

MACHINABILITY STUDY OF COATED AND UNCOATED CARBIDE TOOLS
IN DRILLING INCONEL 718

R I V A L

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Mechanical Engineering)

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

MAY 2014

Specially dedicated to *my parents and all family members*

ACKNOWLEDGEMENTS

In the name of Allah, the most Gracious and most Compassionate

I would like to thank Allah Almighty for blessing and giving me strength to complete this thesis. Special thanks to all my supervisors, Prof. Dr. Safian Sharif and Prof. Dr. Noordin Mohd. Yusof for their continuous support, encouragement and help me in every way I need to go through this study.

I would also like to express my gratitude to all technicians in Production Laboratory, Machine Shop, and Material Laboratory, Faculty of Mechanical Engineering Universiti Teknologi Malaysia, for their cooperation and assistance in various types of laboratory tasks. My grateful to fellow researchers in the Production Laboratory for their advice and support. I would also like to express my sincere appreciation to all of my friends and colleagues in Universiti Teknologi Malaysia for coloring my daily live and helped me in one-way or another.

Deepest gratitude and grateful to all of my families, especially my wife Farayune Hajjar and my daughter Kayyasah Afrah Faiha, who gave me real love, pray, support, understanding, patience, hope and happiness during this study. Finally, I am indebted to Mr. Fuaddy M.Y. for his encouragement and endless support in giving me strength as well as and source of inspiration during this study.

ABSTRACT

Advanced materials such as aero-engine alloys, structural ceramics and hardened steels pose serious challenges for cutting tools material during machining. Nickel-base super alloys are generally known to be one of the most difficult materials to machine. Machining productivity can be significantly improved by employing the right combination of cutting tools, cutting conditions and machine tool without compromising the integrity and tolerance of the machined components. The objectives of this study are to evaluate the machining characteristics of new drill geometry and to established mathematical model of the responses when drilling Inconel 718 using various cutting conditions. Commercially available Inconel 718 was drilled using carbide cutting tool with various point angles at various cutting speed between 4.59 to 21.41 m/min and feed between 0.03 to 0.12 mm/rev in the wet condition and a constant depth of cut. The drills employed in this study were uncoated carbide, TiAlN coated carbide and AlTiN coated carbide with designated ISO grade K20/K30. The performance of the cutting tools in terms of tool life (T), surface roughness (Ra), cutting forces (Fz) and diameter error (DE) was described using factorial design and response surface methodology (RSM). Mathematical models of the drilling responses were developed using the proposed method. Results showed that the developed models were statistically valid and sound based on the experimental results within the acceptable range. The optimum cutting conditions were developed for all the responses with acceptable desirability. Dimensional accuracy and surface layer alteration of the drilled hole when using all type of cutting tools were compared traditionally between three different types of tool. Results showed that the accuracy varied for all chosen machining conditions and tool types but still within acceptable tolerance. Top surface layer and subsurface are significantly affected with ununiform layer and the presence of white layer. Highest microhardness at subsurface layer occurred when using AlTiN coated carbide tool.

ABSTRAK

Bahan termaju seperti aloi angkasa, seramik struktur dan keluli yang dikeraskan memberi cabaran yang serius pada bahan matalat semasa proses pemotongan. Aloi berasas nikel merupakan salah satu bahan yang sangat sukar untuk dimesin. Produktiviti pemesinan dapat ditingkatkan dengan menggunakan kombinasi sesuai pada matalat, keadaan pemotongan dan mesin yang digunakan dengan memperhatikan integriti dan had terima produk yang dimesin. Tujuan penyelidikan ini adalah untuk menilai sifat dari pemesinan matalat yang berbeza geometri dan pembangunan model matematik terhadap respon semasa menggerudi Inconel 718 dengan pelbagai keadaan pemotongan. Penggerudian menggunakan matalat karbida pelbagai sudut geometri pada pelbagai halaju pemotongan di antara 4.59 hingga 21.41 m/min, kadar suapan di antara 0.03 hingga 0.12 mm/pusingan dalam keadaan basah dengan kedalaman pemotongan tetap. Matalat gerudi yang digunakan adalah karbida tak bersalut, karbida bersalut TiAlN dan AlTiN bergred ISO K20/K30. Prestasi matalat seperti hayat matalat (T), kekasaran permukaan (Ra), daya pemotongan (Fz), dan ketepatan diameter (DE) dinyatakan menggunakan kaedah reka bentuk pemfaktoran dan permukaan respon (RSM). Model matematik bagi respon proses penggerudian dibangun menggunakan kaedah di atas. Keputusan menunjukkan bahwa model yang dibangun adalah sah dan kukuh berdasar hasil keputusan yang diperolehi di dalam lingkungan yang dikaji. Keadaan pemesinan yang optimum juga dibangun untuk semua respon pemesinan dengan keperluan yang dapat diterima. Ketepatan dimensi dan lapisan permukaan lubang yang digerudi ketika menggunakan berbagai matalat dibandingkan di antara ketiga-tiga matalat. Keputusan menunjukkan adanya variasi ketepatan pada semua keadaan pemotongan dan matalat, namun ianya masih dalam ketepatan had terima. Lapisan permukaan dan bahagiannya dipengaruhi lapisan tak seragam di lapisan putih. Kekerasan yang tinggi pada lapisan permukaan berlaku ketika menggunakan karbida bersalut AlTiN.

TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	DECLARATION	ii
	DEDICATION	iii
	ACKNOWLEDGEMENTS	iv
	ABSTRACT	v
	ABSTRAK	vi
	TABLE OF CONTENTS	vii
	LIST OF TABLES	xiii
	LIST OF FIGURES	xvi
	LIST OF ABBREVIATIONS AND SYMBOLS	xxi
	LIST OF APPENDICES	xxiii
1	INTRODUCTION	1
	1.1 Overview	1
	1.2 Background of Research	2
	1.3 Problem Statement	3
	1.4 Objectives	3
	1.5 Scope of Study	4
	1.6 Significance of Study	4
2	LITERATURE REVIEW	6
	2.1 Introduction	6

2.2	Nickel Alloys	6
2.2.1	Inconel	8
2.3	Drilling	8
2.4	Cutting Tool	12
2.5	Cutting Force	15
2.6	Tool Life	17
2.7	Tool Wear	18
2.8	Surface Integrity	20
2.9	Dimensional Accuracy	21
2.10	Design of Experiment (DOE)	22
	2.10.1 Two Level Factorial Design	23
	2.10.2 Response Surface Methodology (RSM)	24
2.11	Machinability of Nickel Based Alloy	27
2.12	Summary	33
3	RESEARCH METHODOLOGY	36
3.1	Introduction	36
3.2	Research Design Variables	36
3.3	Workpiece Material	37
3.4	Cutting Tools	38
3.5	Machining Procedure	40
3.6	Tool Wear Measurement	41
3.7	Investigation of Surface Finish	43
3.8	Data Sources and Data Analysis	44
3.9	Dimensional Accuracy	48
3.10	Expected findings and Summary	48
4	RESULTS AND DISCUSSION FOR UNCOATED CARBIDE TOOL	50
4.1	Introduction	50
4.2	Experimental Results for Uncoated Carbide Tool	50

4.3	Analysis of Surface Roughness for Uncoated Carbide Tool	51
4.3.1	Development of First Order Model using 2^k Factorial Design for Surface Roughness of Uncoated Carbide Tool	52
4.3.2	Development of Second Order Model of Surface Roughness for Uncoated Carbide Tool	55
4.4	Analysis of Tool Life for Uncoated Carbide Tool	57
4.4.1	Development of First Order Model using 2^k Factorial Design for Tool Life of Uncoated Carbide Tool	57
4.4.2	Development of Second Order Model of Tool Life for Uncoated Carbide Tool	60
4.5	Analysis of Cutting Force for Uncoated Carbide Tool	63
4.5.1	Development of First Order of Cutting Force using 2^k Factorial Design for Uncoated Carbide Tool	63
4.5.2	Development of Second Order Model of Cutting Force for Uncoated Carbide Tool	66
4.6	Analysis of Diameter Error for Uncoated Carbide Tool	69
4.6.1	Development of First Order Model using 2^k Factorial Design for Diameter Error of Uncoated Carbide Tool	69
4.6.2	Development of Second Order Model of Diameter Error for Uncoated Carbide Tool	72
4.7	Performance of Uncoated Carbide Tool	75
4.7.1	Local Optimization in Uncoated Carbide Tool	75
4.8	Confirmation Run	78
4.9	Summary of Uncoated Carbide Tool	80

5	RESULTS AND DISCUSSION FOR TiAlN COATED CARBIDE TOOL	82
5.1	Introduction	82
5.2	Experimental Results for TiAlN Coated Carbide Tool	82
5.3	Analysis of Surface Roughness for TiAlN Coated Carbide Tool	83
5.3.1	Development of First Order Model using 2^k Factorial Design for Surface Roughness of TiAlN Coated Carbide Tool	83
5.3.2	Development of Second Order Model of Surface Roughness for TiAlN Coated Carbide Tool	87
5.4	Analysis of Tool Life for TiAlN Coated Carbide Tool	88
5.4.1	Development of First Order Model using Factorial Design for Tool Life of TiAlN Coated Carbide Tool	88
5.4.2	Development of Second Order Model of Tool Life for TiAlN Coated Carbide Tool	92
5.5	Analysis of Cutting Force for TiAlN Coated Carbide Tool	93
5.5.1	Development of First Order Model using 2^k Factorial Design of Cutting Force for TiAlN Coated Carbide Tool	93
5.5.2	Development of Second Order Model of Cutting Force for TiAlN Coated Carbide Tool	96
5.6	Analysis of Diameter Error for TiAlN Coated Carbide Tool	98
5.6.1	Development of First Order Model using 2^k Factorial Design of Diameter Error for TiAlN Coated Carbide Tool	98
5.6.2	Development of Second Order Model of Diameter Error for TiAlN Coated Carbide Tool	101

