THE EFFECT OF CRYOGENIC CUTTING TOOLS ON MACHINING DIFFICULT TO CUT MATERIAL

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ABSTRAK

Penyelidikan bahan untuk alat pemesinan adalah satu daripada kritikal elemen dalam pemesinan besi. Ia dikategorikan mengikut peningkatan ketahanan kehausan untuk memotong bahan yang lebih keras, kuat atau reaktif secara kimia. Dalam proses pemesinan, kualiti utamanya bergantung kepada permukaan bahan yang dimesin. Untuk pemesinan bahan yang sukar dipotong, penurunan secara drastik dalam jangka hayat alat pemesinan membuatkan proses pemesinan menjadi sukar. Inconel 718 adalah aloy yang mempunyai ketahanan termal yang tinggi. Inconel mempunyai artikel keras yang membuatkan ianya sukar dipotong. Kesukaran pemesinan Inconel 718 menyebabkan jangka hayat mata alat menjadi rendah dan mengasilkan permukaan yang kasar. Projek ini mengkaji kesan ‘cryogenic treatment’ kepada kehausan mata alat dan permukaan Inconel 718. Tujuan utama projek ini adalah untuk menganalisa perbezaan antara ‘*cryogenic treated*’ dan ‘*untreated*’ PVD semasa pemesinan Inconel 718. ‘*Flank wear*’ dan ‘*crater wear’* pada alat pemesinan akan dikaji. Permukaan Inconel yang telah dimesin juga akan dianalisis. Keputusan menunjukkan pada kelajuan pemotongan yang rendah, 20 dan 30 m/min serta pada *‘feed rate’* 0.05 and 0.08 mm/tooth, *‘non cryogenic’* PVD adalah lebih baik daripada ‘*cryogenic’* PVD. Pada kelajuan pemesinan yang tinggi, ‘*cryogenic’* PVD menghasilkan permukaan yang lebih baik dan kehausan pada mata alat yang lebih rendah. Parameter optimum yang boleh digunakan untuk memperoleh permukaan yang baik dan kehausan mata alat yang rendah ialah pada kelajuan 40 m/min dan ke atas.

ABSTRACT

Material developments for the cutting tool is one of the most critical elements in metal cutting, have always been characterized by an increase in wear resistance to machine harder, tougher, or chemically reactive materials. In machining processes, a major quality related output is integrity of the machined part surface. In machining of difficult to cut material, a drastic decrease in tool-life makes the machining process even more difficult. Inconel 718 is a high strength thermal resistant material alloy which was used for this project. It contains hard particles making it a very difficult to machine. The difficulty of machining Inconel 718 leading to short tool life and poor surface roughness. This project describes a study on the effects of cryogenic treatment on tool wear and surface roughness of Inconel 718. The main aim of this study is to analyze the differences in tool performance between cryogenically treated and untreated PVD during face mill Inconel 718. The flank wear and crater wear on cutting tool are studied for specific operating parameters. It was found that at lower cutting speed, 20 and 30 m/min and lower feed rate, 0.05 and 0.08 mm/tooth, non-cryogenic PVD cutting tool is better compare to cryogenic PVD cutting tool in term of surface roughness and tool wear. At high cutting speed, cryogenic PVD produce low surface roughness and less tool wear. The optimum parameter that can be used to obtain low surface roughness and less tool flank wear for cryogenic PVD is 40 m/min and above.

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LIST OF SYMBOLS AND ABBREVIATIONS

A - Approach distance
d - Depth of cut
D - Diameter of milling cutter, mm
f - Feed rate
L - Length
N - Spindle speed, rev/min
Ra - Surface roughness
R_{MR} - Material removal rate
T_m - Time to mill the workpiece
T - Tool life, min
v - Cutting speed
w - width
^oC - Celsius
^oF - Fahrenheit
^oK - Kelvin
CNC - Computer numerical controller
ISO - International Standard of Operation
PVD - Physical Vapor Deposition
SEM - Scanning Electron Microscope
mm - millimeter
m/min - meter per minute
mm/tooth- millimeter per tooth

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CHAPTER 1

INTRODUCTION

This chapter elaborates the main idea of the project including the title of the project, background of the problem, problem statement, research justification, purpose, important and scope. This chapter briefly explains about the guidance and information of the project.

1.1 Introduction

Machining process is one of the oldest types of process that is being used to machine many kinds of material in this world. It is also known as material removal process. One of the examples of machining process is milling process. It is widely used in manufacturing industry. Milling operation is the process of cutting away material by feeding a workpiece past a rotating multiple tooth cutter. The cutting action of the many teeth around the milling cutter provides a fast method of machining. The machine for holds the workpiece, rotating the cutter, and feeding it, is known as milling machine.

