FEM ANALYSIS ON FACE MILLING OF INCONEL 718

This report submitted in accordance with the requirement of the Universiti Teknikal Malaysia Melaka (UTeM) for the Bachelor Degree of Manufacturing Engineering (Manufacturing Process) (Hons.)

by

CHAN CHEE HOONG

B051310097

930511-07-5225

FACULTY OF MANUFACTURING ENGINEERING

2017

DECLARATION

I hereby declared this report entitled "FEM Analysis on Face Milling of Inconel 718" is the results of my own research except as cited in references.

Signature	:	……………………………
Author's Name	:	CHAN CHEE HOONG
Date	:	JUNE 2017

APPROVAL

This report is submitted to the Faculty of Manufacturing Engineering of UTeM as partial fulfillment of the requirements for the degree of Bachelor of Manufacturing Engineering (Manufacturing Process) (Hons). The member of the supervisory committee is as follows.

……….………………………………..

Supervisor

(DR. MOHD SHAHIR BIN KASIM)

ABSTRAK

Masalah untuk mesin Inconel 718 telah meningkat disebabkan oleh sifat keliatan tinggi dan kerja pengerasan aloi. Di samping itu, pemesinan Inconel 718 memerlukan kos yang sangat tinggi kerana bahan yang sangat mahal dan memakan masa. Ia menyebabkan beberapa masalah dan sekatan kepada penyelidik. Inconel 718 adalah aloi super berasaskan nikel yang boleh menahan suhu yang tinggi dan tahan kakisan. TiAlN yang bersalut dengan karbida digunakan sebagai alat pemotong. Tujuan utama projek ini adalah analisis FEM pada muka pengilangan Inconel 718. Ini juga merangkumi kajian mengenai kesan memotong parameter pada daya paduan dan suhu alat. Parameter pemotongan adalah dalam lingkungan halaju pemotongan, Vc (20 hingga 40 m/min), kadar suapan, fz (0.10-0.20 mm/gigi) dan kedalaman pemotongan, ap (0.1 hingga 0.2 mm). Pendekatan eksperimen telah dilakukan dengan menggunakan Analisis Varian (ANOVA) dan metodologi permukaan sambutan (RSM). Daripada keputusan yang didapati, ia telah diperhatikan bahawa faktor-faktor penting yang mempengaruhi daya paduan adalah kadar dan kedalaman pemotongan manakala halaju pemotongan tidak mempunyai perbezaan yang signifikan pada daya paduan. Interaksi antara kadar suapan dan kedalaman pemotongan mempunyai pengaruh yang paling tinggi atas daya paduan. Sebaliknya, faktor-faktor penting yang memberi kesan kepada suhu alat ialah halaju pemotongan, kadar suapan dan kedalaman pemotongan. Melalui kaedah RSM, parameter optimum menetapkan diperolehi ialah 23.13 m/min untuk halaju pemotongan (Vc), 0.10 mm/gigi untuk kadar suapan (fz), dan 0.10 mm untuk kedalaman pemotongan (ap). Data simulasi kemudiannya disahkan dengan eksperimen yang sebenar. Peratusan relatif ralat sisihan antara simulasi FEM dan eksperimen sebenar untuk daya paduan adalah 10% dan suhu alat adalah 31%. Keputusan simulasi menunjukkan perjanjian yang agak baik dengan keputusan eksperimen dengan mempertimbangkan semua faktor yang mungkin terlibat.

ABSTRACT

Problems to machine Inconel 718 has been increasing due to its high toughness and work hardening nature of the alloy. In addition, the machining of Inconel 718 requires a very high cost due to the material is very expensive and time consuming. It causes several problems and restrictions to the researchers. Inconel 718 is a nickel-based superalloy which can withstand high temperature and corrosion resistant. TiAlN coated carbide inserts were used as the cutting tool. The main purpose of this project is FEM analysis on face milling of Inconel 718. This also includes a study on the effect of cutting parameters on resultant force and tool temperature. The cutting parameters are in the range of cutting speeds from 20 to 40 m/min at a range of feed rates from 0.10 to 0.20 mm/tooth and depth of cut in the range of 0.1 to 0.2 mm. The experimental approach was done by using Analysis of Variance (ANOVA) and Response Surface Methodology (RSM). From the results, it was observed that the significant factors which affect the resultant force are feed rate and depth of cut, while cutting speed has no significant difference in resultant force. Interaction between feed rate and depth of cut has the most influence on resultant force. On the other hand, the significant factors that affect tool temperature are cutting speed, feed rate and depth of cut. Through RSM method, the optimal parameters set obtained was 23.13 m/min, 0.10 mm/tooth and 0.10 mm for cutting speed (Vc), feed rate (fz), depth of cut (ap) respectively. The simulated results were then validated with actual experiment. It is found that the percentage of relative error between FEM simulation and actual experiment for resultant force and tool temperature are 10% and 31% respectively. By considering all the possible errors, the overall trend of the simulated result shows a reasonably good agreement with the experimental result.

