0708-F-011 CRYOGENIC- ASSISTED HIGH SPEED MACHINING

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A report submitted in partial fulfillment of the requirements for the award of the degree of Bachelor of Mechanical Engineering With Manufacturing Engineering

Faculty of Mechanical Engineering
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SUPERVISOR DECLARATION

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

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STUDENT DECLARATION

I declare that this thesis entitled *"Cryogenic Assisted High Speed Machining"* is the result of my own research except as cited in the references. The thesis has not been accepted for my degree and is not concurrently candidature of any other degree.

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To my Beloved Parents

EMLEY AHUA

LIMGIME EMLEY NEGGOG

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ABSTRACT

Titanium and its alloys are widely used in various industries mainly aviation. However, it is considered as difficult-to-machine material due to its unusual high cutting temperature, which leads to many research works on machinability of this material. In the current work, tool wear of titanium aluminum nitride (TiAlN) coating insert in turning of Ti-6Al-4V have been experimentally studied under conventional wet and cryogenic cooling. After each machining time, the tool edge was observed under microscope. Wear images were captured and analyzed by the image analyzer to identify different forms of wear occurrence. Experimental results have shown that for high cutting speed cutting, insert worn rapidly and also chipped in the case of wet turning, whereas no appreciable wear was found in cryogenic turning. In summary, this project achieved the objectives whereby the cryogenic coolant give positive influence on the tool wear.

ABSTRAK

Aplikasi penggunaan titanium dan titanium alloy pada hari ini amat meluas terutama dalam bidang aeroangkasa. Walaubagaimanapun, bahan ini dikategorikan sebagai bahan-sukar-dimesin di atas faktor penjanaan suhu memotong yang luar biasa, dimana ini telah menyumbang kepada pelbagai kerja penyelidikan bagi mengenal pasti sifat bahan ini. Dalam projek ini, kehausan mata alat titanium aluminum nitride (TiAlN) semasa proses larikan Ti-6Al-4V dengan cecair penyejuk tradisional dan cecair penyejuk jenis cryogenic telah dikaji secara experimen. Muka alat dikaji selepas satu jangka masa proses larikan dibuat. Gambar kehausan yang berlaku di mata alat diambil dan dianalisis dengan menggunakan “image analyzer”. Hasil kajian pada kelajuan memotong tinggi menunjukkan mata alat mengalami kehausan yang cepat dan mata alat turut terserpih semasa proses penyejukan tradisional digunakan, manakala tiada kehausan mata alat berlaku ketika penyejuk cryogenic diaplikasi. Sebagai kesimpulan, projek yang telah dijalankan mencapai objektif dimana cecair penyejuk jenis cryogenic mampu memberi kesan positif kepada kehausan mata alat.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter gives a brief description of the project progress including approaches o method application. It includes project background, problem statement, objective and scope of the project on role play by cryogenic cooling in machining.

1.2 Project Background

Titanium is not a new metal in nowadays industry field. It has approximately 60% of the density of steel and alloying would greatly strengthen it. Titanium already enter the industry as a special material with great values such as the combination of high specific strength, heat resistant, good toughness, and other positive properties allows strength-weight ratio saving in high-performance application. It is also nonmagnetic and has good heat-transfer properties. [1]

Titanium popularity increase tremendously these days drive development in machining technology focused on better productivity. In machining operation, heat generated during cutting commonly concentrated at the cutting edge of cutting tool and workpiece. Common prevention way is usage of conventional coolant that would acts as lubricant at relatively low cutting speeds and cooling at high cutting speeds. Correct use of coolants will greatly reduce cutting tool wear and prolonged tool life. However, conventional coolant did not serve as an efficient cooling system. Cryogenic cooling which uses liquid nitrogen as coolant is the alternative ways to bringing down the heat generated.

1.3 Problem Statement

The titanium alloys that have been introduced on the industry meet the requirements needed but the drawback is they are among the most troublesome materials to be machine. The machinability of titanium alloys are limited by their low thermal conductivity and volume specific heat. The machining problem usually encountered is high cutting temperature during the cutting operation.

High cutting temperature affects tool wear, dimensional and form accuracy, surface integrity of the product, inherently characterizes high-speed machining. The excessive tool wear results from high cutting temperature would cause cutting tools failure due to the mechanical breakage, cutting edge blunting, or plastic deformation.

1.4 Project Objective

The aim of this study is to investigate the role of cryogenic cooling on the growth of tool wear in the turning process of titanium alloy, Ti-6Al-4V.

1.5 Scope of Project

The study is focus on turning of Ti-6Al-AV under nitrogen gas, GAN as the cryogenic coolant. Titanium aluminum nitride coated triangular inserts are selected for cutting tools. Cylindrical turning of the alloy is carried out on conventional lathe machine. Machining parameters considered are depth of cut, feed rate and cutting speed. Constant depth of cut and feed were set based on literature. The cutting speed varied range from 70, 90 and 110 m/min . Tool wear image are captured and measurement done by using IM 1700 Series Image Analyzer.

For comparison purpose, wet turning of Ti-6Al-4V done by using conventional coolant at machining parameters of 110m/min, depth of cut 1.00mm and feed 0.1 mm/rev. Tool wear will be compared for the same machining parameters under cryogenic cooling condition.

1.6 Summary

Chapter 1 has been discussed briefly about project background, problem statement, objective and scope of the project on role play by cryogenic cooling in machining to achieve the objective mentioned. This chapter is as a fundamental for the project and act as a guidelines for project research completion.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

From the early stage of the project, various literature studies have been done. Research journal, books, printed or online conference article were the main source in the project guides. The reference sources emphasize on important aspect of titanium alloy machining such as machining parameters, cutting tool, tool wear, surface integrity and the appropriate coolant application.

2.2 Titanium Alloy Machinability

Machining is a major process in the industry in which turning is among the most widely used operations. It has wide application and refers to all types of metal removal which include turning, boring, drilling, reaming, tapping, grinding, milling, gear hobbing and others. Machining titanium alloys were historically been perceived as a difficult-to-machine alloys. Most of the time titanium is classified as difficult-to-machine method can be explained by the properties of this metal as example below [Donachie,1988]:

i. Poor Heat Conductivity

During metal cutting, heat is generated due to the deformation of the material ahead of the tool and also friction at the tool point Heat is generated by the metal cutting action causes a change in the temperature of the workpiece, fluid used and the tool. The heat generated is dissipated to the workpiece, and tool. Titanium alloy's poor heat conductivity increases the temperature at tool cutting edge hence it wears off rapidly.

ii. Work-Hardening Characteristics

Due to its work-hardening characteristics, titanium alloys oppose a complete absence of 'built-up edge" which causes the forming of high shearing angle. This would results high bearing loads per unit area of cutting tool. The combination of high bearing force and the friction force will cause tremendous increases of heat hence resulting in rapid tool breakdown.

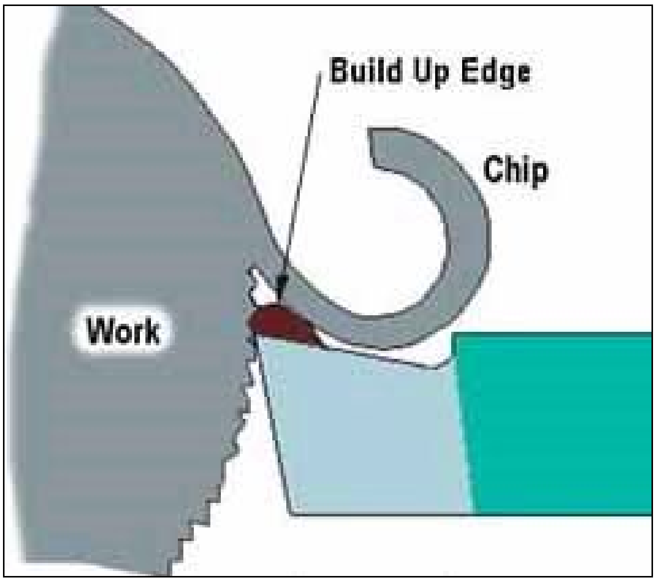


Figure 2.1: Build Up Edge

iii. Serrated Chips Formation

This type of chip formation creates fluctuations in the cutting force especially when alpha-beta alloys likewise titanium alloy, Ti-6Al-4V are machined. Severe flank wear were believed to be partially caused by micro fatigue loading on the tool due to the vibration force, high temperature generation.

2.3 Machining – Turning Process

Turning is the simplest machining operation used for the study of machinability of various materials. Typical machine employed for turning process is conventional lathe or computer-numerical controlled turning center. In either type of machine, basic working principle is the same. The lathe holds the workpiece in cylindrical shape between two rigid supports called chuck which revolves about the centre line of the lathe. The spindle carrying the work is rotated whilst a cutting tool, which is supported in a tool post, is made to travel in a certain direction depending on the form of surface required. If the tool moves parallel to the axis of the rotation of the work a cylindrical surface is produced as in Figure 2.2. Major machining parameters involved in turning process are cutting speed, feed rate and depth of cut. These parameters can be schematically described in Figure 2.3.