This process is widely used for machining on flat surface. Milling process also can be used for all common hole-machining operations normally done on a drill press. The capability to do wide variety of machining operations, and its high metal removal rate, make it very efficient and that is one of the most important machining processes used nowadays.

Nowadays superalloy Inconel 718 has wide applications in various fields of engineering. According to D. G. Thakur et al. (2009), approximately about 75% by weight in the case of aerospace applications and 50% by weight in the case of modern jet engines are the components made of Inconel 718. Other applications include marine equipment, nuclear reactors, petrochemical plants, and food processing equipments. Inconel 718 is a nickel-based superalloy containing niobium (columbium) age-hardening addition that provides increased strength without decrease in ductility (M. Alauddin et al., 1998). E.O Ezugawa et al. (2004) stated that Inconel 718 is non-magnetic, oxidation and corrosion resistance and can be used at high temperature in the range of 217^{o}C to 700^{o}C and at the same time maintain very high strength to weight ratio. Refering to their mechanical properties about 370 (HB) hardness, 1310 (Mpa) of tensile strength, 1100 (Mpa) yield strength and 11.2 (W/mK) of thermal conductivity, D. Dudzinski et al. (2004) categorized Inconel 718 as advance material where it provide good tensile, fatigue, creep and rupture strength. Inconel 718 provides a serious challenge as a work material during machining due to their unique combination of properties such as high temperature strength, hardness, and chemical wear resistance. Although these properties are the desirable design requirements, they pose a greater challenge to manufacturing engineers due to high temperature and stresses generated during machining. The machinability of Inconel 718 depends on the cutting tool that been used. Therefore it is important to choose the right cutting tool to machine this nickel-based alloy. One of a way is to use cryogenic-treated cutting tool.

1.2 Background of the Problem

Material developments for the cutting tool is one of the most critical elements in metal cutting, have always been characterized by an increase in wear resistance to machine harder, tougher, or chemically reactive materials. The execution of cryogenic treatment on cutting tool materials increases wear resistance, hardness, and dimensional stability and reduces tool consumption and down time for the machine tool set up, thus leading to cost reductions (Simranpreet Singh Gill et al., 2010). Although it has been confirmed that cryogenic treatment can improve the service life of tools, the degree of improvement experienced remains ambiguous.

1.3 Problem Statement

In machining processes, a major quality related output is integrity of the machined part surface. In machining of difficult to cut materials, a drastic decrease in tool-life makes the machining process even more difficult. Machining is intrinsically characterized by generation of heat and high cutting temperature. At such elevated temperature, the cutting tool if not enough hot hard may wear out rapidly resulting in increased cutting forces, dimensional inaccuracy of the product and shorter tool life. In order to increase the life of cutting tools, the cryogenic treatment was applied to the cutting tools so that it encountered rapid tool wear when machining difficult to cut materials.

1.4 Research Justification

Conventional cutting fluids are ineffective in controlling the high cutting temperature and rapid tool wear. Further, they also deteriorate the working environment and lead to general environmental pollution. Over the past few years, there has been an increase in interest in the application of cryogenic treatment on different materials. Research has shown that cryogenic treatment increases product life (Simranpreet Singh Gill et al., 2010). Barron, R.F. (1982), had shown a significant increase in the wear resistance for different types of tool and stainless steels. Cryogenic treatment is a process that uses cryogenic temperature to modify materials properties to enhance their performance. Most of the research on cryogenic treatment in the area of machining tools and cutting tool materials has concentrated mainly on tool steels, especially high-speed steel (Jiang Yong et al., 2011). However, not much research has been done to study the effect of cryogenic cutting tools on machining difficult-to-cut material especially on Inconel 718.

1.5 Purpose of the Study

The purpose of this research is to study the machining of Inconel 718 on face milling process by dry condition by using cryogenic treated PVD and non-treated PVD cutting tools. The specific objective of this study is to determine the effect and correlation of cutting parameters to the surface roughness and tool wear.

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1.6 Importance of the Study

The life of cutting tools plays a major role in increasing productivity and, consequently, is an important economic factor. The tool may be cheap, but to turn it means to interrupt the machining process, which costs time and, therefore, money. The execution of the cryogenic treatment on quenched and tempered high speed steel tools increases hardness and improves the hardness homogeneity, reduces tool consumption and down time for the equipment set up, thus leading to cost reductions of about 50% (A. Molinari et al., 2001). This research is important to study the effect and correlation of cryogenic cutting tool to the surface roughness and tool wear.

1.7 Scope of Study

- To understand the concept of cryogenic treated cutting tool
- To measure various tool wears, surface roughness
- To study the effect of cryogenic cutting tool wear over non-cryogenic treated tool.
- To study the effect of cutting parameter like cutting speed, feed rate and depth of cut.
- Cutting velocity – 20, 30, 40, 50 m/min was used
- Feed rate – 0.05, 0.08, 0.10 mm/tooth used
- Depth of cut – 0.5 mm
- The material used is Inconel 718.
- CNC Vertical Milling machine was used to conduct the experiments and measuring instruments like Scanning Electron Microscopy (SEM) and Surface Roughness Tester was used to obtain results.
- PVD tool under cryogenic treated condition was used. However, this treatment done at outside source.