DEDICATION

This thesis work is dedicated to my beloved parents who have always loved me and giving me support as always. Besides that, I would like to especially thank my supervisor, panels and friends for helping me throughout the project towards achieving my goals.

ACKNOWLEDGEMENT

I wish to express my gratitude to my parents for their confidence in me. I would like to thank them for their encouragement throughout the entire progress of the project. Besides that, I would like to express my sincere thanks to my supervisor, Dr. Mohd Shahir bin Kasim for his supervision, guidance and support throughout the project. I would like to thank him for teaching me the extra knowledge than required. The knowledge and experience gained is extraordinary and will be very useful for my future. I would also like to extend my sincere appreciation, especially to panels who gave advice and suggestions for this project. Last but not least, I would like to thank my friends, technician and to whom who have helped me throughout the project.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

FEM	-	Finite Element Method
PVD	-	Physical Vapour Deposition
CVD	-	Chemical Vapour Deposition
TiAlN	-	Titanium Aluminium Nitride
TiN	-	Titanium Nitride
CrN	-	Chromium Nitride
HSS	-	High Speed Steel
CBN	-	Cubic Boron Nitride
PCBN	-	Polycrystalline Cubic Boron Nitride
Al_2O_3	-	Aluminium oxide
DOC	-	Depth of Cut
DOE	-	Design of Experiment
ANOVA	-	Analyis of Variance
RSM`	-	Response Surface Methodology
CAD	-	Computer Aided Design
Vc	-	Cutting speed
fz	-	Feed rate
ap	-	Depth of cut
2FI	-	2 Factors Interaction

LIST OF SYMBOLS

g/cm3	-	Gram per cube centimetre
°C	-	Degree Celcius
°	-	Degree angle
%	-	Percentage
MPa	-	Mega Pascal
W/mK	-	Watt per metre Kelvin
kN/mm2	-	Kilonewton per square millimetre
rpm	-	Revolution per minute
m/min	-	Metre per minute
mm/tooth	-	Millimetre per tooth
mm/rev	-	Millimetre per revolution
mm	-	Millimetre
N	-	Newton
wt. %	-	Weight Percentage

CHAPTER 1

INTRODUCTION

1.1 Project Background

Machining is processes that involve the removal of material and changes of surface appearance of a workpiece after it has been produced through various methods (Kalpakjian *et al.*, 2013). Machining of materials is recognized as removing unwanted materials by using variable cutting parameters with different types of inserts (Steel *et al.*, 2013). There are three types of machining mainly milling, turning and drilling. Milling is a process of cutting away material using a rotary tool with multiple teeth by feeding at a workpiece.

Face milling can be performed using a wide range of different tools. The cutter is mounted on a spindle with an axis of rotation perpendicular to the workpiece surface and tool feeds from the surface towards the centre or outward from the centre (Trent & Wright, 2000; Kalpakjian *et al.*, 2013). Most of the cutters applied with an angle of 45º which is most frequently used. The inserts are indexable as in they are not welded to tool body. The cutting action occurs primarily at the end corners of the milling cutter. Face milling is mostly applied to reduce the dimension or to smoothen the surface of workpiece (Kim & Ehmann, 1993). It is used to cut flat surfaces. There are three axes mainly x-axis, y-axis and z-axis which produces three forces which known as cutting force, feed force and thrust force acting on the workpiece during the machining.