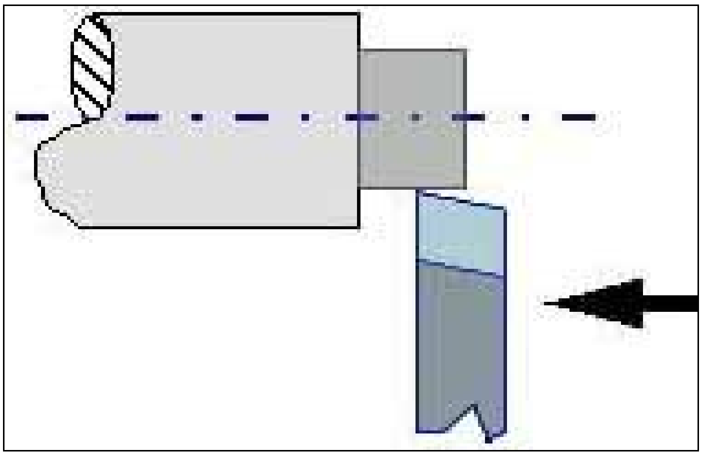


Figure 2.2: Cylindrical Turning of Titanium Bar

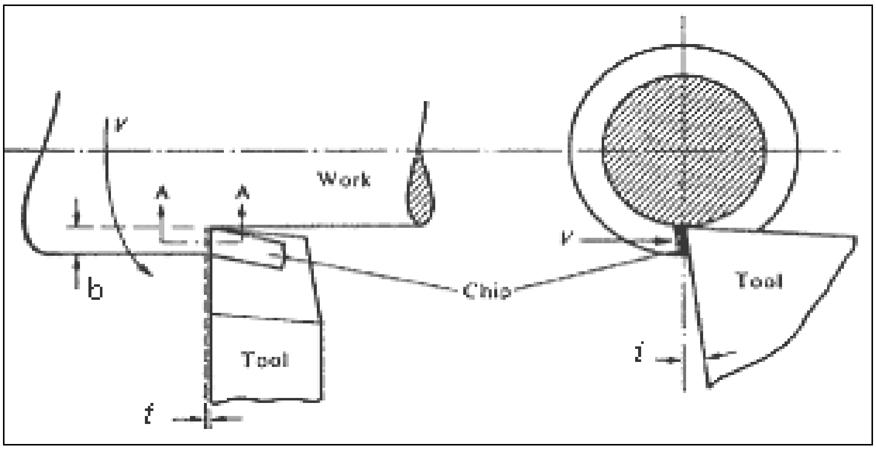


Figure 2.3.: Schematic of turning process showing cutting speed (V), feed rate (t) and depth of cut (b).

The term high-speed machining is subjective and relative. It is very often defined based on the range of cutting speed (V in m/s or m/min) used in the machining. Typical cutting speed that can be used to machine titanium alloys, for instance, on less rigid conventional machine may range 50 – 70 m/min. As the new machine is becoming more rigid, the cutting speed can be increased. Nowadays cutting speed to machine difficult-to-machine like titanium can be as high as 300 m/min with high rigidity machine [Che-Haron, 2001].

In the study of machining-related problems, metal cutting processes are simplified into two-dimensional problem. Figure 2.4 describes the terms and their definitions used in 2D orthogonal cutting arrangement. As shown in the right of Figure 2.4, the wedge-shape tool basically consists of two surfaces intersecting to form the cutting edge. The surface along which the chip flows is known as the rake face, or simply as the tool face and that ground back to machined surface is known as the flank.

The depth of the individual layer of material removed by the action of the tool is known as the undeformed chip thickness. One of the most important variables in metal cutting is the slope of the face and this slope is specified in orthogonal cutting by the angle between the tool face and a line perpendicular to the new work surface. This angle is known as the rake angle. The rake angle can be positive, zero or negative as shown in the right of Figure 2.4. The tool flank plays no part in the process of chip removal; however the angle between the flank and the new work surface can significantly affect the tool wear rate and is defined as the clearance angle.

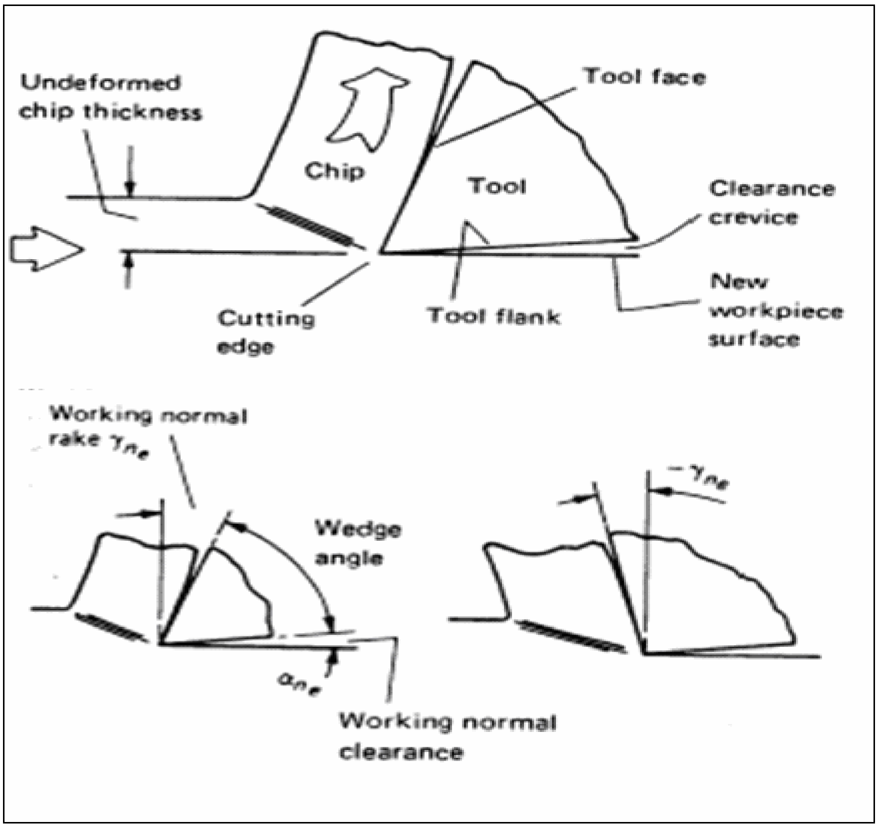


Figure 2.4: Terminology used in orthogonal metal cutting (Boothroyd, 1975).

2.4 Cutting Tools

Cutting tool is one of the most important devices in manufacturing processes. The basic research on design and manufacture of cutting tools for various machining process have become quite significant since the early fifties. Since then, the design of cutting tools has revolutionized from simple regrindable single-pointed tool with the tool shank to disposable inserts of various geometries made of advanced materials [Shaw, 2005; Jawahir, 1988]. Tool materials have also been improved from common high-speed steel and carbide to advanced carbides coated with various coatings of better toughness, hardness and heat-resistant properties.

Cutting tool geometries are standardized according to ISO designation. Major geometric information for a cutting tool are shape, rake angle, flank (or clearance) angle, included angle and approaching angle. Some useful definitions of ISO designation are given in the Appendix. Details can be found in tooling catalogue such as Kennametal. Figure 2.5 illustrates some disposable turning inserts of various geometries.

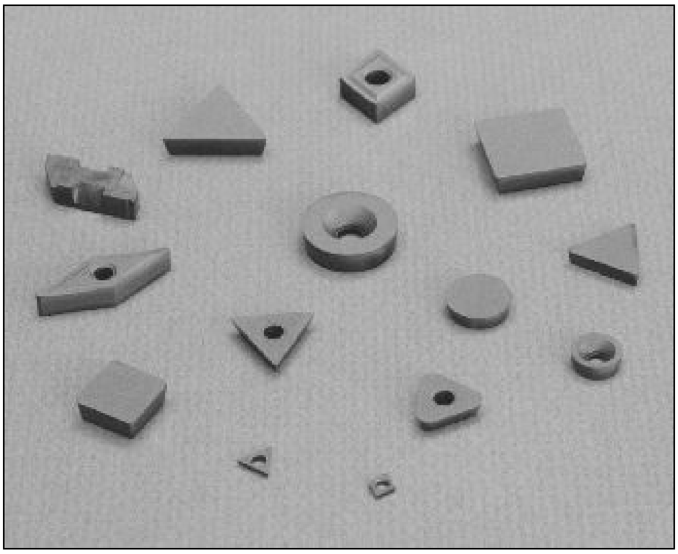


Figure 2.5: Various turning inserts

2.5 Cutting Fluids

One of the aims in any metal cutting is to have a longer cutting tool life. The most significant way to achieve this is by application of cutting fluids to carry away the heat generated. The use of a cutting fluid will serve not only to reduce the tool wear, but also give better surface finish and good dimensional control. The proper selection, mixing and application of cutting fluids is crucial especially in titanium alloy machining operation. Correct use of coolants will greatly reduce the cutting tool wear thus increasing tool life. Large quantity of cutting fluids is needed to dissipate heat generated during machining operations of titanium. Best tool life can be achieved by utilization of correct coolant. Common type of coolant used in metal machining are:

i. **Soluble Oils**

Oil will not dissolve in water but can form an intimate mixture or emulsion by adding emulsifying agents. These fluids have average lubricating abilities and good cooling properties. Soluble oils are suitable for light cutting operations on general purpose machines where high rates of metal removal are not main concern. Since there are many forms of soluble oil in the market, the suppliers' instruction should be followed regarding the proportions of the `mix' to obtain its best functionality.

ii. Mineral Oils

Mineral oils are suitable for heavier cutting operations because of good lubricating properties and are commonly found in production machines where high rates of metal removal are employed. Mineral oils are very suitable for steels but should not be used on copper or its alloys since it has a corrosive effect.

iii. Water

It has a high specific heat but is poor in lubrication. It is used as a cooling agent during grinding operation.

iv. Alternatives Coolant

Prompted by the environmental concern about conventional cutting fluid such as oil based coolant, cryogenic coolant received increase attention. Since cryogenic coolant is environmental friendly, and did not pose health threat to machine operator, many research studies on cryogenic machining have been done. Results obtained mentioned it positively affects tool life, surface integrity and dissipate more heat than conventional coolant.

