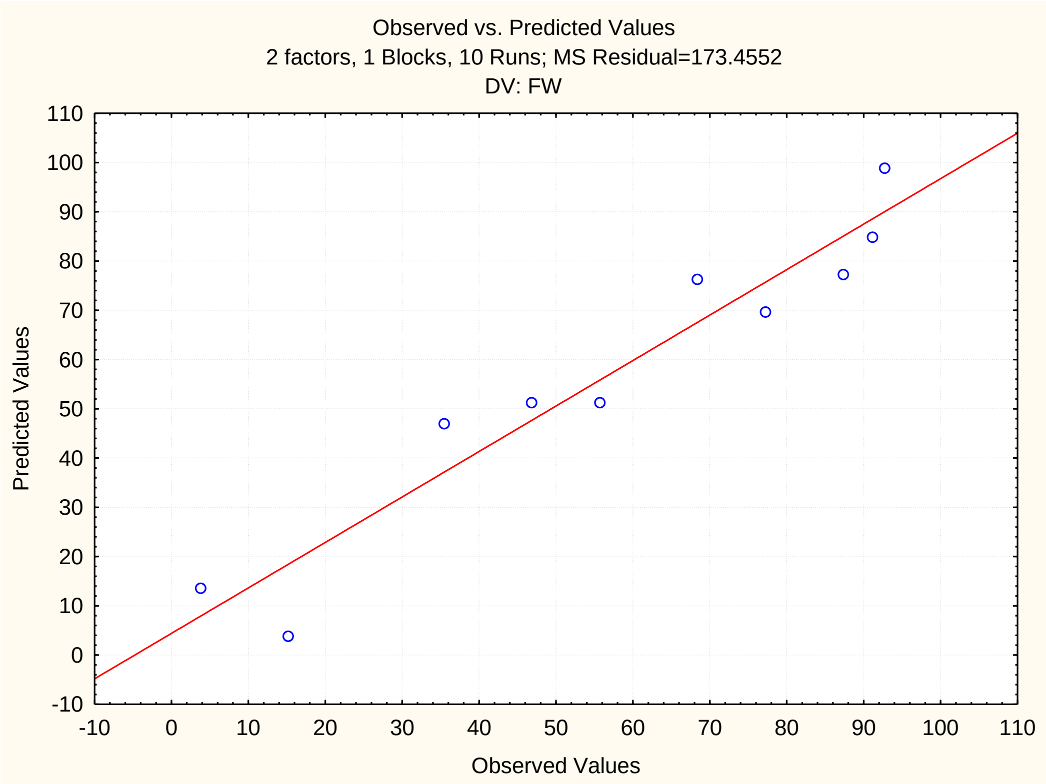


Figure 4.4: Observed VS predicted value

Figure 4.5 shows the contour plot of parameters combination. This plot is very useful to identify acceptable process parameter set that would lower than down tool wear. Since the lower flank wear is desirable, green region shows the suitable combination for minimum possible flank wear with the parameter range considered.