1.8 Definition of Terminology

- Absolute zero: The lowest temperature possible at which all molecular motion ceases. It is equal to −273°C (−459°F) (www.scienceclarified.com)

- Kelvin temperature scale: A temperature scale based on absolute zero with a unit, called the Kelvin, having the same size as a Celsius degree (www.scienceclarified.com).
- Superconductivity: The ability of a material to conduct electricity without resistance. An electrical current in a superconductive ring will flow indefinitely if a low temperature (about −260°C) is maintained (www.scienceclarified.com).
- Austenite: Solid solution of carbon and other constituents in a particular form of iron known as γ (gamma) iron. This is a face-centred cubic structure formed when iron is heated above 910° C (1,670° F); gamma iron becomes unstable at temperatures above 1,390° C (2,530° F) (www.britannica.com).
- Martensite: A solid solution of carbon in alpha-iron that is formed when steel is cooled so rapidly that the change from austenite to pearlite is suppressed; responsible for the hardness of quenched steel (www.thefreedictionary.com)
- Quenching: The rapid cooling of a workpiece to obtain certain material properties (http://en.wikipedia.org)
- Tempering: Process of improving the characteristics of a metal, especially steel, by heating it to a high temperature, though below the melting point, then cooling it, usually in air. The process has the effect of toughening by lessening brittleness and reducing internal stresses (www.britannica.com)
- Cold Working: Altering the shape or size of a metal by plastic deformation. Processes include rolling, drawing, pressing, spinning, extruding and heading, it is carried out below the recrystallisation point usually at room temperature. Hardness and tensile strength are increased with the degree of cold work whilst ductility and impact values are lowered. The cold rolling and cold drawing of steel significantly improves surface finish (http://metals.about.com)

Chapter two elaborate the meaning and the information of the project where its inform the detail about the project and where the ideas, data and information of the project area collect from various article and journal as a reference in order to understand the concept of the project. The information and knowledge gain in this chapter is discussed in the Chapter 2.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter provides literature review of some significant contributions related to the cryogenic cutting tool when machining difficult-to-cut material. The collection of information are all related to cryogenically treated and non-treated PVD cutting tool on machining Inconel 718 which will enlighten valuable information on knowledge in terms of cryogenic, difficult to cut material, milling process, cutting tool requirements, dry condition, tool wear, tool life, and surface roughness.

2.2 Difficult to cut material

Advanced engineering materials, such as structural ceramics, titanium alloys, Inconel alloy, and tantalum offer unique combination of properties like high strength at elevated temperature, resistance to chemical degradation, and wear resistance. Therefore, these advanced materials are being used in making components for aerospace, electronics, defense, paper and pulp, chemical processing, nuclear waste disposal, dental, orthopedic, and sea water services. This is because of their unique combination of properties like high strength at elevated temperatures, resistance to chemical degradation and wear resistance. Ability to maintain these properties at elevated temperatures severely hinders the machinability of these materials, thus they are generally referred to as difficult to cut material. These materials are often difficult-to-cut due to their physical and mechanical properties such as high strength and low thermal conductivity, which make the cutting forces and cutting temperature very high and lead to a short tool life.

Because of its high thermal performance, nickel-based super alloy has been widely applied to rocket engine parts, gas turbines, and other machinery. However, it causes excessive wear of cutting tools during machining because of its rather high cutting temperature caused by its very poor thermal conductivity (S. Sun et al., 2010). Therefore, it is clear that more effective methods for enhancing separation of the chip from the tool and cooling the cutting tool without affecting local heating of the workpiece are required.

2.2.1 Inconel 718

Nickel-based superaloy such as Inconel 718, containing a niobium (columbium) has been widely used in the aircraft and nuclear industry due to their exceptional thermal resistance and their ability to retain mechanical properties at elevated temperature of service environment over 700^{o}C. Applications of Inconel 718 include marine equipment, nuclear reactors, petrochemical plants, and food processing equipments. A. Jawaid et al. (2001) classified nickel-based superaloy as difficult to cut material due to their high shear strength, work hardening tendency, highly abrasive carbide particles in the microstructure, strong tendency to weld and form built edge and low thermal conductivity. They have tendency to maintain their strength at high temperature which is generated during machining.