2.6 Cryogenic Machining

Work of Hong (1999) involved on the temperature effects in titanium properties and different cryogenic cooling strategies comparison. New economical cryogenic cooling approach was developed and the results shows there are advantages compared to conventional cooling. The main benefits are the tool life is extended by five times and the workpiece having better surface finish due to better chip handling. Modified tool for coolant application provides effective cooling that removed more heat from the machining zone area thus improving the tool life (Ahsan Ali, 2007)

Venugopal, Paul and Chattopadhyay (2006) has studied the microcrystalline uncoated carbide tool wear resulted in cryogenic turning of Ti-6Al-4V alloy bars. Results have been compared with dry and wet machining with soluble oil coolant. It has been reported that cryogenic cooling by liquid nitrogen jets enabled substantial improvement in tool life through reduction in adhesion–dissolution–diffusion tool wear through effective control of machining temperature at the cutting zone.

Choudhury (2006) has carried the experimental investigation of cryogenic cooling effects on tool wear during high speed machining of stainless steel. The experimental results obtained shows the flank wear is reduced by 37.39% than in dry cutting machining. The cutting temperature that attribute to tool wear also decreasing, thus tool life is improved. It is concluded that cryogenic cooling is high speed machining coolant alternatives as it more advantageous at high speed.

Experimental investigation of cryogenic cooling by Dhar et al. (2001) on tool wear and product quality in plain turning of steel by two types of carbide inserts of different geometry. Cutting forces and temperature were found to reduce while machining steel with tribologically modified carbide inserts. The most significant contribution of application of liquid nitrogen jets in machining is the high reduction in flank wear. Such reduction in tool wear might have been possible for retardation of abrasion and notching, decrease of adhesion and diffusion type thermal sensitive wear at the flanks and reduction of built-up edge formation at the cutting edges.

Hong et. Al (2002) works with cryogenic cooling effect on friction and cutting force and this time he again agree that liquid nitrogen is an effective lubricant in machining. This is proven by the reductions of feed force, effective coefficient of friction between the chip and the tool face, and the thickness of the secondary deformation layer in the chip microstructure. Cryogenic machining tends to increase the cutting force because the work material becomes harder and stronger at lower temperature. However, the lower temperature makes the material less sticky, reducing the frictional force inherent in the cutting process.

Most of the studies examined more frequently the amount of flank wear in determining the tool life. Work done by Wang et al, (2000) stated tool wear was mainly restricted to the flank face but remarkable wear on cutting tool rake face also being noticed. In machining of some materials, it was obtained reductions in tool flank wears up to five folds with cryogenic indirect cooling. Venugopal et. al (2007) investigated crater formation during a cryogenic jet cooling in machining of titanium alloy and the percentage reductions in amount of maximum crater wear with machining of 5min were seen 33% for 70m/min, 20% for 85m/min and 77% for 100m/min by cryogenic cooling as compared to dry machining .

Venugopal et.al (2005) investigate the tool wear in cryogenic turning of Ti6Al4V. The author found that cryogenic cooling with liquid nitrogen jets enables substantial reduction in tool wear, both on the crater and flank surfaces. He also verified that the crater surface lesser extent under cryogenic compare to dry and soluble oil cooling. Edge depression of the cutting tool insert significantly decreased due to effective control of cutting temperature by cryogenic. Application of cryogenic cooling in machining Ti-6Al-4V alloy provides reduction in tool wear which can lead to enhancement of productivity along with environmental friendliness.

In addition, Bhattacharyya et al. (1993) compared flank wear growths between two cryogenic workpiece cooling methods, dipping the workpiece into liquid nitrogen and continual application of liquid nitrogen onto the testpiece in turning of Kevlar reinforced plastics. They obtained wear rate was higher with low cutting speed and with chipbreaker tool in continual pouring of liquid nitrogen. Meanwhile a comparison of machining under dry cutting, cryogenic workpiece pre-cooling and cryogenic chip cooling was done by Ding et al (2001); they concluded that both methods of cryogenic machining performed better than dry cutting.

2.7 Tool Wear

Tool wear is defined as the gradual failure experienced by cutting tools due to regular machining operation. It has been extensively studied especially on conventional cutting tools. Generally, there are four types of wear usually occurred on the tool. One or more wear modes can happen at the same time. Major wear forms at earlier stage of machining process are observed as crater wear and flank wear. As the machining progresses, other forms of wear such as groove wear and chip notch can add to the crater and flank wears. Typical forms of wear observed on turning tools can be best described by Figure 2.6 (Venkatesh, 1980) which includes:

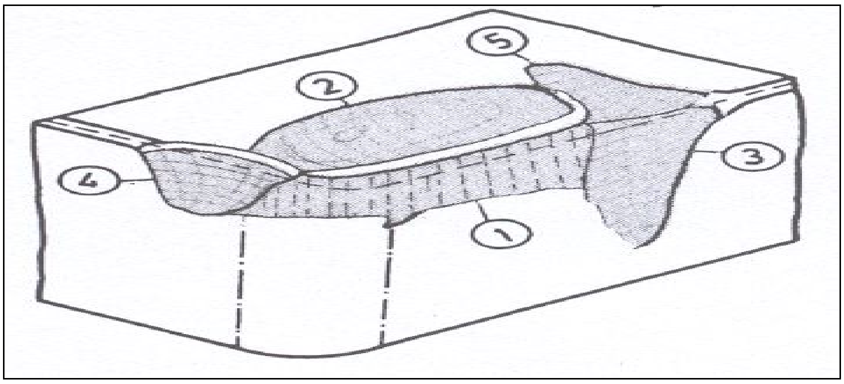


Figure 2.6: Wear forms on turning tools at reusable state

(1) Flank wear, (2) Crater wear, (3) Primary groove or wear notch, (4) Secondary groove or oxidation wear, (5) Outer chip notch, (6) Inner chip notch.

i. Flank Wear

Flank wear happen on the flank face of the cutting tool and results in the formation of a wear land. Wear formation is not uniform along the major and minor cutting edges of the tool. This type of wear most commonly results from abrasive wear of the cutting edge against the machined surface.

ii. . Crater Wear

The crater wear happen when the chip flows across the rake face, resulting in severe friction that would leaves a scar on the rake face. The wear can increase the working rake angle and reduce the cutting force, but unfortunately it will also weaken the strength of the cutting edge. The depth of crater wear is the most commonly used parameter in evaluating the rake face wear.

iii. Notch Wear

Notch wear is a combination between flank and crater wear which occurs to the point where the major cutting edge intersects the work surface. Notch wear is also called notching and depth-of-cut notching.

iv. Chipping

Chipping of the tool involves removal of relatively large discrete particles of tool material. Tools subjected to discontinuous cutting conditions are particularly prone to chipping. Built-up edge formation also has a tendency to promote tool chipping. Each time some of the built-up material is removed it may take with it a lump (piece) of tool edge.

2.8 Image Analyzer

Image Analyzer is an image processing tool that can be used to analyze, edit and enhance images. It is not comparable to a fully fledged image analyzer such as scanning electron microscope (SEM) but it is able to stand its ground on beginner researcher level. The editing and enhancement features are worth a closer inspection.

After observing the specimen's surface on screen, image can be captured into Image Analyzer. The operations menu available is basically the central menu of the image processing software. It provides access to basic editing features like zooming, scale, or color enhancement.

Other features include:

- Automatic brightness, contrast, gamma and saturation adjustment
- Color model conversion
- Retinex filter for reducing shadows and increasing local contrast

2.9 Machining Parameters for Titanium Alloys

Nowadays, a broad base of titanium machining knowledge exist due to fast growing of it application in industries. Titanium alloys machining process requires data access relating to machining parameters include tool life, forces, power requirement, cutting tools, and cutting fluids for efficient material removal [Donachie,1988]. New development in cutting tool unfortunately does not help in overcome the titanium alloy machining problems so as the forces and power requirement. Most of the machining problems occur due to high cutting temperature. The most significant ways is to reduce the temperature by application of coolant during machining processes. Most cryogenic studies on titanium alloys results improvement in its machinability [Yakup, 2008].