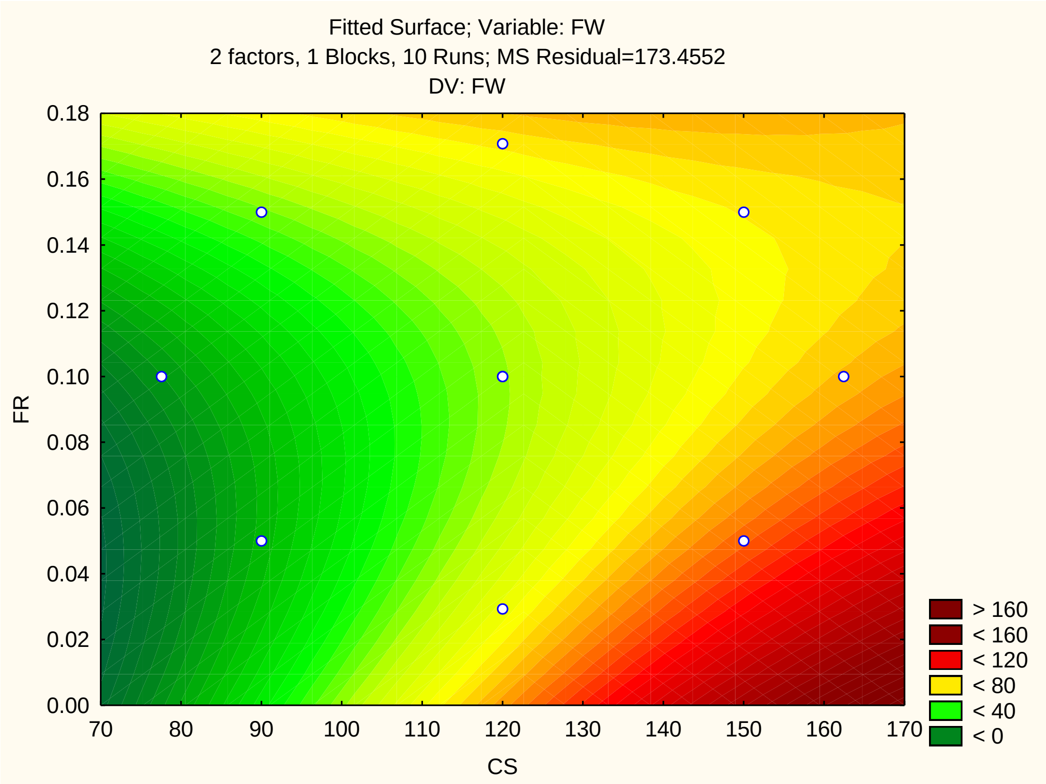


Figure 4.5: Surface contour plot for flank wear

4.4 CUTTING SPEED AND FEED RATE AGAINST CRATER WEAR

Table 4.3 shows the anova result for the crater wear. Due to Anova table, it is indicates that the parameter cutting speed for the linear term again affects crater wear significantly as P-value less than 0.05 while for the quadratic term, it is still less significant. Similar with the flank wear, both terms of feed rate are also less significant. The amount of experimental error was found to be 6.91% and it is still accpetable for CNC turning centre.

Table 4.3: Anova for crater wear

	Anova ; Var.:CW; R-sqr=.93089; Adj:.8445 (Spreadsheet59) 2 Factors, 1 Blocks, 10 Runs; MS Residual=203.2259 DV: CW				
Factor	SS	df	MS	F	p
(1)CS (L)	8820.44	1	8820.44	43.40216	0.002749
CS (Q)	123.77	1	123.767	0.60901	0.478761
(2)FR (L)	82.33	1	82.328	0.4051	0.559064
FR (Q)	801.72	1	801.716	3.94495	0.117963
1L by 2L	582.09	1	582.093	2.86427	0.165823
Error	812.9	4	203.226		
Total SS	11762.24	9			

The normal probality plot of expected normal value versus residual value is shown in figure 4.6. It does not exhibit any particular bias in any part of the data. However the spread of the points around the fitted line is somewhat uneven. The spread is larger for smaller values of expected normal values. Figure 4.6 shows the residual values are normally distributed when the values of expected is more than -0.6. However the expected normal value less than -0.6 can be considered as outliers because the points were deviated from the normal plot.

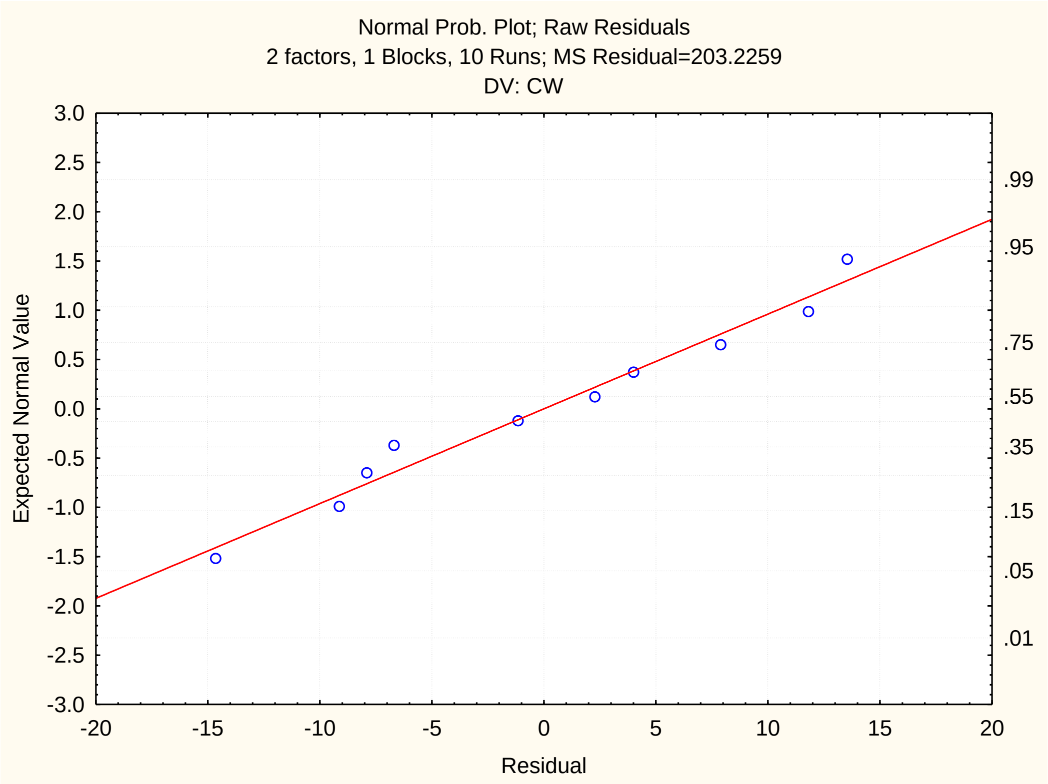


Figure 4.6: Normality plot for crater wear

Figure 4.7 indicates that the data can be used for other analysis as the observed values plot are lies near to the predicted value line. The model for statistical analysis was linear main effect + 2 ways set by default. Although, most of the experimental values are lies far from the predicted values, but due to R-square value, the experiment is still can be continued.