Inconel 718 has wide applications in various fields of engineering particularly where properties such as high temperature resistance, corrosion resistance, creep resistance, good ductile to brittle transition temperature during low temperature application, and high strength to weight ratio etc. are of importance. It has been established that Inconel 718 has good yield strength (550MPa) even an elevated temperature (760°C). The use of Inconel 718 in such aggressive environments hinges on the fact that it maintains high resistance to corrosion, mechanical and thermal fatigue, mechanical and thermal shock, creep, and erosion at elevated temperatures. In aero engines, these materials are specifically used for the manufacture of turbine blades, which operate at high temperature and pressure. Inconel 718 retains strength over a wide temperature range, attractive for high temperature applications where aluminum and steel would soften.

Inconel 718 provides a serious challenge as a work material during machining due to their unique combination of properties such as high temperature strength, hardness, and chemical wear resistance. Although these properties are the desirable design requirements, they pose a greater challenge to manufacturing engineers due to high temperature and stresses generated during machining. The two basic problems in machining of superalloy Inconel 718 are the following:

i. Less tool life due to the work hardening and attrition properties of the alloy.

ii. Metallurgical damage to the workpiece due to very high cutting forces, which also gives rise to work hardening, surface tearing, and distortion.

2.2.2 Machinability of Inconel 718

When selecting a material, several factors must be considered, including the cost, strength, resistance to wear, and machinability. The machinability of a material is difficult to quantify, but can be said to posses the characteristics such as results in a good surface finish, promotes long tool life, requires low force and power to turn and provides easy collection of chips.

The machinability index can be significantly affected by the properties of the material being machined, properties and geometry of the cutting tool, cutting conditions employed and other miscellaneous factors such as rigidity of the machine tool, cutting environment, etc. Machining productivity can be significantly improved by employing the right combination of cutting tools, cutting conditions and machine tool that will promote high speed machining without compromising the integrity and tolerance of the machined components.

The machinability also can often be measured in terms of the number of components produced per hour, the cost of machining the component, or the quality of the finish on a critical surface. Problems arise because there are so many practitioners carries out a wide variety of operation, each with different criteria's of machinability. A material may have good machinability by one criterion, but poor machinability by another. Machinability may be assessed by one or more of criteria below:

i. Tool life – the amount of material removed by a tool, under standardized cutting condition, before the tool performance becomes unacceptable or the tool is worn by a standard amount.

ii. Limiting rate of metal removal – the maximum rate at which the material can be machined for a standard short tool life.

iii. Cutting force – the force acting on tool or the power of consumption.

iv. Surface finish – the surface finish achieved under specified cutting condition.

v. Chip shape – the chip shape as it influences the clearance of the chips from the tool, under standardized cutting condition.

Inconel 718 is widely used for many industrial applications due to its unique properties. However, machinability of the material is considered to be poor due to its inherent characteristics. The machinability studies of Inconel 718 had been carried out by earlier researchers mostly at low or medium cutting speed. Machinability indices used in such cases have the characteristics such as cutting force, surface roughness, cutting temperature, etc (D. G. Thakur et al., 2009).

Nickel-based superalloys are widely employed in the aerospace industry, in particular in the hot sections of gas turbine engines, due to their high-temperature strength and high corrosion resistance. They are known to be among the most difficult to cut materials. D. Dudzinski et at. (2004) stated that the properties responsible for the poor machinability of the nickel-based superalloys, especially of Inconel 718 are:

i. a major part of their strength is maintained during machining due to their high-temperature properties,
ii. they are very strain rate sensitive and readily work harden, causing further tool wear,
iii. the highly abrasive carbide particles contained in the microstructure cause abrasive wear,
iv. the poor thermal conductivity leads to high cutting temperatures up to 1200 °C at the rake face,
v. nickel-based superalloys have high chemical affinity for many tool materials leading to diffusion wear,
vi. welding and adhesion of nickel alloys onto the cutting tool frequently occur during machining causing severe notching as well as alteration of the tool rake face due to the consequent pull-out of the tool materials,
vii. due to their high strength, the cutting forces attain high values, excite the machine tool system and may generate vibrations which compromise the surface quality.

The difficulty of machining resolves into two basic problems: short tool life and severe surface abuse of machined workpiece. The heat generation and the plastic deformation induced during machining affect the machined surface. The heat generated usually alters the microstructure of the alloy and induces residual stresses. Residual stresses are also produced by plastic deformation without heat. Heat and deformation generate cracks and microstructural changes, as well as large microhardness variations.

Residual stresses have consequences on the mechanical behaviour, especially on the fatigue life of the workpieces. Residual stress is also responsible for the dimensional instability phenomenon of the parts which can lead to important difficulties during assembly. Extreme care must be taken therefore to ensure the surface integrity of the component during machining. Most of the major parameters including the choice of tool and coating materials, tool geometry, machining method, cutting speed, feed rate, depth of cut, lubrication, must be controlled in order to achieve adequate tool lives and surface integrity of the machined surface (D. Dudzinski et al. 2004).