CHAPTER 3

METHODOLOGY

3.1 Introduction

Current chapter generally discusses methodology of the project, with a focus on growth of tool wear during turning process of titanium alloy, Ti-6Al-4V under conventional and cryogenic cooling condition. Relevant data collection is done in order for further research analysis in subsequent chapter.

3.2 Methodology Flow Chart

The methodology flow chart is a visual representation of the sequence of the project. A completed flowchart organizes the topic and strategies done to ensure smooth working flow of project. Figure 3.1 illustrated a simple flow chart shows the flow processes of this project. As illustrated, the first step is literature study on related topic. Machining work started by using conventional lathe machine. Next is the tool wear measurement by using image analyzer. The final step is comparison between results obtained in all machining processes.

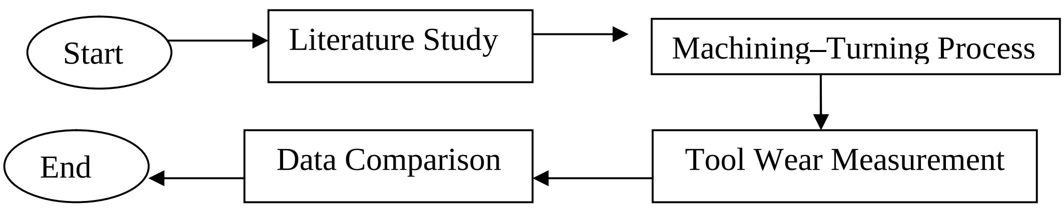


Figure 3.1: Simple Flow Chart

3.3 Literature Study

First and for most, literature studies on various sources likewise research journal, books, printed or online conference article to develop better understanding in project processes. Materials with main focus study of titanium alloy turning under cryogenic turning being main references for this project.

3.4 Workpiece Material

The workpiece material used in all of the experiments was a 25mm diameter alpha–beta Ti-6Al-4V titanium alloy bar of a nominal composition (wt.%) given as Al:6; V: 4; Ti:remainder. Ti-6Al-4V accounted about 50% of the total titanium alloys used in the industry. It is a unique alloy and offers attractive properties with inherent workability, good shop fabricability and also a standard alloy for castings that must exhibit superior strength. The mechanical properties of the tested material are shown in Table 3.1. Before the experiment, a layer of 0.20 mm was removed to eliminate any surface defect.

Table 3.1: Properties of the Ti-6Al-4V

Workpiece Material	Ti-6Al-4V
Tensile Strenth (MPa)	900
0.2% Yield Strength (MPa)	830
Modulus of Elasticity (Gpa)	114
Specific Heat (J/kg^{o}C)	560

Source: Titanium: A Technical Guide (2000)

3.5 Cutting Tool Materials

Titanium aluminum nitride (TiAlN) insert of ISO Catalog number TPGR 160308K with PVD coating KC5010 grade supplied by Kennametal. Inc was used for the experiments. The tools were triangular shaped with 60º angle of each edge. The tools composition was a PVD TiAlN coating over a very deformation-resistant unalloyed, carbide subtrate.

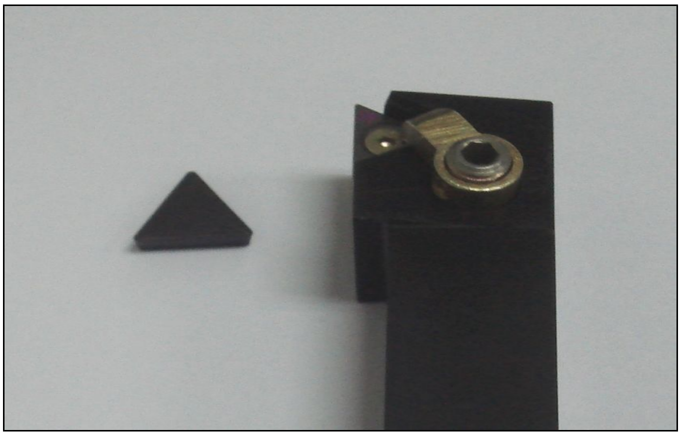


Figure 3.2: Triangular Insert and Tool Holder

3.6 Machining Tests

All of the machining experiments were carried out on an ERL 1330 conventional lathe machine. Work piece were discarded when the diameter-to-length ratio reached 0.40. The machining parameters are as shown in Table 3.2 for conventional machining, while for cryogenic cooling is shown in Table 3.3. For each experiment, a fresh cutting edge was used.

The first experiment was done under conventional cooling condition. The coolant was applied at the tool tip at appropriate flow. After 0.5 min or 65mm cutting length, tool edge was observed under microscope. Each titanium bar can only underwent four experiments with total two minutes machining time. Next is machining experiments under cryogenic cooling. The experiment has been carried out under cryogenic environments which coolant is supplied to the tool tip by external pipe at appropriate pressure. Figure 3.3 and Figure 3.4 illustrates cryogenic and conventional machining setup respectively.

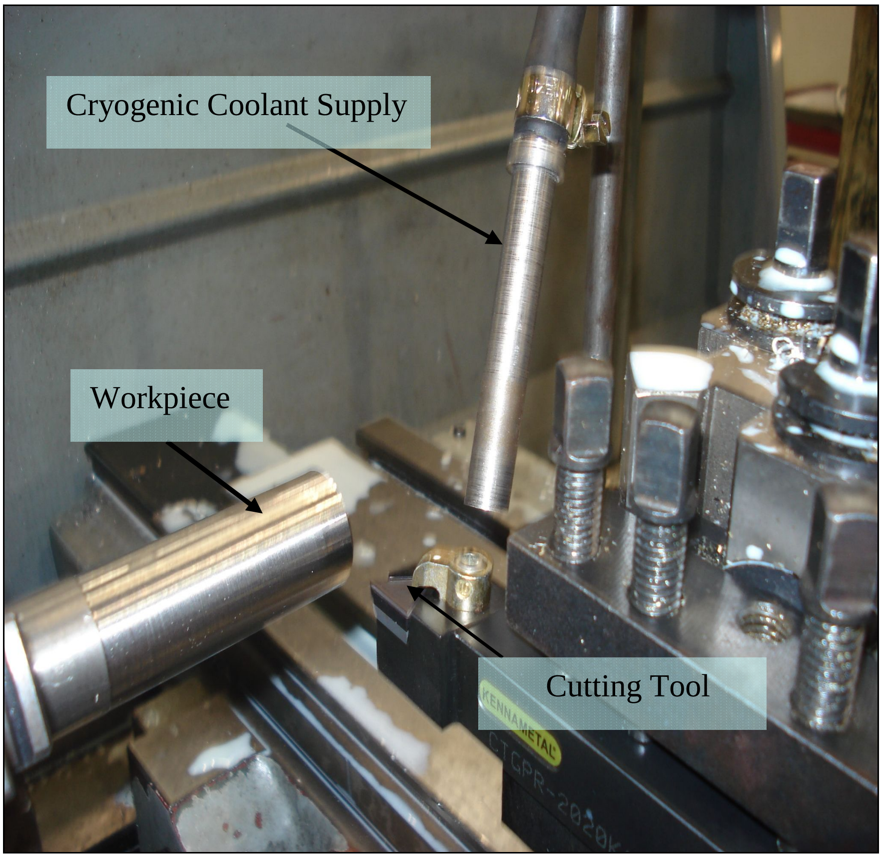


Figure 3.3: Turning Process under Cryogenic Cooling

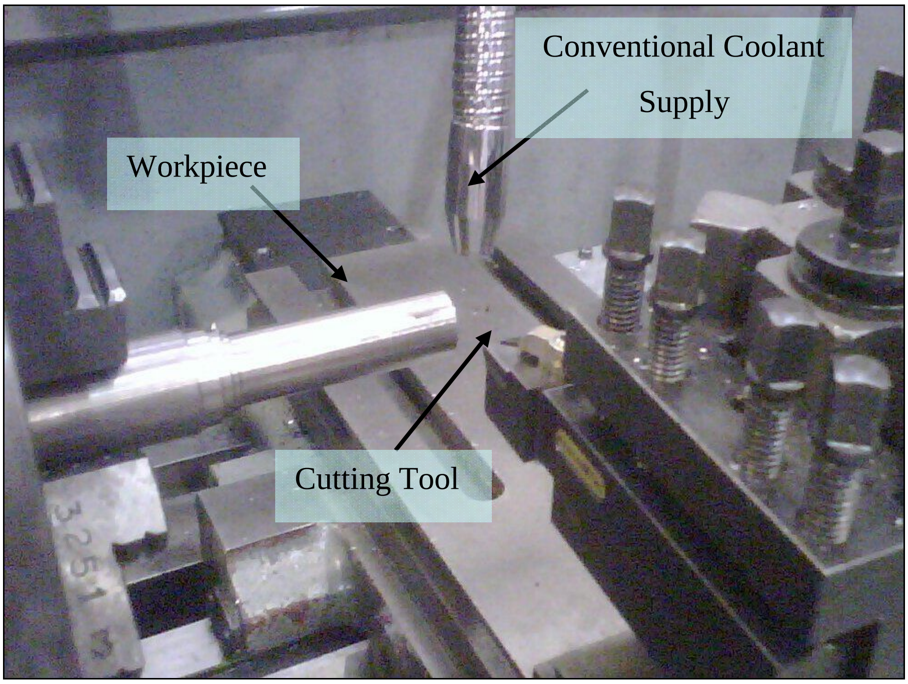


Figure 3.4: Turning Process under Conventional Coolant

Table 3.2: Machining Parameters for Conventional Coolant

Tool	Titanium Auminium Nitride Coated Triangular Insert
Cutting Speed (m/min)	110
Depth of Cut (mm)	1.00
Feed Rate (mm/rev)	0.100