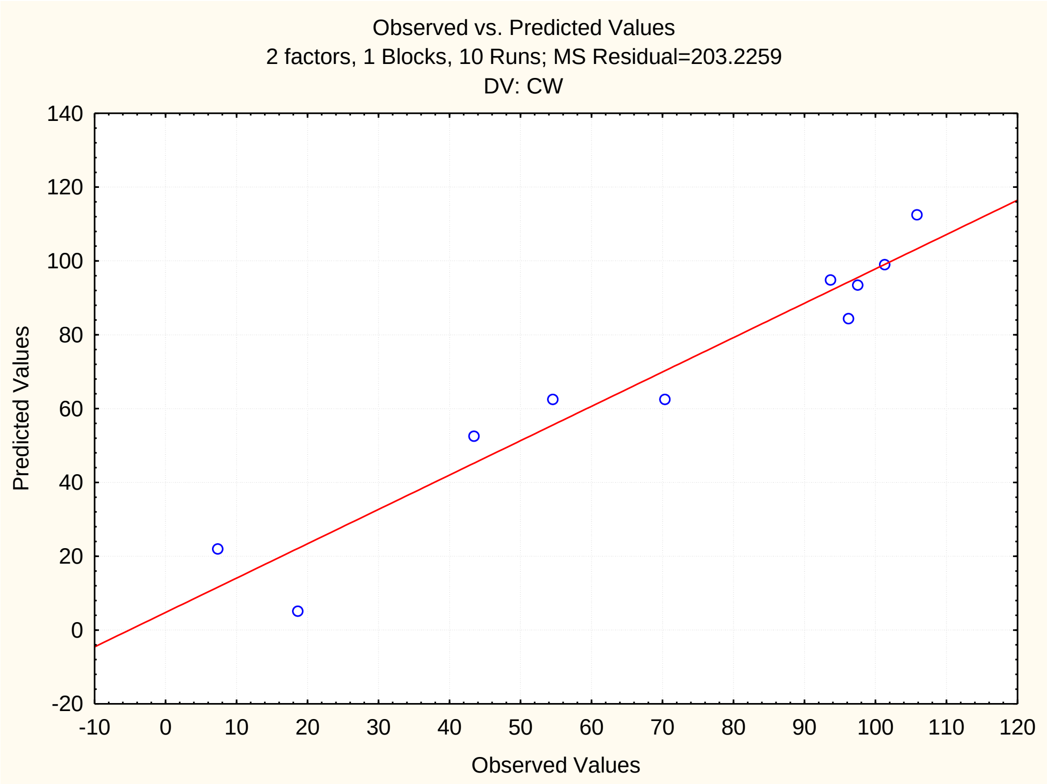


Figure 4.7: Observed VS predicted value for crater wear

The last criteria to be determine in this section is to find the range of cutting speed and feed rate for the crater wear. Figure 4.8 below shows that the combination both parameters between 85-95 mm/min and 0.12-0.15 mm/rev were located in the green region which is the minimum value for the crater wear. From the figure below, combination for cutting speed and feed rate between 140-160 mm/min and 0.02-0.03 mm/rev are give the more effect on both wears.