According to D. Dudzinski et at. (2004), the mechanics of machining Inconel 718 is not sufficiently understood yet for industrial applications and machining Inconel 718 can be consider as poor machinability because:

i. This material keeps its mechanical properties at high temperature.
ii. Carbides included in the material increase greatly the abrasive wear.
iii. Low thermal conductivity leads to high temperature during machining.
iv. Nickel-based alloys have a chemical affinity giving diffusion wear.
v. Cutting forces are quite high during the machining.

2.2.3 Cutting tool in machining Inconel 718

Nowadays, the revolution in manufacturing especially in the aerospace industries was encourage to the need for new and more developments on tool material. D. Dudzinski et at. (2004) state that the requirements for any cutting tool material used for machining nickel-based alloys should include:

i. Good wear resistance
ii. High hot hardness
iii. High fracture toughness
iv. High thermal shock properties
v. Adequate chemical stability at elevated temperature

vi. High yield strength at cutting temperature

Turning, milling and drilling are common operations carried out in the manufacture of jet engine mounts and blades, while turning and drilling are the predominant machining operations in the manufacture of disks for gas turbines. Most published work on the machining of nickel-based alloys deal with turning, then with milling, while drilling has received little attention (D. Dudzinski et at. 2004).

2.3 Machining

Machining can be defined as the process of removing material from a workpiece in the form of chips. The term metal cutting is used when the material is metallic. Machining is a family of shaping operations, the common feature of which is removal of material from a starting work part so the remaining part has the desired geometry. In order to increase the life of cutting tools, a common approach used in the past has been to heat treat tool materials, which provides greater control over the range of properties for a given tool material. In terms of annual dollars spent, machining is the most important of the manufacturing processes. The fundamental techniques of machining were established with the beginning of the mass production technology, pioneered by Henry Ford’s transfer lines. Machining operations consumes a large amount of money annually worldwide. Over US$ 100 billion is spent annually worldwide on metal part finishing processes such as turning, milling, boring and other cutting operations.

It is also known that the machining industry converts about 10% of all the metal produced into swarf (wastage). It is envisaged that up to 20% savings should be possible by using the correct choice of tooling and machining conditions. The key benefits of machining are listed below:

i. It is generally regarded as the optimum way to produce prototype or limited number production run components.
ii. It has the least effect on the properties of materials.

iii. It can be used to generate the most conceivable surface contours, dimensional tolerances and surface textures.
iv. It can be applied to all available materials.

The importance and versatility of machining process can be further appreciated by the fact that nearly every device in the society has one or more machined surfaces or holes. Typical problems that can be associated with machining operations range from the high cost of consumable tooling and set up time for high volume production to components often requiring several machining operations, thereby making it difficult to effectively control the machine shop and consequently an increase in work in process. These, in addition to the large amount of scrap produced, tend to form the basis for continued research and development activities in this area of manufacturing technology. Machining still remains a major industrial activity despite recent significant developments in near-net shape forming techniques.

The machining system consist of cutting tool, workpiece and machine tool with the cutting tool playing a major role as the cutting speed employed depend to a greater extent on the cutting tool materials. Machinists are continually exploring a cutting tool–machine tool–workpiece combination which will allow rapid metal removal rate for roughing cuts with large depth of cuts at very fast speeds and will also produce required surface finishes and dimensional accuracy associated with finishing passes. To achieve this efforts have been made in developing cutting tool materials that can survive aggressive conditions at the cutting edges (E.O. Ezugwu, 2005). Machining process can be divided into three processes as below:

i. Machining – material removal by a sharp cutting tool, e.g., turning, milling, drilling
ii. Abrasive processes – material removal by hard, abrasive particles, e.g., grinding
iii. Nontraditional processes - various energy forms other than sharp cutting tool to remove material

2.3.1 Cutting Condition

Three dimensions of a machining process:

a) Cutting speed, v – m/min
b) Feed, f – mm/tooth
c) Depth of cut, d – mm

For certain operations, material removal rate, R_{MR} is calculated using Equation 1.

$$R_{MR} = v f d \tag{1}$$

where v = cutting speed; f = feed; d = depth of cut

2.3.2 Introduction to Milling Operation

Milling is the process of cutting away material by feeding a workpiece past a rotating multiple tooth cutter. The cutting action of the many teeth around the milling cutter provides a fast method of machining. The machined surface may be flat, angular, or curved. The surface may also be milled to any combination of shapes. The machine for holding the workpiece, rotating the cutter, and feeding it is known as the Milling machine.

The geometric form created by milling is a plane surface. Other work geometries can be created either by means of the cutter path or the cutter shape. Owing to the variety of shape possible and its high production rates, milling is one of the most versatile and widely used machining operations.