Table 3.3: Machining Parameters for Cryogenic Coolant

Tool	Titanium Auminium Nitride Coated Triangular Insert
Cutting Speed (m/min)	70, 90, 110
Depth of Cut (mm)	1.00
Feed Rate (mm/rev)	0.100

3.5 Tool Wear

Tool wear commonly occur at the related surfaces of cutting tool. Previous research done stated that flank wear and crater wear were main wear occur during titanium alloy machining. Wear observation can be done easier compare to other wear types. Tool wear images taken for qualitative and quantitative wear growth comparison using optical microscope and image analyzer shown in Figure 3.5.

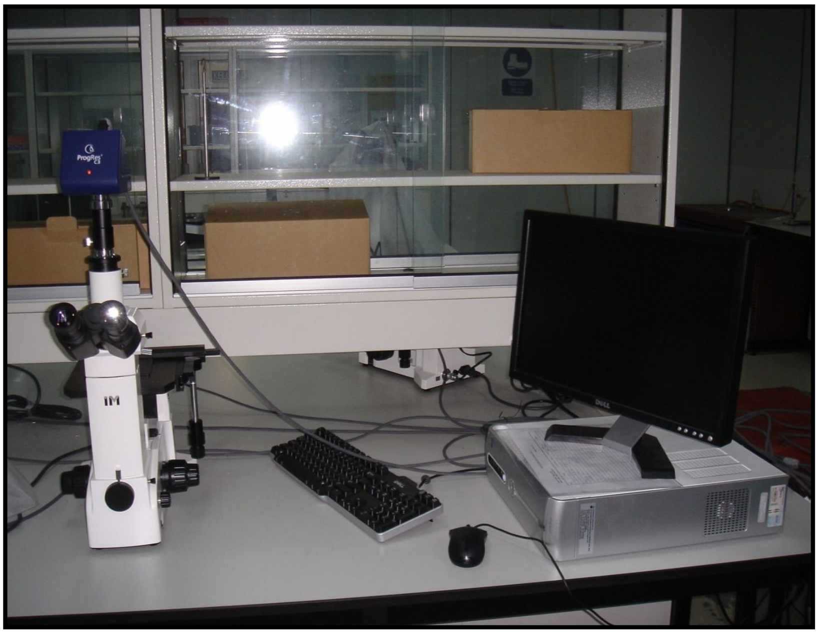


Figure 3.5: IM 1700 Series Image Analyzer

3.5.1 Tool Wear Measurement

After each machining tests, optical microscope Jenoptik image analyzer was used for image capture and also tool wear measurement. The flank wear and crater wear were measured with a magnification of 10X. The measurements were limited by the poor image quality due to analyzer limitation. The amount of tool wear was based on maximum value.

3.6 Data Comparison

After all the machining done under conventional and cryogenic cooling, analysis of tool wear taken place until the final machining. The data obtained from conventional and cryogenic machining at 110 m/min, depth of cut 1.00 mm and feed 0.10 mm /rev is compared. The tool wear growth at 0.50 min, 1.00 min, 1.50 min and 2.00 min were compared qualitatively and quantitatively.

3.7 Summary

Turning process of titanium alloy has been done under conventional and cryogenic coolant. Image analyzer is used to observe tool wear growth after each experiment. Afterwards, the results were compared at the same machining parameters. The results obtained are following graph patterns if compared with the literature study. These results would further being interpret in Chapter 4- Results and Discussion.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

Chapter 4 is generally discuss the results obtained throughout the experimental research analysis on the tool flank wear (µm) and tool crater wear (µm) found after a period of machining process.

4.2 Cutting Speed

Titanium and its alloy are readily machinable at the cutting speed range of 30m/min to 60 m/min with minimal tool wear [Kitagawa et al, 1997]. In industry, the cutting velocity commonly used started approximately at 60m/min [Hong et al, 2001]. For this project, the cutting speed range 70 m/min to 110 m/min were tested in cryogenic machining of this difficult-to-machine material. The cutting velocity is enhanced to 110 m/min and it is considered as a potential high speed for conventional turning of titanium alloy.

Due to limitation on the current lathe machine, only three cutting speed were chosen based on the machine spindle speed availability. The cutting speed was calculated by using the following Formula 4.1:

$$V = \pi D N \qquad (4.1)$$

Where π = mathematical constant value approximately equal to 3.14159.

D = initial diameter of titanium alloy bar, in meter.

N = spindle speed available, rpm

4.3 Analysis of Tool Wear

Dhar et al. (2001) had mentioned about the most significant contribution of application of liquid nitrogen jets in machining is the high reduction in flank wear. Venugopal et.al (2005) also acknowledged that cryogenic cooling with liquid nitrogen jets enables substantial reduction in tool wear, both on the crater and flank surfaces. Choudhury (2006) stated flank wear occurrence during cryogenic cooling condition is reduced by 37.39% than in dry cutting machining. Based on these statements, the occurrence of tool wear had been analyze and measured in order to investigate how the cryogenic coolant help in machining process of titanium alloy Ti-6Al-4V.

By using IM 1700 Image Analyzer, tool wear analysis is done to observe wear occurrences from machining experimentation. The table 4.1 and table 4.2 for both type of tool wear respectively. In this study, main focus was on flank wear and crater wear by the factor that based on various studies done for turning process of Ti-6Al-4V revealed the tool wear was mainly restricted to flank wear and crater wear.

Since there is no wear develop at all of the cutting speed range under cryogenic cooling experiments as shown in Figure 4.1, only wear result at highest cutting speed, 110 m/min were shown and compared with tool wear growth in conventional cooling.

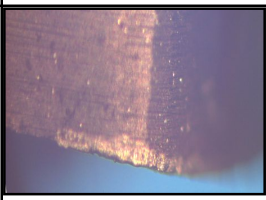
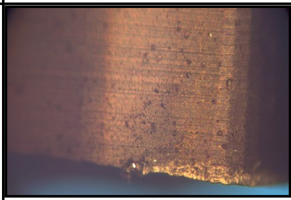
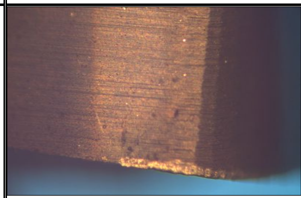
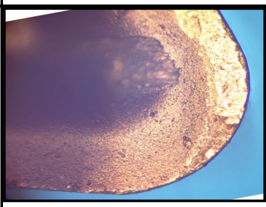
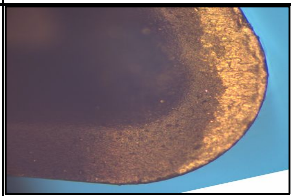
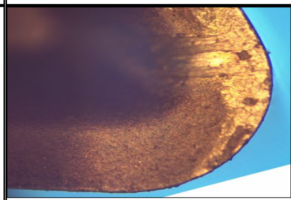
Cutting Speed	70 m/min	90 m/min	110 m/min
Flank Wear			
Crater Wear			

Figure 4.1: Tool Wear Growth under Cryogenic Cooling after 65mm Cutting Length

4.2.1 Flank Wear Analysis

The tool flank wear occurred at conventional and cryogenic cooling was compared by the machining time ranges 0.5 min to 2.00 min. The machining take place at a cutting speed of 110 m/min with depth of cut 1.00mm and feed 0.1mm/rev. Table 4.1 compares the flank wear occurrence in turning with conventional and cryogenic cooling respectively. As revealed in the table, no wear observed with cryogenic cooling while dramatic wears occurring with conventional coolant. This is also clearly demonstrated in Figure 4.2.

Furthermore, the microphotograph images taken at 10X shows the tool wear increasing. Figure 4.3 and 4.4 consistently show flank wear condition in conventional and cryogenic cooling respectively. The growth of flank wear in conventional cooling follows typical wear trend where it is increases gradually proportional to the machining time. On the other hand, flank wear is remaining zero during cryogenic cooling condition. The overall results shows cryogenic cooling reduces the flank wear tremendously.