Inconel 718 is a high temperature and corrosion resistant nickel based alloy and widely used due to its excellent mechanical and chemical properties at extreme condition (Thirumalai *et al.*, 2012). The demand of Inconel 718 has been increasing rapidly. Inconel 718 plays an important role in the development of aero engines. It is mainly applied in the aerospace industry and nuclear reactors. However, Inconel 718 is known as difficult-to-cut material. Problems to machine Inconel 718 has been increasing due to its high toughness and work hardening nature of the alloy (Amin *et al.*, 2011). The two main problems of

Inconel 718 are short life span of tool life due to work hardening and metallurgical damage of workpiece (Rahman *et al*., 1997).

There are physical interaction between the cutting tool edge and workpiece in each milling process. Cutting edge determines the product quality and the tool life (Denkena *et al*., 2012). The hardening surface layer of Inconel 718 increases the stress at tool-workpiece interface that makes it difficult to cut in the vicinity of the cutting zone (Hosseinkhani & Ng, 2013). The forces acting on the tool-workpiece interface produce high friction coefficient and cause tool wear increases. Tool wear impairs the surface finish and tool life is reduced. The cutting edge becomes softer and leads to deformation and deflection due to high temperature (Liu *et al*., 2002). Chip formation involves workpiece shearing from the vicinity of the shear zone. In the vicinity of chip deformation begins, the workpiece exhibits a form of negative strain-hardening (Cobbett, 2008).

Resultant force is mainly affected due to the parameters of feed rate, cutting speed and depth of cut (Qian & Hossan, 2007). Many researchers have conducted the machining of Inconel 718 through actual experiment. However, the machining of Inconel 718 requires a very high cost due to the material is very expensive and time consuming (Amin *et al*., 2011). Hence, the effect of cutting parameters on the resultant force and temperature will be simulated and compared with actual experiments which to be done after the simulations. Therefore, Advantedge software will be used to simulate the machining of Inconel 718.

In this project, the simulation will investigate about the cutting forces by using various parameters which affect the forces (Fx, Fy and Fz) and temperature. These are the three main cutting forces on an individual tooth per cut in the X, Y and Z directions respectively. By using Third Wave Advantedge software, more accurate results can be obtained compared to experimental approach. Furthermore, it does not require any cost to conduct the simulation.

1.2 Problem Statement

Inconel 718 is known as nickel-based super alloy material which can withstand high temperature and corrosion resistant. They are one of the most difficult-to-cut materials due to their properties and the tool life is extremely short (Tanaka *et al*., 2016). Inconel 718 a type of material which can perform well and has high demand in aerospace, gas turbine and automobile industries. It can be applied in range temperature of -217 °C to 700 ℃

(Alauddin *et al*., 1998). Its low microstructure dislocation makes the Inconel 718 have high tensile and yield strength properties (Sharman *et al*., 2001).

Inconel 718 has much lower thermal conductivity than other alloy steels. The cutting temperature of the tool and workpiece are very high during machining. The combination of high applied forces and temperatures cause flank wear and tool chipping (Joshi, 2000). High tensile strength and shear strain of Inconel 718 make the process slow to form flakes (Sharman *et al*., 2001). The repetitive cyclic load causes notch wear and flaking due to its high cutting forces (Kasim *et al*., 2013). During cutting process, the defects on the rake face and flank tools such as notches and scratches initiates that fracture begins to occur. The defects cause shorter life span of tool.

The fatigue crack growth of Inconel 718 is also influence by cyclic load and hold times (Hornqvist *et al*., 2011). In loading cycle, the hold times at high temperature are present at about 650 °C. With such a high temperature hold times, the fatigue crack growth rate may become extremely high (Gustafsson *et al*., 2011). It may be due to damage in the crack tip vicinity causing it to fail by intergranular fracture. The crack will propagate to a critical length where fracture will occur.

Plain carbon steel shows a rapid decrease in its hardness as temperature increases. High speed steel is slightly better compared to plain carbon steel. On the other hand, cemented carbide and ceramics are significantly harder at elevated temperature. Heat generation occurs resulting of plastic deformation and friction along the tool–chip and tool–workpiece interface. High hot hardness is required so that the temperature of cutting tool is maintained without plastic deformation.