Milling is an interrupted cutting operation: the teeth of the milling cutter enter and exit the work during each revolution. This interrupted cutting action subject the teeth to a cycle of impact force and thermal shock on every rotation. The tool material and cutter geometry must be designed to withstand these conditions. (Groover M.P, 2007)

Milling is characterized with an interrupted cutting action where each tooth produces a chip of variable thickness. The cutting circumstances are more adverse than that in turning. Since nickel alloys work harden rapidly, once the milling cutter starts cutting, it will become more and more difficult to further machining due to the hardening effect. H.Z. Li et al. (2006) said that when the cutting edge is not sharp enough, the metal is pushed instead of cut. This will result in higher cutting force and higher temperature.

2.3.2.1 Classification in Milling

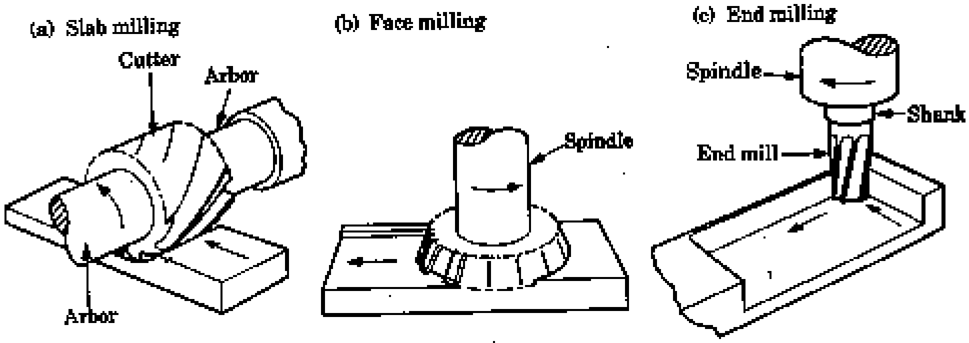

Figure 2.1: Classification in Milling (Kalpakjian S., Schmid S., 2006)

There are two types of milling operation that are peripheral milling and face milling. In peripheral (or slab) milling, the milled surface is generated by teeth located on the periphery of the cutter body. The axis of cutter rotation is generally in a plane parallel to the workpiece surface to be machined. In this milling, the rotating direction of the cutter distinguished two form of milling:

i. Up Milling

Up milling is also referred to as conventional milling. The direction of the cutter rotation opposes the feed direction when the teeth cut into the workpiece. For example, if the cutter rotates clockwise, the workpiece is fed to the right in up milling.

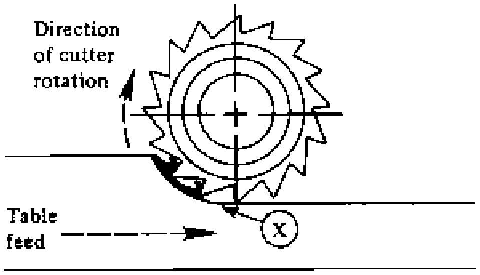

Figure 2.2: Up milling rotating direction (Geoffrey Boothroyd and Winston A. Knight, 1989)

ii. Down Milling

Down milling is also referred to as climb milling. The direction of cutter rotation is same as the feed motion. For example, if the cutter rotates counterclockwise , the workpiece is fed to the right in down milling.

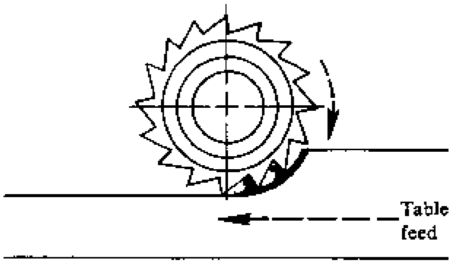

Figure 2.3: Down milling rotating direction (Geoffrey Boothroyd and Winston A. Knight, 1989)

The chip formation in down milling is opposite to the chip formation in up milling. The figure for down milling shows that the cutter tooth is almost parallel to the top surface of the workpiece. The cutter tooth begins to mill the full chip thickness. Then the chip thickness gradually decreases.

The experiment conducted by H.Z. Li et al. (2006) shown that the development of flank tool wear more rapid for up milling than down milling. There were six cutting passes performed for the down milling cases and four cutting passes performed for the up milling cases. For the cases of down milling, the width of flank wear was about 0.1mm after the first cutting pass. After the sixth cutting pass, the width of flank wear was about 0.3mm. The width of flank wear for up milling was over 0.2mm even after the first cutting pass. After the fourth cutting pass, it reached as high as 0.5mm, compared with the width of flank wear of only 0.19-0.25mm for the down milling cases after the same cutting pass.