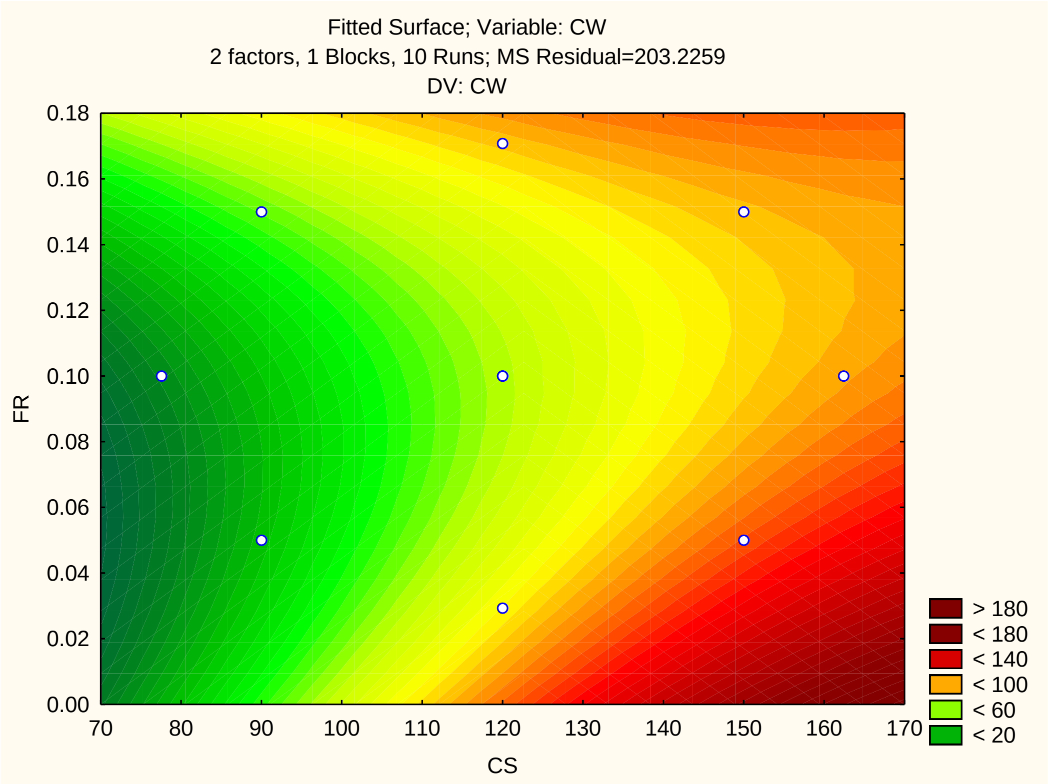


Figure 4.8: Surface contour plot for crater wear

4.5 PERFORMANCE OF DIAMOND TOOL

After all analysis was done, the final stage is to investigate the performance of diamond tool for both wear in titanium machining. The main focus in this section is to compare the previous study that stated the crater wear is more critical than flank wear in machining titanium. Table 4.4 shows the visual progress of both wear. From the table, it is clear that effect of feed rate and cutting speed for the both wear can be seen respectively. It is prove that crater wear is more critical than flank wear. Table 4.5 shows the measured value of both wears for increased machining time..

Table 4.4: Tool wear growth under conventional cooling after 50mm cutting length

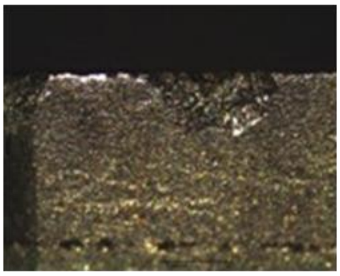
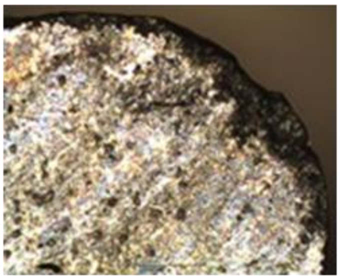
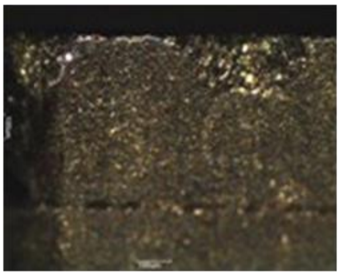
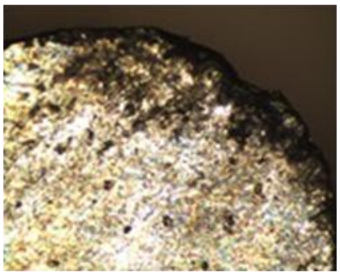
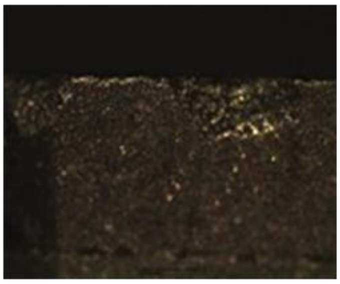
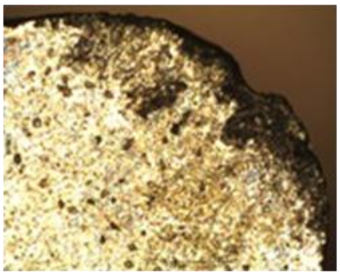
No.Experiment	Flank Wear	Crater Wear
11		
12		
13		