5.7	Performance of TiAlN coated Carbide Tool	103
	5.7.1 Local Optimization in TiAlN Coated Carbide Tool	104
5.8	Confirmation Run	106
5.9	Summary of TiAlN Coated Carbide Tool	108
6	DIMENSIONAL ACCURACY IN DRILLING OF INCONEL 718	110
6.1	Introduction	110
6.2	Hole Diameter in Drilling of Inconel 718	110
	6.2.1 Hole Diameter When Using Uncoated Carbide Tool	111
	6.2.2 Hole Diameter When Using TiAlN Coated Carbide Tool	114
	6.2.3 Hole Diameter When Using AlTiN Coated Carbide Tool	117
6.3	Roundness of the Drilled Hole	120
	6.3.1 Roundness Error When Using Uncoated Carbide Tool	121
	6.3.2 Roundness Error When Using TiAlN Coated Carbide Tool	123
	6.3.3 Roundness Error When Using AlTiN Coated Carbide Tool	125
6.4	Summary	127
7	SURFACE INTEGRITY IN DRILLING INCONEL 718	130
7.1	Introduction	130
7.2	Surface Roughness	131
7.3	Surface Layer	132
7.4	Microhardness	136
7.5	Summary	138

8	CONCLUSIONS AND RECOMMENDATIONS	139
8.1	Introduction	139
8.2	Conclusions	139
8.3	Recommendations for Future Work	143
	REFERENCES	145
Appendices	A - D	155 - 161

LIST OF TABLES

TABLE NO.	TITLE	PAGE
2.1	Summary table of machining nickel alloy	33
3.1	Machining parameters	37
3.2	Mechanical properties of Inconel 718	37
3.3	Chemical composition of Inconel 718 by percent of weight (Appendix B)	38
3.4	Geometry of the twist drill	39
3.5	The summary of independent variables of the drilling experiments for each type of tool	44
3.6	Design plan for drilling experiment (coded)	45
3.6	Design plan for drilling experiment (actual)	46
4.1	Results for uncoated carbide tool	51
4.2	ANOVA for surface roughness using factorial model when using uncoated carbide tool	53
4.3	ANOVA for surface roughness using CCD model	56
4.4	ANOVA for tool life using factorial model when using uncoated carbide tool	58
4.5	ANOVA for tool life using CCD model when using uncoated carbide tool	61
4.6	ANOVA for cutting force using factorial model when using uncoated carbide tool	65
4.7	ANOVA for cutting force using CCD model when using uncoated carbide tool	67

4.8	ANOVA for diameter error (DE) using factorial model when using uncoated carbide tool	70
4.9	ANOVA for diameter error (DE) using CCD model when using uncoated carbide tool	73
4.10	Set of goals for optimization in drilling of Inconel 718 when using uncoated carbide tool	77
4.11	Possible solutions for optimization in drilling of Inconel 718 when using uncoated carbide tool	77
4.12	Output from the point prediction in drilling Inconel 718 using uncoated carbide tool	79
4.13	Confirmation experiments in drilling Inconel 718 using uncoated carbide tool	79
4.14	Summary of the significant factor for uncoated tool	81
5.1	Result for TiAlN coated carbide tool	83
5.2	ANOVA for factorial model of surface roughness using when using TiAlN coated carbide tool	85
5.3	ANOVA for surface roughness using CCD model when using TiAlN coated carbide tool	87
5.4	ANOVA for factorial model of tool life using when using TiAlN coated carbide tool	89
5.5	ANOVA for tool life using CCD model when using TiAlN coated carbide tool	92
5.6	ANOVA of factorial model for cutting force when using TiAlN coated carbide tool	94
5.7	ANOVA for cutting force using CCD model when using TiAlN coated carbide tool	97
5.8	ANOVA of factorial model for diameter error when using TiAlN coated carbide tool	100
5.9	ANOVA for diameter error using CCD when using TiAlN coated carbide tool	102

5.10	Set of goals for optimization in drilling of Inconel 718 using TiAlN coated carbide tool	105
5.11	Possible solutions for optimization in drilling of Inconel 718 using TiAlN coated carbide tool	105
5.12	Output from the point prediction in drilling Inconel 718 using TiAlN coated carbide tool	107
5.13	Confirmation experiments in drilling Inconel 718 using TiAlN coated carbide tool	107
5.14	Summary of the significant factor for TiAlN coated tool	109
6.1	Hole diameter when drilling Inconel 718 using uncoated carbide tool	111
6.2	Hole diameter when drilling Inconel 718 using TiAlN coated carbide tool	115
6.3	Hole diameter when drilling Inconel 718 using AlTiN coated carbide tool	118
6.4	Roundness error when drilling Inconel 718 using uncoated carbide tool	122
6.5	Roundness error when drilling Inconel 718 using TiAlN coated carbide tool	124
6.6	Roundness error when drilling Inconel 718 using AlTiN coated carbide tool	126
6.7	Average hole diameter when drilling Inconel 718 using various types of carbide tool	128
6.8	Average roundness error when drilling Inconel 718 using various types of carbide tool	128
6.9	Data summary in dimensional accuracy and roundness error	129
7.1	Drilling Parameter	131
7.2	Summary	138