In face milling, the cutter is mounted on a spindle having an axis of rotation perpendicular to the workpiece surface. The milled surface results from the action of cutting edges located on the periphery and face of the cutter. There are several types of face milling such as:

i. Conventional face milling – the diameter of the cutter is greater than the workpiece width, so the cutter overhangs the work on both.
ii. Partial face milling – the cutter overhangs the work on only one side.

iii. End milling - The cutter in end milling generally rotates on an axis vertical to the workpiece. It can be tilted to machine tapered surfaces. Cutting teeth are located on both the end face of the cutter and the periphery of the cutter body.

iv. Profile milling – a form of end milling in which the outside periphery of a flat part is cut.
v. Pocket milling – used to mill shallow pockets into flat parts.
vi. Surface contouring – a ball nose cutter is fed back and forth across the work along a curvilinear path at close intervals to create a three-dimensional surface form.

In a milling process, cyclic thermal and mechanical stress are the two effective factors that play significant role in controlling the tool life, failure modes and wear mechanism.

2.3.2.2 Cutting Parameters in Milling

In milling, the speed and motion of the cutting tool is specified through several parameters. These parameters are selected for each operation based upon the workpiece material, tool material, tool size, and more.

1. Cutting speed - The speed of the workpiece surface relative to the edge of the cutting tool during a cut, measured in m/min.

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 mm/tooth.

3. Depth of cut - The depth of the tool along the axis of the workpiece as it makes a cut, as in a facing operation. A large axial depth of cut requires a low feed rate, or else it will result in a high load on the tool and reduce the tool life. Therefore, a feature is typically machined in several passes as the tool moves to the specified axial depth of cut for each pass.

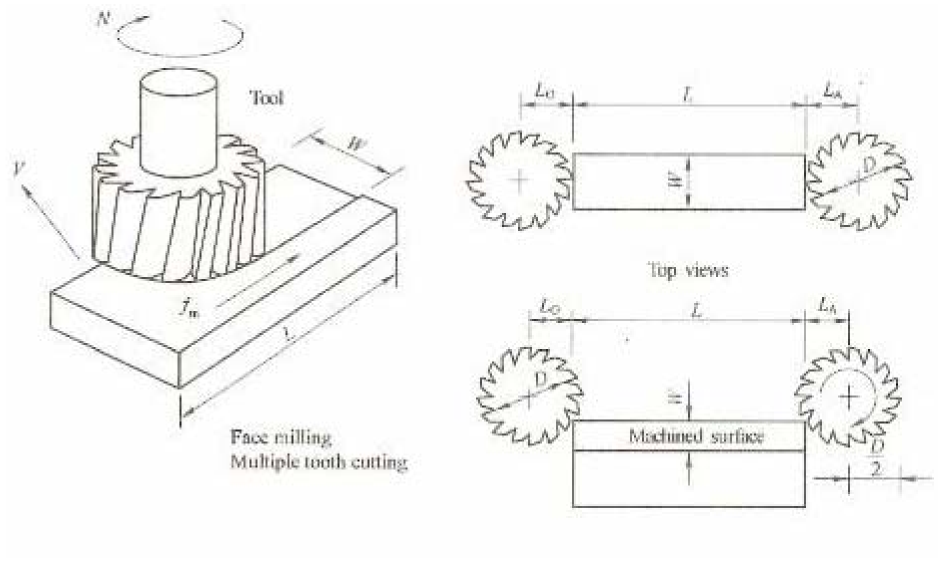

Figure 2.4: Face milling (http://www.vulcanmold.com/article/Milling.html)

The cutting speed is determined at the outside diameter of a milling cutter. This can be converted to spindle rotation speed using formula:

$$N = v/\pi D$$

where

N= Spindle rotation D = diameter of milling cutter, mm; v= cutting speed, m/min

Material removal rate in milling is determined using the product of the cross-section area of the cut and the feed rate. Accordingly, if a slab-milling operation cutting a workpiece with width, w, at a depth, d, the material removal rate is:

$$R_{MR} = wdf$$

This equation can be applied to end milling, side milling, face milling and other milling operation making the proper adjustment in the computation of cross-sectional area of cut.

The time required to milling a workpiece of length, L must account for the approach distance required to fully engage the cutter. First, consider the case of slab milling, to determine the time to perform a slab milling operation, the approach distance, A to reach full cutter depth is given by:

$$A = \sqrt{d(D - d)}$$

where,

d = depth of cut, mm; D = diameter of milling cutter, mm. The time to mill the workpiece T_m is therefore

$$T_m = (L+A) / f$$

For face milling, it is customary to allow for the approach distance. A plus an over-travel distance, L_O. There are two possible cases as shown in Figure 2.6, in both cases $L_A = L_O$. The first case is when the cutter is centered over the rectangular workpiece, A and O are each equal to half the cutter diameter. That is,

$$L_A = L_O = D/2$$

where,

D = cutter diameter,mm

The second case is when the cutter is offset to one side of the work. In this case, the approach and over travel distance are given by

$$A = O = \sqrt{w(D - w)}$$

Where w = width of the cut,mm. Machining time in either case is therefore given by:

$$T_m = (L+A) / f$$

2.4 Cutting Tools

Many types of tool materials, ranging from high carbon steel to ceramics and diamonds, are used as cutting tools in today's metalworking industry. It is important to be aware that differences do exist among tool materials. The best tool is the one that has been carefully chosen to get the job done quickly, efficiently, and economically. A cutting tool must have the following characteristics in order to produce good quality and economical parts:

1. Hardness — hardness and strength of the cutting tool must be maintained at elevated temperatures, also called hot hardness.
2. Toughness — toughness of cutting tools is needed so that tools don't chip or fracture, especially during interrupted cutting operations.
3. Wear Resistance — wear resistance means the attainment of acceptable tool life before tools need to be replaced.