Table 4.1: Flank Wear

No.	**Machining Time (min)**	**0.5**	**1.00**	**1.50**	**2.00**
1.	Conventional (µm)	217.274	310.8108	489.308	565.421
2.	Cryogenic (µm)	0	0	0	0

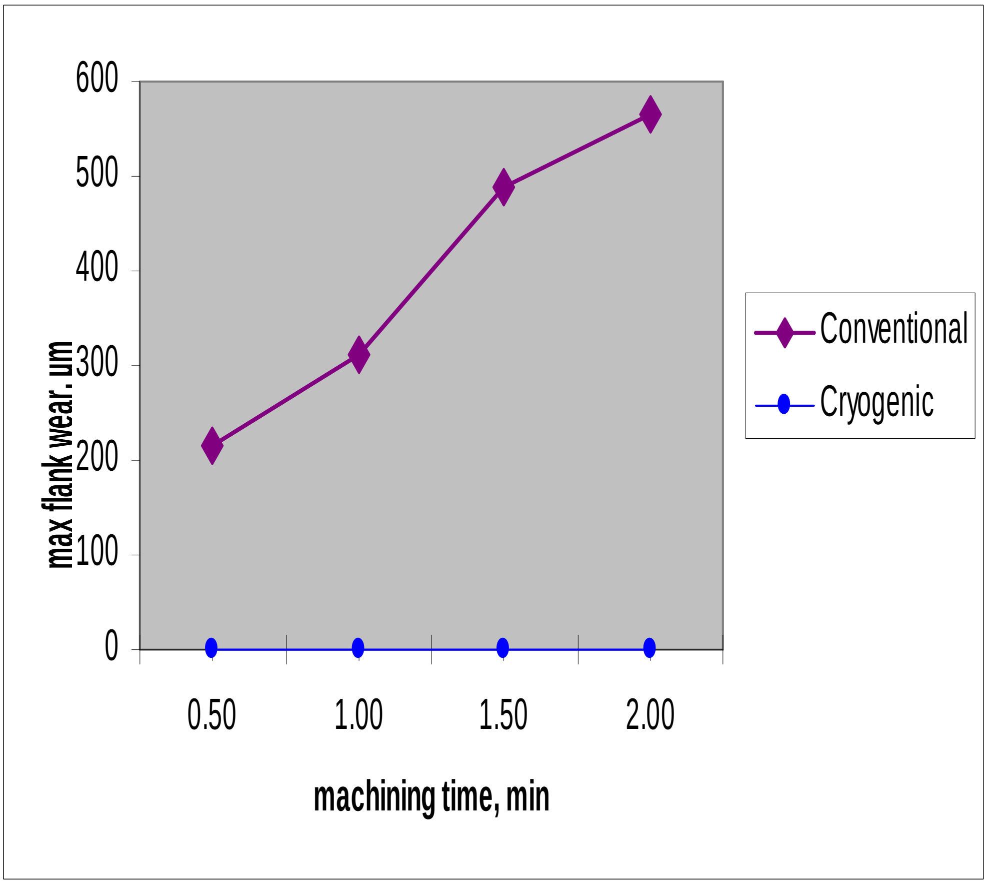


Figure 4.2: Graph of Tool Flank Wear versus Machining Time

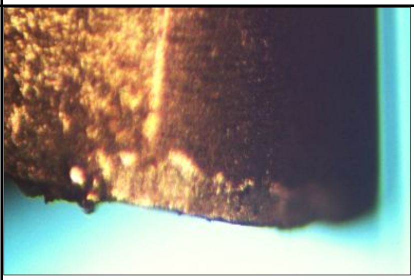
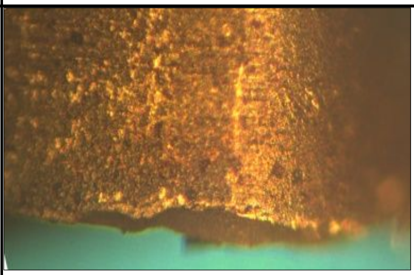
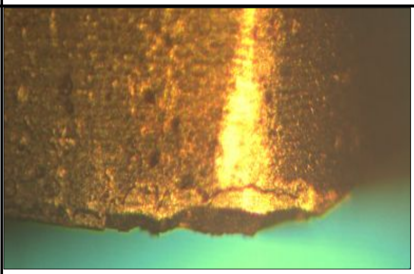
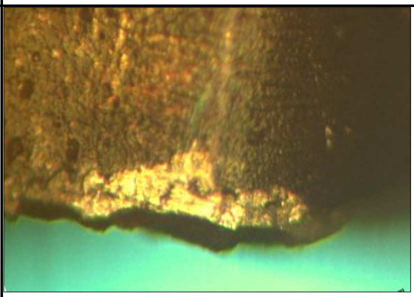
Time (min)	Conventional	Description
0.5		Flank wear is clearly shown even only after 0.5min of turning process. The maximum flank wear is about 217.274 µm.
1.0		The flank wear shown in (see figure) increase in value to 310.8108 µm. Tool is chipped after 1.00 minute.
1.5		After 1.50 min of machining, the tool wear grows to 489.308 µm. More chipping occurrence did taken place too.
2.0		Final machining of titanium at 2.00 minutes, flank wear increase to 565.421 µm. The tool chipped more than before.

Figure 4.3: Wear Occurrence on the Tool Flank Face during Conventional Machining at 110 m/min, depth of cut 1.00 mm, and feed 0.10 mm/ rev.

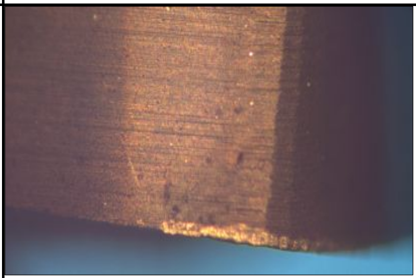
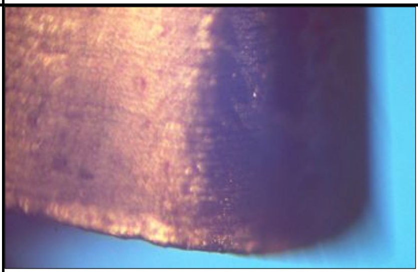
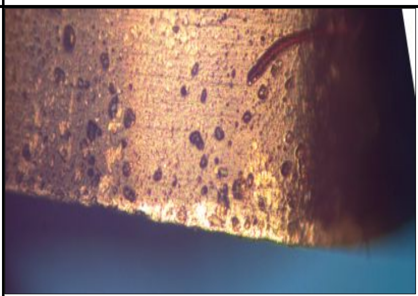
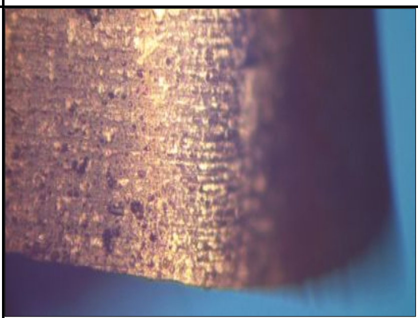
Time (min)	Cryogenic	Description
0.5		Only deposited titanium alloy is shown on the flank edge. No wear occurrence yet.
1.0		No wear occurrence.
1.5		No wear occurrence.
2.0		No wear or bounded titanium alloy shown. The flank face is seen like new cutting edge.

Figure 4.4: Wear Occurrence on the Tool Flank Face during Cryogenic Machining at 110 m/min, depth of cut 1.00 mm, and feed 0.10 mm/ rev.

Obvious growth of flank wear was found in the former while no wear in the latter. The white layer seen in Figure 4.4 for early machining was merely titanium material adhered to the tool edge by its machine. As the machining proceed, this layer was removed by continuous chips flow, as no more bounded titanium seen in the images of 2.00 minute in Figure 4.4. For fair justification, Figure 4.5 compared fresh cutting edge and cutting edge after 2.00 minute machining end with conventional coolant and cryogenic cooling.

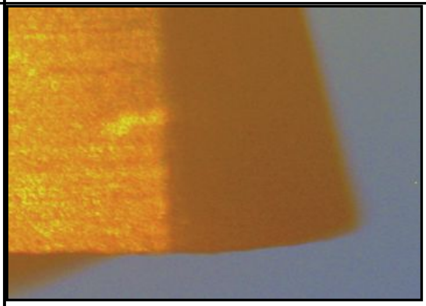
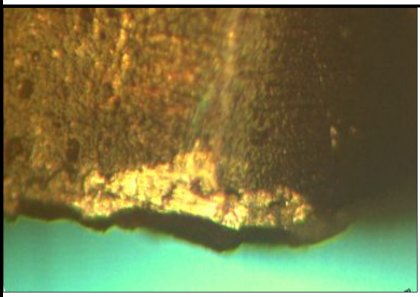
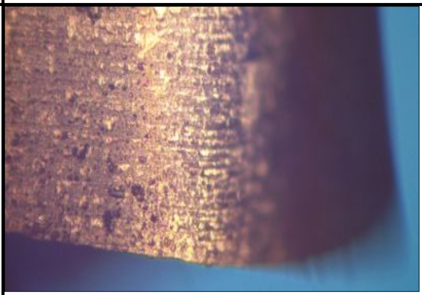
Machining	Flank Face	Description
Fresh		New cutting edge- before machining process.
Conventional		Flank wear clearly shown. Chipping did also occurred after 2.00 minute of machining
Cryogenic		No wear occurred. The flank face is seen like new cutting edge.