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
2.1	The main parts of twist drill body (Lindberg, 1990)	10
2.2	Factors influencing the drilling of materials	11
2.3	Curly chip ejected from the hole (Schnieder, 2001)	12
2.4	Comparison of toughness and hardness for each cutting tool materials (Stephenson and Agapiou, 1997)	13
2.5	Forces components in drilling process (Stephenson and Agapiou, 1997)	17
2.6	Measurement of flank wear (ISO 3685. 1977)	19
2.7	Objectives of response surface methods (Lawson and Erjavec, 2001)	25
2.8	Central Composite Design for 3 factors	27
3.1	Workpiece material	38
3.2	Schematic diagram of drilling tool	39
3.2	Sample of uncoated tool drill ($\alpha: 125^0$)	40
3.3	Schematic diagram of experimental set up	40
3.4	Machining set up	41
3.5	Nikon Digital Counter (Model CM-6F)	42
3.6	Optical microscope	42
3.7	Handysurf model E-35A and measurement location	43
3.8	Shimadzu micro hardness tester and hardness measurement	43
3.9	Flowchart outlining the steps undertaken in statistical analysis	47
3.10	Mitutoyo KN810 – Coordinate Measuring Machine (CMM) and measurement of diameter and roundness	48

3.11	Schematic diagram of the experimental approach that will be applied in this research	49
4.1	Main effects for surface roughness in factorial model when using uncoated carbide tools	53
4.2	Response Surface for surface roughness in factorial model for uncoated carbide tools	54
4.3	Main effects for tool life when using uncoated carbide tool	58
4.4	Response surface of factorial model for tool life using uncoated carbide tools	60
4.5	Diagnostic plots for CCD model of tool life when using uncoated carbide tool	62
4.6	Response surface for CCD tool life model when using uncoated carbide tool	63
4.7	Main effects for cutting force when using uncoated carbide tools	64
4.8	Response surface of factorial model for cutting force when using uncoated carbide tools	66
4.9	Diagnostic plots for CCD model of cutting force when using uncoated carbide tool	68
4.10	Response surface of CCD cutting force model when using uncoated carbide tool	69
4.11	Main effects for diameter error (DE) when using uncoated carbide tools	70
4.12	Response surface of factorial diameter error (DE) model when using uncoated carbide tools	71
4.13	Diagnostic plots for diameter error (DE) when using uncoated carbide tool	74
4.14	Response surface for diameter error (DE) in CCD model when using uncoated carbide tool	75
4.15	Overlay plot of optimized cutting condition in drilling of Inconel 718 using uncoated carbide tool	78
5. 1	Main effect for surface roughness using TiAlN coated carbide tool	84

5.2	Response surface of factorial model for surface roughness using TiAlN coated carbide tool	86
5.3	Main effect for tool life using TiAlN coated carbide tools	89
5.4	Response surface of factorial model for tool life using TiAlN coated carbide tools	91
5.5	Main effects for cutting force using TiAlN coated carbide tool	94
5.6	Response surface of factorial model for cutting force using TiAlN coated carbide tool	96
5.7	Response surface for CCD cutting force model when using TiAlN coated carbide tool	98
5.8	Main effects for diameter error using TiAlN coated carbide tools	99
5.9	Response surface of factorial model for diameter error TiAlN using coated carbide tool	100
5.10	Response surface for CCD of diameter error model when using TiAlN coated carbide tool	103
5.11	Overlay plot of optimized cutting conditions in drilling of Inconel 718 using TiAlN coated carbide tool	106
6.1	Comparison of hole diameter for new tool when drilling Inconel 718 using uncoated carbide tool	112
6.2	Comparison of hole diameter for worn tool when drilling Inconel 718 using uncoated carbide tool	112
6.3	Tool condition after drilling using uncoated carbide tool with $V_c; 18 \text{ m/min}$, $f; 0.1 \text{ mm/rev}$, $\alpha; 130^\circ$. (a) new tool, (b) worn tool	114
6.4	Comparison of hole diameter for new tool when drilling Inconel 718 using TiAlN coated carbide tool	115
6.5	Comparison of hole diameter for worn tool when drilling Inconel 718 using TiAlN coated carbide tool	116
6.6	Tool condition after drilling using TiAlN coated carbide tool with $V_c; 18 \text{ m/min}$, $f; 0.1 \text{ mm/rev}$, $\alpha; 120^\circ$. (a) new tool, (b) worn tool	117
6.7	Comparison of hole diameter for new tool when drilling	