Machining of metals has been carried out for decades and various cutting tools are still developing till present. However, material such as Inconel 718 is still a challenging problem to machine. Thus, higher cutting forces are required during machining Inconel 718. Main parameters such as feed rate, cutting speed and depth of cut are the factors that affect machining (Soo *et al*., 2004). Different parameters will have different outcome of cutting forces. For instant, cutting forces increases as the feed rate increases (Colak, 2012; Alauddin *et al*., 1998).

The most frequent problem faced in process of machining of Inconel 718 is short tool life. The forces acting during machining is the factor that causes it to happen. In order to extend tool life, coatings has been applied. Tool with PVD coated and CVD coated are widely applied. However, cutting forces is depending on different types of coated tool. A

CVD coated tool tends to generate higher cutting forces compared to a PVD coated tool (Rahman *et al*., 1997).

The main challenge in machining is increasing productivity while maintaining products quality (Devillez *et al*., 2007). In order to achieve the requirements, optimum parameters have to be selected. Many parameters are depending on the temperature during cutting such as cutting speed, tool life and mechanics of chip formation. Nevertheless, criteria such as tool life and cutting forces should not be neglected. A lot of cutting experiments need to be carried out to find the optimum parameters. It not only costs a lot but also time consuming. Therefore, finite element method is used to run the simulations.

Finite element method (FEM) is mainly for the study which requires complex machining process. Advantedge software can be used to simulate the face milling of Inconel 718. It can be done in a shorter time and at a lower cost as compared to experimental approach. By applying the FEM in machining processes, different cutting parameters can be set to investigate the different cutting forces. The simulation is run based on the real machining operation. The most optimum parameters can be determined using simulation results to produce lower cutting forces and temperature.

1.3 Objectives

During machining process, the cutting effectiveness might be reduced due to several factors such as tool wear or flank wear. Tool wear very fast are mostly due to the high cutting forces. Cutting forces are influenced by the cutting parameters. The purpose of this project is to decrease the cutting forces and temperature during machining Inconel 718. The objectives to be achieved are as follows.

a) To simulate the face milling process of Inconel 718 via FEM software.
b) To evaluate the effect of cutting parameters on resultant force and tool temperature.
c) To validate the simulation result with actual experiment.

1.4 Scopes

In this project, the scopes will be focusing as below:

a) Inconel 718, 36 HRC as workpiece material.
b) Dry conditions with chilled air as coolant.
c) Round cutting insert with PVD coated of TiAlN.
d) Cutting tool with diameter of 50 mm.
e) Cutting tool consisting of five teeth.
f) Advantedge software is used for simulation.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Many studies regarding Inconel 718 were reported in the literature. The literature covers a variety of theories and topics. Therefore, this chapter will focus mainly on topics related to machinability and finite element simulation of Inconel 718 based on the literature review. Literature review is important to ensure the understanding of the knowledge about Inconel 718 and to justify the reason of the research.

2.2 Inconel 718

Inconel 718 is a type of nickel based super alloy. It is categorized as difficult-to-cut material. Inconel 718 is used for aerospace engines, steam turbine, bearing industry, nuclear and automotive applications (Patil *et al*., 2014). It has a higher strength to weight ratio compared to other materials such as steels. Inconel 718 is a precipitation-hardenable nickel alloy containing less amount of aluminum and titanium while amounts of iron, niobium and molybdenum are more as shown in Table 2.1 below (METALS, 2011).

Some of the properties that Inconel 718 are high mechanical properties, resistance to corrosion, thermal fatigue and shock at elevated temperatures (Colak, 2012). Table 2.1 and Table 2.2 show the chemical composition and properties of Inconel 718 respectively.

Table 2.1: Chemical composition of Inconel 718 (METALS, 2011)

Element	Content in %
Nickel	50-55
Chromium	17-21
Aluminium	0.2-0.8
Molybdenum	2.8-3.3
Boron	0.006
Iron	17
Carbon	0.08
Cobalt	1.0
Copper	0.3
Manganese	0.35
Niobium	4.75-5.5
Phosphorus	0.015
Sulphur	0.015
Silicon	0.35
Titanium	0.65-1.15

Table 2.2: Properties of Inconel 718 (METALS, 2011)

Properties	Values
Density	8.19 g/cm^3
Melting point	1425 °C
Ultimate tensile strength	1375 MPa
Yield Tensile Strength	1100 MPa
Thermal conductivity	11.4 W/mK
Modulus of elasticity	204.9 kN/mm^2

2.2.1 Machinability of Inconel 718

Machining refers to a process of removing material from a workpiece. Due to Inconel 718 nature, the common problems during machining Inconel 718 is difficult are resolved into two. Tool life of the cutting tool is short due to work hardening and properties of Inconel 718. The surface tearing due to high cutting forces on machined surface itself (Rahman *et al*., 1997).