Table 4.5: Wear progress

Machining time (min)	Flank wear (μm)	Crater wear (μm)
0.87	3.7975	7.3544
0.5	15.1899	18.6203
0.29	35.443	43.4177
0.3	46.8354	54.5443
0.33	55.6962	70.3418
0.17	68.3544	93.6709
1.11	77.2152	96.2025
0.2	87.3418	97.4684
0.24	91.1392	101.2658
0.52	92.7342	105.8608
0.87	103.7975	111.3924
0.5	112.6582	113.9241
0.29	115.1899	121.519
0.3	116.4557	129.1139
0.33	121.519	140.5063
0.17	124.0506	146.8354
1.11	125.3165	154.4303
0.2	126.5823	167.0886
0.24	128.7345	171.0442
0.52	130.9242	173.6438

The graph for both wears versus machining time were developed which are shown in figure 4.9 and figure 4.10. Flank wear curve in figure 4.9 does not follow typical wear curve as would be seen in other types of tool such as carbide tools. Its wear increase drastically in earlier machining time and then tends to level-off. On the other hand, crater wear curve in figure 4.10 shows typical trend of tool wear where gradual increase at the early stage and rapid increase other.

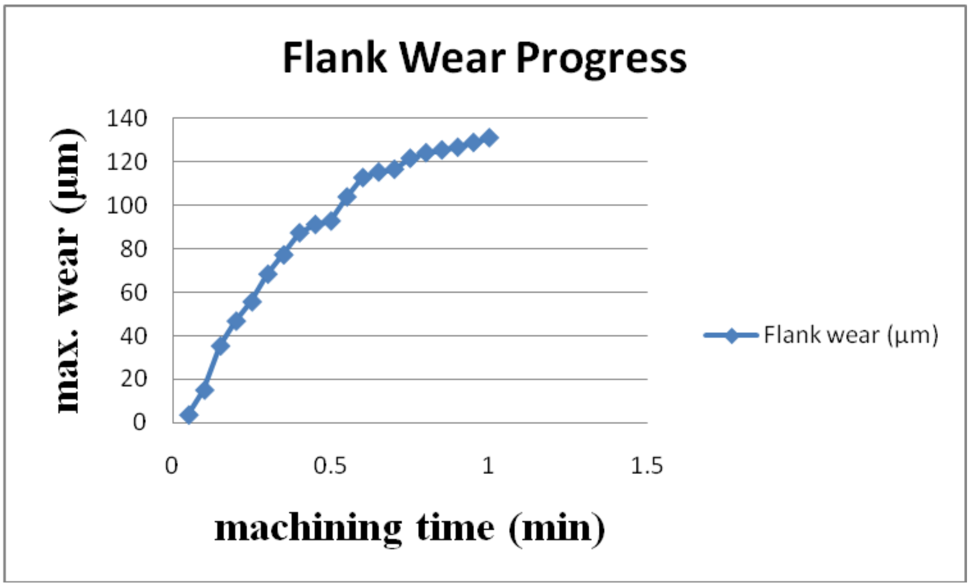


Figure 4.9: Graph of flank wear versus machining time

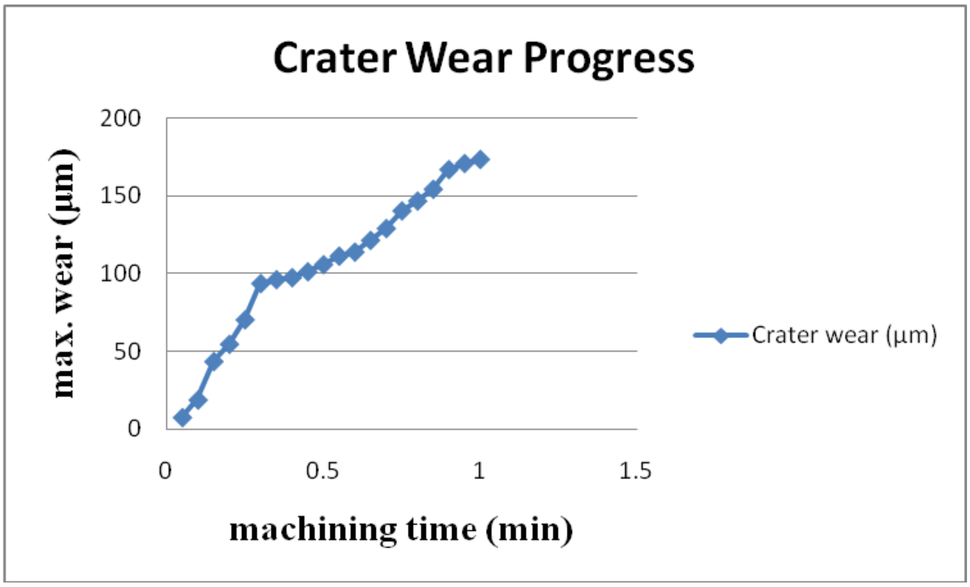


Figure 4.10: Graph of crater wear versus machining time

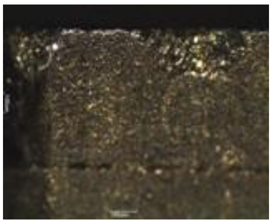
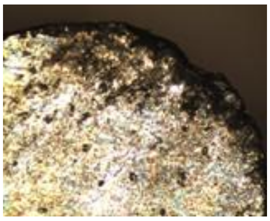
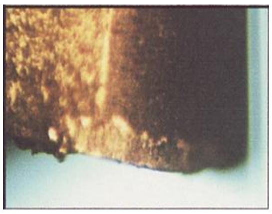
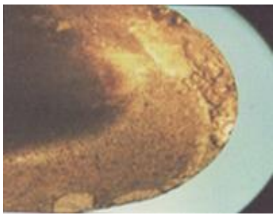
4.6 COMPARISON BETWEEN PCD AND COATED CARBIDE

From the result above, it indicates that PCD has the greater performance in machining titanium. To prove the statement, below is shown some of the data and visual picture between PCD and coated carbide. It is shown that PCD is better than coated carbide. Taking 0.5 min as the machining time, table 4.6 and table 4.7 show the comparison between the two inserts.

Table 4.6: Quantitative comparison

Type of Wear	PCD	Coated Carbide
Flank Wear (μm)	11.3924	217.274
Crater Wear (μm)	11.2659	53.421

Table 4.7: Qualitative comparison

Cutting Tool	Flank wear	Crater Wear
PCD		
Coated Carbide		

4.7 DISCUSSION

The first half of the experiment result was analyzed in the STATISTICA as the second half is repeatable process and obviously the wear is not repeatable. The wear of diamond tool is generally much slower than conventional coated carbide tool. Flank wear curve does not follow typical trend of other tools whereas crater wear is almost similar to typical wear curve.

From the analysis, it had been the possible error that affects the experiment outcome. The inconsistency of wear values as can be seen in the results might due to the presence of several phenomena, such as workpiece deflection under strong rotating forces, vibration of the machine tool and heat generated by plastic deformation.