	Inconel 718 using AlTiN coated tool	119
6.8	Comparison of hole diameter for worn tool when drilling Inconel 718 using AlTiN coated tool	119
6.8	Tool condition after drilling using AlTiN coated carbide tool with V_c ;18 m/min, f ;0.1 mm/rev, α ; 130^0 . (a)new tool, (b)worn tool	120
6.9	Illustration of LSC technique (Kurt <i>et.al</i> ,2008)	121
6.10	Roundness error for new tool when drilling Inconel 718 using uncoated tool	122
6.12	Roundness error for worn tool when drilling Inconel 718 using uncoated tool	123
6.11	Roundness error for new tool when drilling Inconel 718 using TiAlN coated carbide tool	124
6.12	Roundness error for worn tool when drilling Inconel 718 using TiAlN coated carbide tool	125
6.13	Roundness error for new tool when drilling Inconel 718 using AlTiN coated carbide tool	126
6.14	Roundness error for worn tool when drilling Inconel 718 using AlTiN coated carbide tool	127
7.1	Average surface roughness (Ra) in drilling of Inconel 718	131
7.2	Hole subsurface layer when drilling Inconel 718 using uncoated carbide tool in machining condition 2 ((a)exit, (b)middle, (c)entry)	133
7.3	Hole subsurface layer when drilling Inconel 718 using uncoated carbide tool in machining condition 2 ((a)exit, (b)middle, (c)entry)	133
7.3	Hole subsurface layer when drilling Inconel 718 using TiAlN coated carbide tool in machining condition 2 ((a)exit, (b)middle, (c)entry)	134
7.4	Hole subsurface layer when drilling Inconel 718 using TiAlN coated carbide tool in machining condition 3 ((a)exit, (b)middle, (c)entry)	134
7.5	Hole subsurface layer when drilling Inconel 718 using	

	AlTiN coated carbide tool in machining condition 2 ((a)exit, (b)middle, (c)entry)	135
7.6	Hole subsurface layer when drilling Inconel 718 using AlTiN coated carbide tool in machining condition 3 ((a)exit, (b)middle, (c)entry)	135
7.7	Microhardness change to distance in drilling Inconel 718 in machining condition 2	137
7.8	Microhardness change to distance in drilling Inconel 718 in machining condition 3	137

LIST OF ABBREVIATIONS AND SYMBOLS

A	-	Factor of cutting speed
B	-	Factor of feed
C	-	Factor of point angle
ANOVA	-	Analysis of variance
BUE	-	Built up edge
CCD	-	Central composite design
CMM	-	Coordinate measuring machine
DE	-	Diameter error (mm)
D_A	-	Average hole diameter
D_T	-	Tool diameter
F_z	-	Cutting force/thrust force (N)
f	-	feed (mm/rev)
HRC	-	Hardness Rockwell unit
RSM	-	Response surface methodology
Ra	-	Surface roughness (μm)
SEM	-	Scanning electron microscopy
T	-	Tool life (minute)
$x_1, x_2, x_3, \dots, x_k$	-	Input variables

α	-	Point angle (degree)
V_c	-	Cutting speed (m/min)
y	-	Response
ε	-	Error

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	Publications	153
B-1	Material certificate of Inconel 718	154
B-2	Material certificate of Inconel 718 (continue)	155
C-1	Graph of cutting force (Fz) when drilling Inconel 718 using uncoated carbide tool (Vc= 18 m/min, f= 0.1 mm/rev, $\alpha= 130^0$)	156
C-2	Graph of cutting force (Fz) when drilling Inconel 718 using TiAlN coated carbide tool (Vc= 18 m/min, f= 0.1mm/rev, $\alpha= 130^0$)	157
D-1	Sample of calculation for converting empirical model from coded to actual factors (Ra)	158
D-2	Sample of calculation for converting empirical model from coded to actual factors (T)	159

CHAPTER 1

INTRODUCTION

1.1 Overview

Advanced materials such as superalloys aero-engine alloys, structural ceramic and hardened steels poses serious challenges to cutting tools material during machining. Superalloys are heat resistant alloys of nickel, nickel-iron, or cobalt that exhibit a combination of mechanical strength and resistance to surface degradation generally not similar to the other metallic compounds. The primary uses of these alloys are in; (a) gas turbines for aircraft, such as discs, combustion chambers, bolts, castings, system in shaft exhaust, blades , vanes; (b) steam turbines in power plants, likes bolts, blades, heaters in stack gas; (c) reciprocated engines, likes in turbocharger, valves at the exhaust, hot plugs, etc.; (d) metal processing, likes for hot work tool and dies, dies for casting; (e) medical equipments, such as parts in dentistry, prosthetic devices; (f) space shuttles; (g) heat treatment equipment; (h) nuclear power plant; (i) petrochemical and chemical industries; (j) equipment for pollution control; and (k) coal gasification and liquefaction system (Choudury and El Baradie, 1998). Content of nickel is about 50% in nickel base alloys, where else in nickel-iron base alloy, nickel is found to be the main solute component.