Figure 4.5: Wear Occurrence on the Tool Flank Face

As evidence in Figure 4.5, the flank wear growth during conventional and cryogenic cooling is far outweighing each other. After 2.00 minute of conventional cooling, the cutting edge shows huge wear growth. This led to removal of relatively large tool edge material namely chipping. On the other hand, after 2.00 minute of cryogenic cooling machining, the wear is remains zero. The tool edge is comparable with fresh, unworn cutting edge. At this point, the cryogenic did show impressive reduction in tool flank wear.

4.2.2 Crater Wear Analysis

The tool crater wear occurred at conventional and cryogenic cooling was compared by the machining time ranges 0.5 min to 2.00 min. The machining take place at a cutting speed of 110 m/min with depth of cut 1.00mm and feed 0.1mm/rev. Table 4.2 compares the flank wear growth in turning with conventional and cryogenic cooling respectively. As revealed in the table, there is also no wear observed with cryogenic cooling while wears occurs enormously with conventional coolant. Figure 4.5 is the wear plot illustrated crater wear occurrence.

The microphotograph images taken at 10X shows the tool crater wear increasing. Figure 4.7 and 4.8 show consistent crater wear condition in respective conventional and cryogenic cooling. The growth of crater wear in conventional cooling follows typical wear trend as it is increases gradually proportional to the machining time. On the other hand, the wear is remaining zero during cryogenic cooling condition. The overall results shows cryogenic cooling reduces the crater wear monstrously.

Table 4.2: Crater Wear

No.	Machining Time (min)	0.5	1.00	1.50	2.00
1.	Conventional (µm)	53.421	110.50	143.125	158.35
2.	Cryogenic (µm)	0	0	0	0

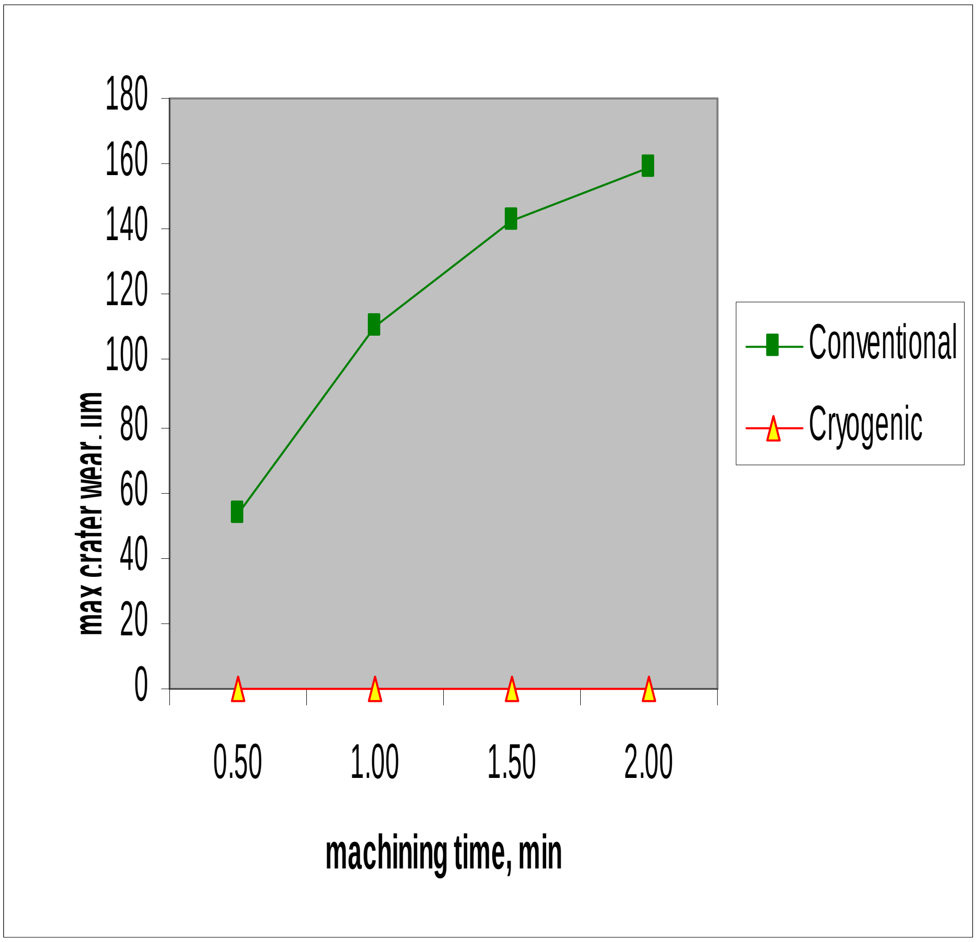


Figure 4.6: Graph of Tool Crater Wear versus Machining Time

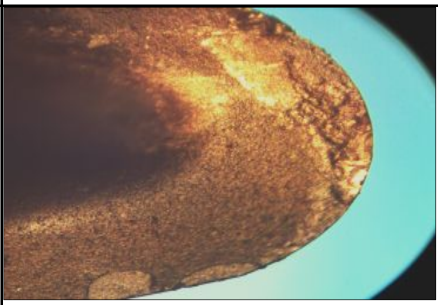
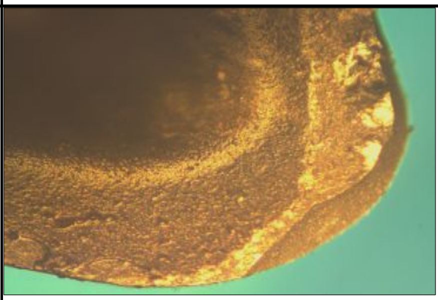
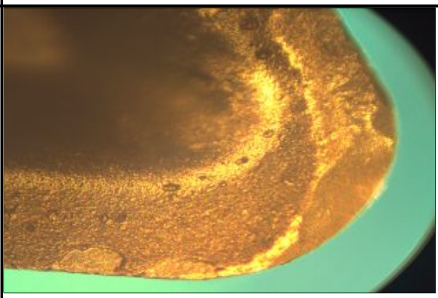
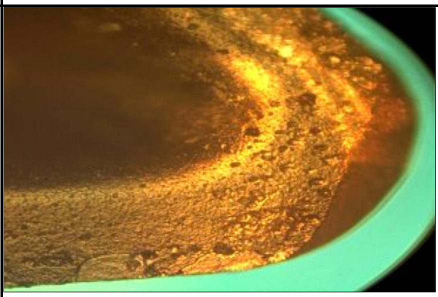
Time (min)	Conventional	Description
0.5		Flank wear is start taken place after 0.50 minute of turning process. The crater wear is about 53.421 µm.
1.0		The crater wear is clearly shown in increase in value to 110.50µm. Tool is chipped after 1.00 minute.
1.5		After 1.50 min of machining, the wear grows to 143.125 µm.
2.0		The tool wear increase to 158.35µm final machining of titanium at 2.00 minutes,.

Figure 4.7: Wear Occurrence on the Tool Crater Face during Conventional Machining at 110 m/min, depth of cut 1.00 mm, and feed 0.10 mm/ rev.

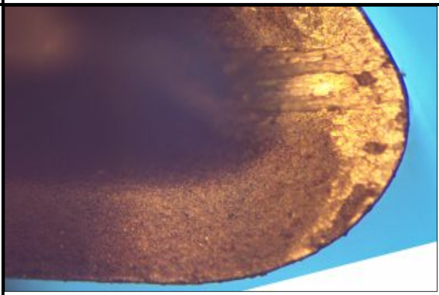
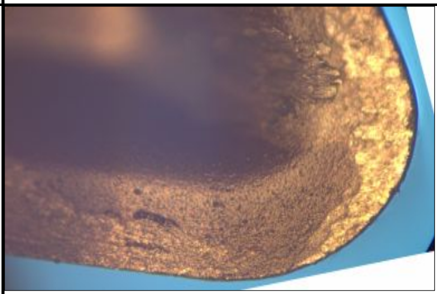
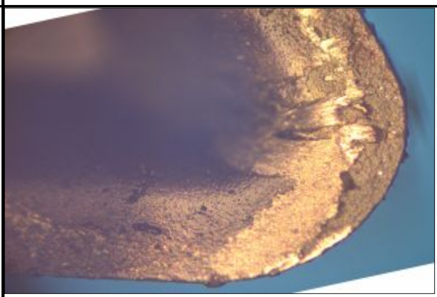
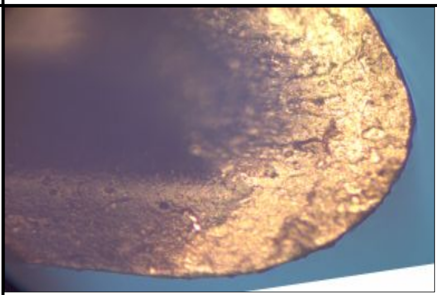
Time (min)	Cryogenic	Description
0.5		Only deposited titanium alloy is shown on the cutting edge. No wear occurrence yet.
1.0		No wear occurrence.
1.5		No wear occurrence.
2.0		No wear shown even after 2.00 minute of machining.