4.7.1 Workpiece deflection

Workpiece deflection under strong rotating forces caused the true depth of cut to be different from the nominal one. Non infinite stiffness of the tool-machine-workpiece system implies elastic deformations of the machine tool structure or of the clamping device. The unknown geometry of the raw part also made the true cutting depth different from the planned one. Therefore, workpiece deflection is recognized as one of the main sources of dimensional and geometric errors in precision machining.

4.7.2 Vibration of the workpiece

Vibration of the workpiece due to rotating is a critical aspect of manufacturing errors during turning machining. Workpiece deflection is recognized as one of the main sources of dimensional and geometric errors in precision machining. Workpiece vibration is a very significant problem due to turning process because of the high cutting forces generated and the very small tolerances required on produced parts.

4.7.3 Heat generated

Heat generated by plastic deformation and friction involved in chip deformation was transferred to the workpiece, tool and machine tool. Subsequently, the chips produced during machining also caused scratches on the titanium surface. This eventually affected the surface roughness of titanium.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 INTRODUCTION

This section will be stated the conclusion of the overall experiment and also some recommendations to improve the experiment in the future.

5.2 CONCLUSION

Based on micrograph study, flank wear and crater wear has been formed as a major wear form on diamond tool during machining titanium. The cutting speed was the most significant machining parameter that affects the wear. In this project, diamond tool wear when machining titanium has been successfully investigated using STATISTICA software and optimal microscope. Crater wear and flank wear curve had been developed in machining titanium. Generally diamond tool wear is far less than coated carbide in machining titanium and it shows that PCD wear progress is slow.

5.3 RECOMMENDATIONS

In order to improve the experiment in the future, there are some recommendations here that had been provided to get excellent result:

i. Use the proper optimal microscope
ii. Etching the cutting tool edge in hydrofluoric acid (HF) to remove any unbound material that might present before performing the analysis
iii. An additional for machining time to determine total machining time for titanium
iv. Use the cryogenic as a coolant