Among the nickel base superalloys, Inconel is generally known to be one of the most difficult materials to be machined because of its high hardness, high strength at high temperature, affinity to react with tool materials, and low thermal diffusivity. Nickel base superalloys have some characteristics that are responsible for its poor machinability. They have an austenitic matrix, and like stainless steels, they

work hardened rapidly during machining. These alloys also have the tendency to weld with the tool material due to the high temperature generated during machining. The tendency to form BUE (built up edge) during machining and the presence of hard abrasive carbides in their microstructure also deters machinability. Machinability is the term used to describe how easily a material can be cut to a desired shape with respect to the tooling and machining processes involved. Machining productivity can be significantly improved by employing the right combination of cutting tools, cutting conditions and machine tool without compromising the integrity and tolerance of the machined components. This is particularly essential for the economic machining of difficult to machine materials such as Inconel 718.

1.2 Background of Research

Most of research findings on the machinability of Inconel have dealt with the turning operation and, to a certain extent, milling operation. The machinability of Inconel in drilling operation has not been widely reported. This may come as surprise as hole drilling is among the most common and demanding process in machining. New machining conditions on drilling of Inconel could be further exploited. Further research on drilling mechanism and its effect on this kind of material will ensure better machining efficiency.

This study is undertaken to investigate the performance of new drill geometry of coated and uncoated carbide when drilling Inconel 718 under various cutting conditions. Design of experiment (DOE) approach is used to develop mathematical models for the selected machining responses when drilling of Inconel 718.

The continuing demand for improved productivity through the use of properly selected drilling tool and drilling conditions for a given application has generated interest in understanding the drilling performance on the selected material. It is expected that the findings from this research would enhance new knowledge and provide a better understanding of the machining characteristics when drilling of

Inconel 718. In addition, it would provide significant benefits to the machining industries in particular aerospace and petrochemical industries.

1.3 Problem Statement

Does the performance of different drill geometry and coating of carbide tool when drilling Inconel 718 deliver better results in term of surface integrity, cutting forces, tool life and dimensional accuracy.

1.4 Objectives

The objectives of the study comprising the following:

- i. To determine the optimum machining conditions when drilling Inconel 718 using uncoated and coated carbide tools of different tool geometry
- ii. To develop mathematical models for tool life, surface roughness and cutting force of uncoated and coated carbide tools when drilling Inconel 718
- iii. To evaluate the effect of the cutting conditions on tool life, tool wear, cutting force when drilling Inconel 718
- iv. To study the surface integrity and microhardness of the drilled hole by mean of quality from different type of tools and geometry
- v. To investigate the dimensional accuracy in terms of diameter and roundness of the drilled hole when drilling Inconel 718 by using different type of tools and geometry

1.5 Scope of Study

The scope of this research is focused on drilling Inconel 718 using three types of cutting tools, which include uncoated and two coated carbide tools (TiAlN and AlTiN). Experimental studies were conducted under various independent variables which include cutting speed, feed rate, geometry and coatings material. In this study, the cutting speed applied in the range of 4.59 to 21.41 m/min and feed rate between 0.03 to 0.012 mm/rev. The geometry of the tool was specially manufactured with different point angle in the range 116.5 to 133.4 degree. The workpiece was mounted above dynamometer to record the produced force when drilling with wet condition. At the end of the study the performance of each cutting tools was evaluated by means of factorial design and response surface methodology (RSM), then mathematical models (empirical equations) for tool life, surface roughness, cutting force and diameter error were developed. Subsequently, the optimum cutting conditions for carbide tools in drilling Inconel 718 were established. The surface characteristics and dimensional accuracy were investigated based on the quality criteria.

1.6 Significance of Study

The enormous cost involved in the machining of nickel alloys and other aerospace materials has prompted continuous research and development of suitable cutting tool materials and geometries, as well as cutting techniques that ensure greater material removal rate with minimum surface and subsurface damages to the machined component. Although research on drilling had been conducted expensively, investigations on the drilling of nickel base superalloys are still limited especially in relation to optimization of cutting conditions on the machining responses. In this study the machining parameters such as cutting speed, feed rate was selected within wide range of value to identify several behavior of independent variables. The geometry of the tools was set especially the point angle which cover the geometry that commercially available. The mathematical models that are developed can assist the aerospace industries to determine suitable conditions in

drilling Inconel 718 within the range of this study for a specific target. Eventually, this will help to reduce the cost and time to the aerospace machining industries in the future. Dimensional accuracy in term of hole diameter and roundness that produced by drilling process were investigate especially in relation to the tool types and geometry. Surface and subsurface of the drilled holes are thoroughly investigated in terms of surface layer, microcracks and hardness.