According to Tanaka *et al.* (2016), Inconel 718 is one of the most widely used nickel-based alloys due to its excellent properties under very high temperature conditions especially for aviation, turbines and many more applications. However, Inconel 718 is classified as a difficult-to-cut material because of its special characteristics such as work hardening, low thermal conductivity and high affinity for tool materials.

Nickel-based super alloys like Inconel 718 are difficult to machine. Surface abuse and short tool life are the major issues since it is often used as components in engines and turbines. Several reasons are due to the following (Steel *et al*., 2013).

a) High hot hardness and strength causing deformation of the cutting tool.
b) The fast work hardening causing severe notch wear.
c) Presence of carbide particles cause abrasion tool wear.
d) Low thermal diffusivity leads to high local temperature on cutting edge.

Most important considerations of machinability of nickel based alloys are short tool life and surface of machined workpiece (Ezugwu *et al*., 1999). According to Dudzinski *et al.* (2004), they also said that the common problems during machining Inconel 718 is difficult are resolved into two which are short tool life and surface of machined workpiece. The poor machinability of nickel based alloy caused by the properties as follows;

a) Strength of material is maintained due to their high temperature properties (Dudzinski *et al*., 2004).
b) Presence of hard abrasive carbides cause high abrasive wear (Jawaid *et al*., 2001).
c) Work hardening occurs rapidly during machining (Ezugwu *et al*., 1999).
d) Poor thermal diffusivity of generates high temperature at the tool tip (Kasim *et al*., 2013).
e) Production of continuous chips which hard to control and leads to degradation of the cutting tool (Trent & Wright, 2000).

2.3 Machining Process

Machining is one of the materials removing process to form into desired shape. Turning, milling, and drilling are some of the examples of primary machining processes. It involves transforming small chips from the workpiece. Tools like milling cutters and lathes are used for chip formation during machining process. Figure 2.1 shows the tool and workpiece interface during cutting process.

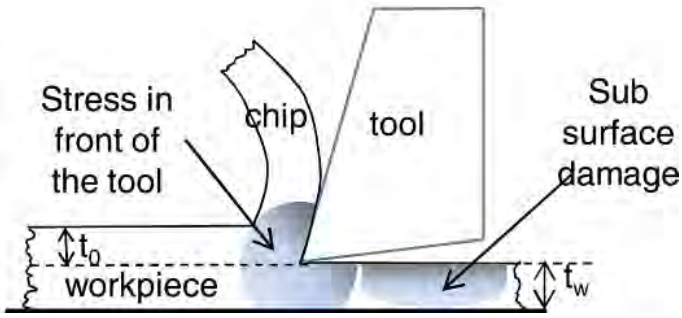

Figure 2.1: Tool and workpiece interface (Saptaji, 2013)

2.3.1 Milling process

Face milling is milling operation which is the most common form of machining. It is widely used especially to produce flat surface parts. Facing process can provide a high tolerances and good surface finish. It has a short lead time for machining. Workpiece can be machined into various shapes like flat, curved or angular shapes. It also can have combinations of variety of shapes.

The cutting conditions in milling are selected based on the types of work and qualitative requirements. The types of face milling cutters and cutting material are also the conditions that need to be considered (Orendac *et al.*, 2009). In face milling, the feed rate, cutting speed and depth of cut are important factors to consider. The influence of tool geometry on tool life also should not be neglected.

The position of cutting edge of the cutting tool is important based on type of cutting operation. In machining of material like Inconel 718, it will face difficulty due the material is nickel based and has hardening effect. It might produce a high cutting force and cutting edge of the tool will wear rapidly. The workpiece will be pushed harder if the cutting edge of the cutting tool is not sharp enough (Li *et al.*, 2006). It has been a challenging problem. Therefore, it is necessary to develop an efficient method to solve problem such as using simulation to reduce cost.