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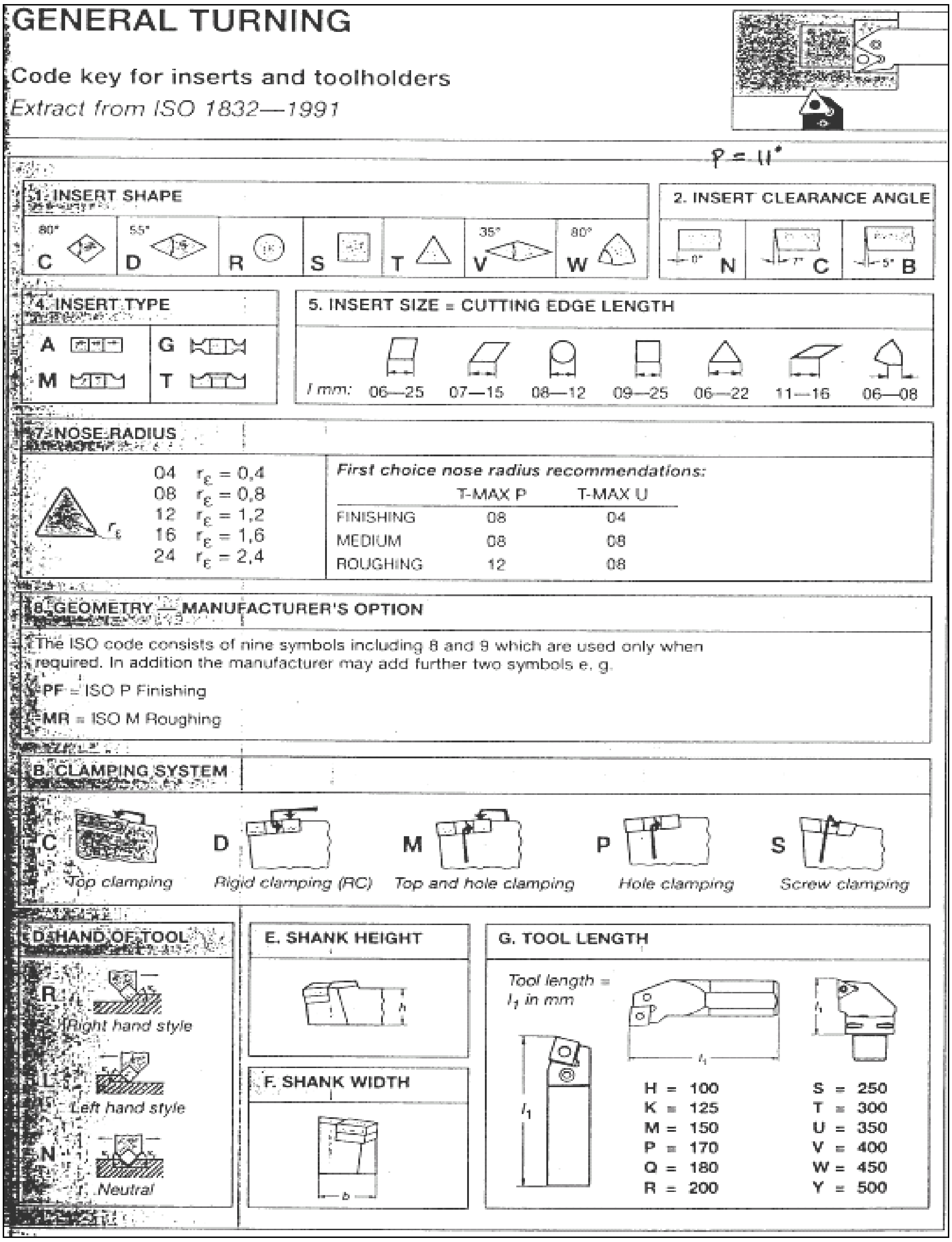
Appendix A1

(I) ISO- Designation of Turning Tool Geometry



GENERAL TURNING

Code key for inserts and toolholders

Extract from ISO 1832—1991

ρ = 11°

1. INSERT SHAPE

80° C | 55° D | R | S | T | 35° V | 80° W

2. INSERT CLEARANCE ANGLE

0° N | 7° C | 5° B

4. INSERT TYPE

A | G | M | T

5. INSERT SIZE = CUTTING EDGE LENGTH

l mm:	06—25	07—15	08—12	09—25	06—22	11—16	06—08

7. NOSE RADIUS

04	r_ε = 0,4
08	r_ε = 0,8
12	r_ε = 1,2
16	r_ε = 1,6
24	r_ε = 2,4

First choice nose radius recommendations:

	T-MAX P	T-MAX U
FINISHING	08	04
MEDIUM	08	08
ROUGHING	12	08

8. GEOMETRY — MANUFACTURER'S OPTION

The ISO code consists of nine symbols including 8 and 9 which are used only when required. In addition the manufacturer may add further two symbols e. g.