REFERENCES

- Alauddin M., Mazid M.A., El Baradi M.A. and Hashmi M.S.J. (1996). Optimization of surface finish in end milling inconel 718, *Journal of Material Processing Technology*, 56; 54-65.
- Alauddin M., Mazid M.A., El Baradi M.A. and Hashmi M.S.J. (1996). Modelling of cutting force in end milling inconel 718, *Journal of Material Processing Technology*, 58; 100-108.
- Alauddin M., Mazid M.A., El Baradi M.A. and Hashmi M.S.J. (1998). Cutting forces in the end milling of inconel 718, *Journal of Material Processing Technology*, 77; 153-159.
- Alsagoff S.E, and Mannan, M.A. (2004). Hole quality in drilling of annealed Inconel 718. *SME Technical Paper. NAMRC thirty-two conference, June 1-4, Charlotte- North Carolina.* 1-8.
- Anderson M.J., and Whitcomb P.J. (2007). *DOE Simplified: Practical Tools for Effective Experimentation.* Second Edition. Productivity Press. New York.
- Armarego E. J. A and Brown R. H. (1969). *The Machining of Metals.* Prentice Hall Inc., Englewood Cliffs, New Jersey
- Armarego E. J. A., Verezub S. And Samaranayake P. (2002). "The Effect of Coatings on the Cutting Process, Friction, Forces and Predictive Cutting Models in Machining Operations." *Proc. Instn. Mech. Engrs.*, Vol. 216, Part B, pp. 347-355.
- Aruna M., and Dhanalakshmi V. (2010). Response surface methodology in finish turning Inconel 718, *International Journal of Engineering Science and Technology*, Vol. 2(9), 4292-4297
- Arunachalam R.M., and Mannan M.A. (2000). Machinability of nickel based high temperatures alloys, *Machining Science Technology*, 4-1, 127-168

- Arunachalam R.M., Mannan M.A. and Spowage A.C.(2004). Residual stress and surface roughness when facing age hardened Inconel 718 with CBN and ceramic cutting tools, *International Journal of Machine Tools & Manufacture*, 44 ; 879–887.
- Arunachalam R.M., Mannan M.A. and Spowage A.C.(2004). Surface integrity when machining age hardened inconel 718 with coated carbide cutting tools, *International Journal of Machine Tools & Manufacture*, 44 ; 1481–1491
- Bahr B., and Mankad T. (1999). “Study on Tool Geometry in High Speed Drilling of Aluminium Sheet Metal.” SAE Technical Paper, 1999-01-2295.
- Bera S. and Bhattacharyya A. “On the Determination of Torque and Thrust During Drilling of Ductile Materials.” *Proceedings of the 8th International M.T.D.R Conference*, UMIST, September 1967, pp. 879-892.
- Boothroyd G. (1975). *Fundamentals of metal machining and machine tools*. McGraw-Hill, Washington DC.
- Bono M., and Ni J. (2001). The effects of thermal distortions on the diameter and cylindricity of dry drilled holes. *International Journal of Machine Tool and manufacture*. 41; 2261-2270.
- Braga D.U., Diniz A.E., Miranda G.W.A, and Coppini N.L. (2002). Using a minimum quantity of lubricant (MQL) and a diamond coated tool in the drilling of aluminum-silicon alloys. *Journal of Materials Processing Technology*. 122; 127-138.
- Bushlya V., Zhou J.M., Lenrick F., Avdovic P. and Stahl J-E. (2011). Characterization of white layer generated when turning aged Inconel 718. *Procedia Engineering*. 19; 60-66.
- Bushlya V., Zhou J. and Stahl J.E. (2012). Effect of cutting conditions on machinability of superalloy Inconel 718 during high speed turning with coated and uncoated PCBN tools. *Procedia CIRP*. 3; 370-375.
- Chen Y.C., and Liao Y.S. (2003). Study on wear mechanisms in drilling of Inconel 718 superalloy. *J. of Materials Processing Technology*. 140; 269-273
- Choudury I.A and El-Baradie M.A. (1998). Machining nickel base superalloys; Inconel 718, Proceedings of the I MECH Part B Journal of Engineering Manufacture, 212-3; 195-206.
- Choudury I.A and El-Baradie M.A. (1998). Machinability of nickel-base super alloys: a general review. *J. of Material Processing Technology*. 77;278-284.