2.4.1 Cutting Tool Classification

1. Single-Point Tools
   - One dominant cutting edge
   - Point is usually rounded to form a nose radius
   - Turning uses single point tools

2. Multiple Cutting Edge Tools
   - More than one cutting edge
   - Motion relative to work achieved by rotating
   - Drilling and milling use rotating multiple cutting edge tools

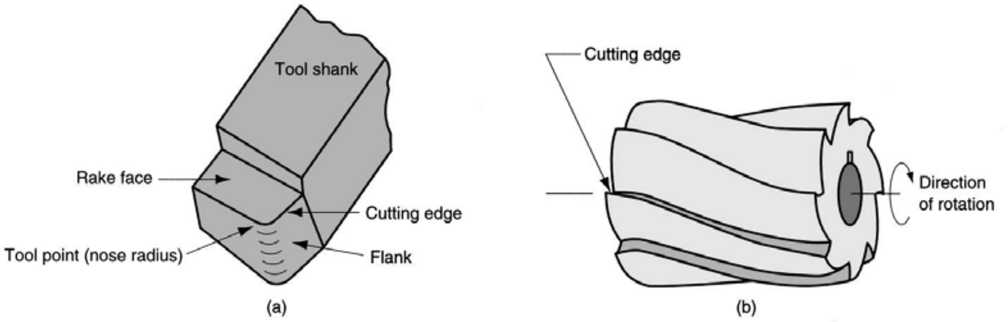

Figure 2.5: (a) A single-point tool showing rake face, flank, and tool point; and (b) a helical milling cutter, representative of tools with multiple cutting edges.

2.4.2 Cutting tool for Machining Inconel 718

Success in metal cutting depends upon the selection of the proper cutting tool (material and geometry) for a given material (E. Paul Degarmo et al., 1984). In this research, Inconel 718 is the material that will be machined. The requirement for the tool that will be machining Inconel 718 are wear resistance, high hot hardness, high strength and toughness, good thermal shock properties, adequate chemical stability at elevated temperature. According to E.M Trent (2000), cutting tools that usually used when milling Inconel 718 are:

i. Cemented carbides
ii. Synthetic diamond and CBN
iii. Ceramics
iv. High-speed steels
v. Cermets
vi. Coated carbides

2.4.3 Physical Vapor Deposition (PVD)

The introduction of PVD for cuttings tool in the metal cutting industry is one of the main success stories in the industrial application of modern coating technology over the last 30 years. The first PVD coating material to have a commercial application on cutting tool was TiN in the early 1980s and since the 1990s most cutting tools are PVD coated particularly in applications where sharp edges are required such as threading, grooving, end-milling, etc and in cutting applications that have a high demand for a tough cutting edge like drilling. In solid carbide cutting tools (end-mills and drills), PVD is the standard coating technology. The TiAIN coating is currently the most widely deposited PVD coating for cutting tools but other coatings such as TiCn and CrN offer better solutions in certain applications.

In the areas of machining and tooling, PVD coatings are widely used to increase the life and productivity of production cutting tools saving companies billions of dollars worldwide. The use of PVD coatings on cutting tools saves money in three ways. Firstly PVD coated cutting tools can be run faster reducing cycle times and enabling the production of more components in less time. Secondly, it can reduce wear and pickup. In metal cutting different wear processes exist depending on the workpiece material. These wear mechanism include abrasive wear on the flank and clearance face of the cutting tool, crater wear on the rake face, caused by the chemical interaction between the cut chip and the tool surface, built-up edge on the cutting edge and depth-of-cut notching caused by abrasion by the outer edge of the chip. None of these wear mechanism exists in isolation however one usually predominates. For example when cutting low-silicon aluminum a built-up-edge is generated that affects the quality of the finished product whereas high-silicon aluminum causes the tool to wear predominantly due to abrasion. PVD coatings are resistant to all forms of wear increasing the life of cutting tools reducing tool-changing costs.

Thirdly, the PVD coatings on cutting tools reduce the need for cutting fluid. Cutting fluids cost companies today up to 15% of their total production cost. High speed cutting and dry machining involve extremely high temperatures at the cutting edge. PVD

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