PF = ISO P Finishing

MR = ISO M Roughing

B. CLAMPING SYSTEM

C *Top clamping* | D *Rigid clamping (RC)* | M *Top and hole clamping* | P *Hole clamping* | S *Screw clamping*

D. HAND OF TOOL

R *Right hand style*

L *Left hand style*

N *Neutral*

E. SHANK HEIGHT

h

F. SHANK WIDTH

b

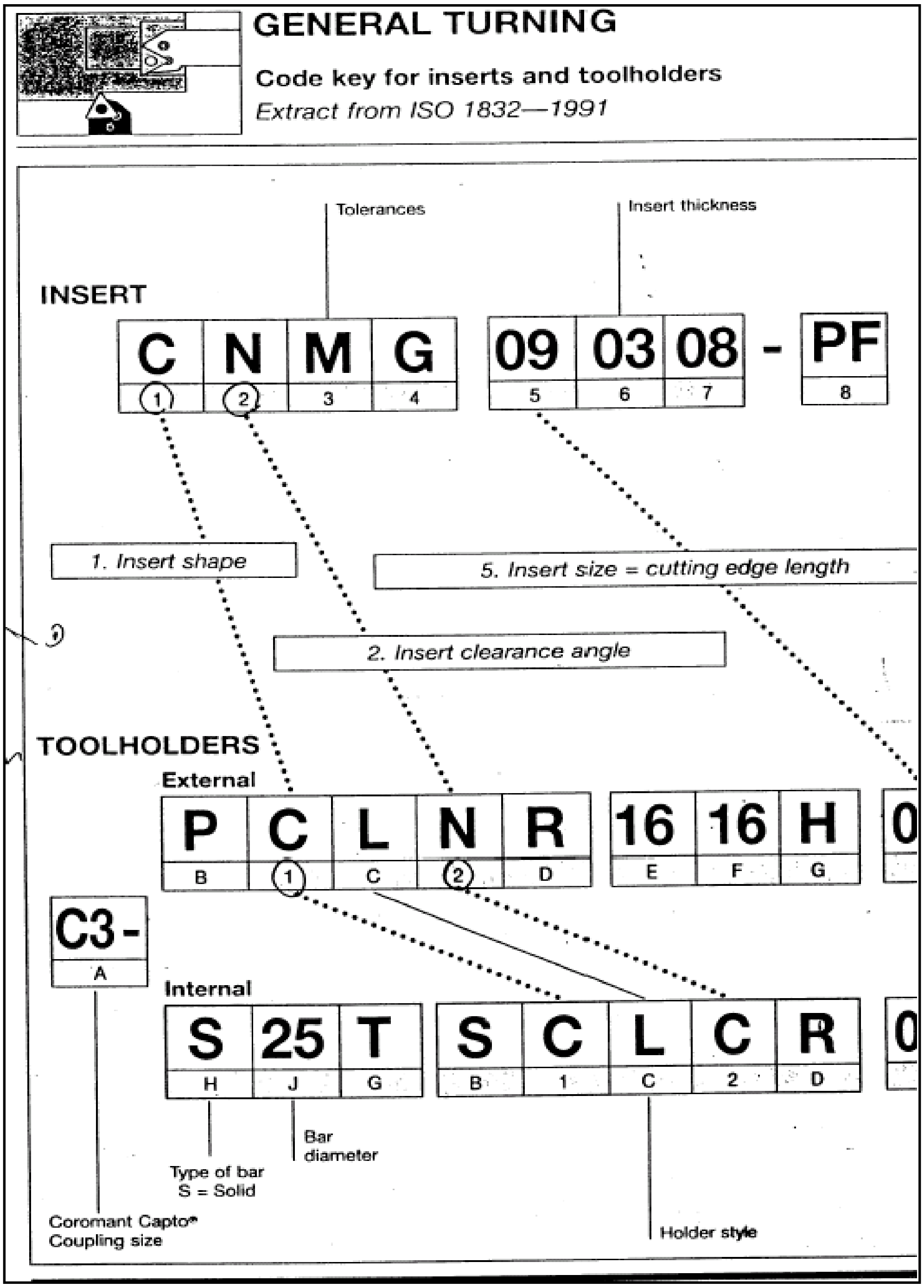
G. TOOL LENGTH

Tool length = l_1 in mm

H =	100	S =	250
K =	125	T =	300
M =	150	U =	350
P =	170	V =	400
Q =	180	W =	450
R =	200	Y =	500

Appendix A2

(II) ISO- Designation of Turning Tool Geometry



BORANG PENGESAHAN STATUS TESIS

JUDUL **PERFORMANCE OF DIAMOND TOOL IN MACHINING TITANIUM**

SESI PENGAJIAN: **2010/2011**

Saya _______________**AHMAD NAZMI BIN MOHD ROSE**__________
(HURUF BESAR)

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UNIVERSITI MALAYSIA PAHANG

FACULTY OF MECHANICAL ENGINEERING

I certify that the project entitled "Performance of Diamond Tool in Machining Titanium" is written by Ahmad Nazmi Bin Mohd Rose. I have examined the final copy of this project and in my opinion; it is fully adequate in terms of scope and quality for the award of the degree of Bachelor of Engineering. I herewith recommend that it be accepted in partial fulfillment of the requirements for the degree of Bachelor of Mechanical Engineering with Manufacturing Engineering.

Dr. Abdul Adam Bin Abdullah ………………………….

Examiner Signature