Figure 4.8: Wear Occurrence on the Tool Crater Face during Cryogenic Machining at 110 m/min, depth of cut 1.00 mm, and feed 0.10 mm/ rev.

Growth of crater wear was obviously found in the conventional cooling while no wear in the cryogenic cooling condition. The white layer seen in Figure 4.8 was merely titanium material bounded to the tool edge after its machining. As the machining proceeds, this layer was slowly removed by continuous chips flow, as thinner bounded titanium layer seen in the images of 2.00 minute in Figure 4.8. For fair justification, Figure 4.9 compared fresh cutting edge and cutting edge after 2.00 minute machining end with conventional coolant and cryogenic cooling.

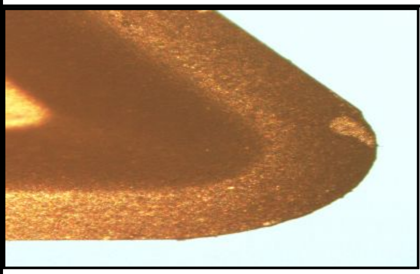
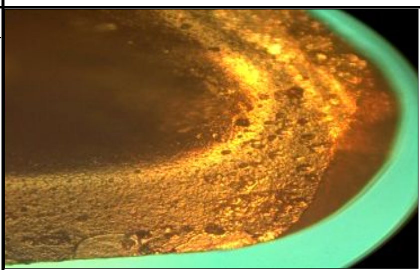
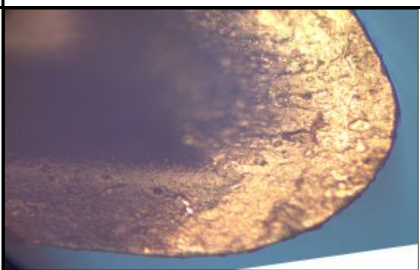
Machining	Flank Face	Description
Fresh		New cutting edge- before machining process.
Conventional		Crater wear occurred at the cutting edge.
Cryogenic		No wear occurred. The crater face is seen like new cutting edge. The white layer seen is adhered titanium material.

Figure 4.9: Wear Occurrence on the Tool Crater Face

As in Figure 4.9, the comparison between growths of crater wear during conventional and cryogenic cooling is clearly shown. The cutting edge experienced obvious carter wear soon after 2.00 minute of conventional cooling. On the other hand, the wear is remains zero even after machining end of cryogenic cooling. The tool cutting edge is also comparable with fresh, unworn cutting edge except for the bound titanium material on cutting crater face.

4.3 Summary

As a summary, it can be said that the cryogenic coolant is help in the reduction of tool wear. The application of cryogenic coolant has improved the wear problems faced in the machining process of titanium alloy, Ti-6Al-4V. These problems as described here are the tool flank wear and crater wear due to high temperature generation during the machining. This conclusion is proven according to the literature that had been made.

CHAPTER 5

CONCLUSION

5.1 Introduction

Chapter 5 summarizes all the main research points of this project. It concludes the crucial information and observation obtained during the project.

5.2 Conclusion

In conclusion, the study on turning of titanium alloy, Ti-6Al-4V under conventional and cryogenic cooling condition was successfully performed. Coolants were considered as important parameters that affect the cutting heat generation during the machining. The cutting speed range 70 m/min to 110 m/min tested in the experiments. The highest speed 110 m/min is considered as high speed for machining titanium alloy with the current conventional turning machine. For the highest speed tested, cryogenic coolant was found to be a better choice than the conventional oil based coolant in reducing tool wear. Wear plots were analyze between the types of coolant over machining time in order to have better understanding relative contribution of cryogenic coolant to the growth of tool wear.

5.3 Recommendation

There are some recommendations to be considered in improving the details of this project. A better precision of microscope is highly recommended to be use for tool wear analysis. It is recommended to etching the cutting tool edge in hydrofluoric acid (HF) for a period of time to remove any unbound material that might present before performing the analysis. This is crucial to see clearly the wear occurrence after the machining process. Other than that, the experiments also can be conducted for longer machining time or longer cutting length in order to determine total machining time of titanium alloy under cryogenic cooling before the wear occurred.

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APPENDIX

APPENDIX A
GANTT CHART FOR FINAL YEAR PROJECT

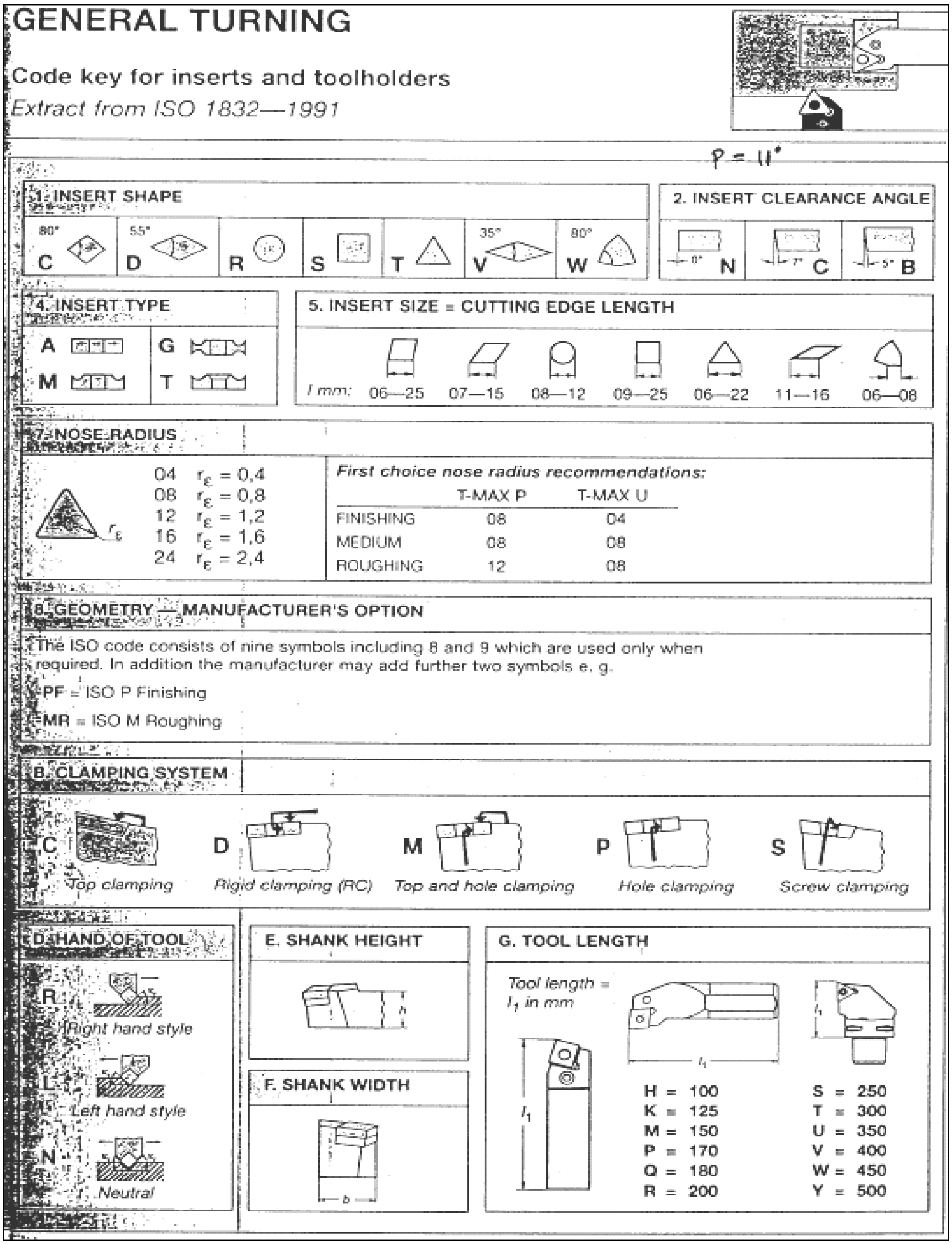
a) FINAL YEAR PROJECT 1

PSM 1 ACTIVITIES	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
Literature Survey														
Identify Scope of Project														
Identify Problem Statements, Objectives														
Methodology														
Proposal Writing														
FYP 1 Presentation														

b) FINAL YEAR PROJECT 2

PSM 2 ACTIVITIES	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15
Literature Study															
Methodology															
i) Machining [Turning]															
ii) Analysis															
iii) Comparison															
Result Interpretation															
Report Writing															
FYP 2 Presentation															
Log Book and Report Submission															

Appendix B: (I) ISO- Designation of Turning Tool Geometry



GENERAL TURNING

Code key for inserts and toolholders

Extract from ISO 1832—1991

P = 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

r_ε

04 $r_\varepsilon = 0{,}4$
08 $r_\varepsilon = 0{,}8$
12 $r_\varepsilon = 1{,}2$
16 $r_\varepsilon = 1{,}6$
24 $r_\varepsilon = 2{,}4$

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 C: (II) ISO- Designation of Turning Tool Geometry