- Deng C.S and Chin J.H. (2005). Hole roundness in deep hole drilling as analysed by Taguchi methods. *International Journal of Advance Manufacturing Technology*. 25; 420-426.
- Devillez A., Le Coz G., Dominiak S., and Dudzinski D. (2011). Dry machining of Inconel 718, workpiece surface integrity. *Journal of materials Processing Technology*. 211. 1590-1598.
- Diamond W.J. (2001). *Practical experiment design for engineers and scientists*. Third edition. John Wiley & Sons. New York.
- Dudzinski D., Molinari A., and Schulz H. (2002). *Metal Cutting And High Speed Machining*, Kluwer Academic/Plenum Publisher. New York.
- Dudzinski D., Devillez A., Moufki A., Larrouquere D., Zerrouki V., and Vigneau J. (2004). A review of developments towards dry and high speed machining of Inconel 718 alloy. *Int. J. of Machine Tools & Manufacture*. 44; 439-456.
- Electronic Space Products International (2006). Machining Nickel and Nickel Alloys, *Technical Data*.
- El Wardany T.I., Mohammed E. and Elbestawi M.A. (1996). Cutting temperature of ceramics tools in high speed machining of difficult to cut materials, *Int. J. Mach. Tools Manufact.*, Vol 36; 611-634.
- Erkens G., Cremer R., Hamoudi T., Bouzakis K.D., Mirisidis J., Hadjiyiannis S., Skordaris G., Asimakopoulos A., Kombogiannis S., Anastopoulos J., and Efstathiou K. (2003). Supernitrides: A novel generation of PVD hardcoatings to meet the requirements of high demanding cutting applications, *Annals of the CIRP*, Vol 52.
- Ezilarasan C., Senthil Kumar V. S., Velayudham A., and Palanikumar K. (2011). Modeling and analysis of surface roughness on machining of Nimonic C-263 alloy by PVD coated carbide insert. *Transaction of Nonferrous Metals Society of China*. 21; 1986-1994.
- Ezugwu E.O., and Pashby I.R. (1992). High speed milling of nickel based superalloys, *Journal of Material Processing Technology*, 33, 429-437.
- Ezugwu E.O., and Lai C.J. (1995). Failure modes and wear mechanisms of M35 high-speed steel drills when machining inconel 901. *Journal of Material Processing Technology*. 49; 295-312.
- Ezugwu E.O, Wang Z. M, and Machado A.R (1999), The machinability of nickel based alloys: a review. *Journal of Material Processing Technology*. 86; 1-16

- Ezugwu E.O., and Bonney J. (2000). Effect of high pressure coolant supply when machining nickel based, Inconel 718, alloy with coated carbide tools, *Journal of Materials Processing Technology*, 153-154; 1045-1050.
- Ezugwu E.O. (2004). High speed machining of aero-engine alloys. *J. of the Brazilian Society of Mechanical Science & Engineering*. 26; 1-11.
- Ezugwu E.O., and Bonney J., da Silva A.B. and Machado A.R. (2004). Evaluation of the performance of different nano-ceramic tool grades when machining nickel base, inconel 718, alloy, *Journal of the Braz. Soc. of Mech. Sci. & Eng.*, Vol XXVI, No. 1/13.
- Ezugwu E.O., and Bonney J. (2005). Finish machining of nickel-base Inconel 718 alloy with coated carbide tool under conventional and high pressure coolant supplies. *Tribology Transactions*. 48; 76-81.
- Ezugwu E.O., Bonney J., Fadare D.A. and Sales W.F. (2005). Machining of nickel-base, Inconel 718, alloy with ceramic tools under finishing conditions with various coolant supply pressure, *Journal of Materials Processing Technology*, 162–163; 609–614.
- Ezugwu E.O., Fadare D.A., Bonney J., Da Silva R.B and Sales W.F. (2005). Modelling the coorelation between cutting and process parameters in high speed machining of Inconel 718 alloy using an artificial neural network, *International J. of Machine Tools & Manufacture*, 45; 1375-1385.
- Gatto A. and Iuliano L. (1997). Advanced coated ceramic tools for machining superalloys, *Int. J. Machine Tool Manufacture*, Vol. 37, 591-605.
- Haan D.M., Batzer S.A, Olson W.W. and Sutherland J.W (1997). An experimental study of cutting fluid effects in drilling, *Journal of Material Processing Technology*, 71;305-313.
- Heinemann R.K. (2012). The effect of starting hole geometry on borehole quality and tool life of twist drill. *International Journal of Manufacturing Technology*. 60; 519-526.
- Herbert C.R.J., Axinte D.A., Hardy M.C., and Brown P.D. (2011). Investigation into the characteristics of white layers produced in a nickel based superalloy from drilling operations. *Procedia Engineering*. 19; 138-143.
- Herbert C.R.J., Kwong J., Kong M.C., Axinte D.A., Hardy M.C., and Withers, P.J. (2012). An evaluation of the evolution of workpiece surface integrity in hole

- making operations for a nickel-based superalloy. *Journal of Materials Processing Technology*. 212; 1723-1730.
- Hood R., Soo S.L., Aspinwall D.K., Andrews P., and Sage C. (2011). Twist drilling of Hayness 282 superalloy. *Procedia Engineering*. 19; 150-155.
- International Standardization Organization (1977). *Tool-Life Testing with Single-Point Turning Tools*. ISO 3685.
- Jawaid A., Koksai S. and S. Sharif (2001). Cutting performance and wear characteristics of PVD coated and uncoated carbide tools in face milling 718 aerospace alloy, *Journal of Material Processing Technology*, 116 ; 2-9.
- Jindal P.C., Santhanam A.T., Schleinkofer U., and Shuster A.F. (1999). Performance of PVD TiN, TiCN, and TiAlN coated cemented carbide tools in turning, *International Journal of Refractory Metals & Hard Materials*, 17, 163-170.
- Kim D., and Ramulu M. (2004). Drilling process optimization for graphite/bismaleimide-titanium alloy stacks, *Composite Structures*, 63; 101-114.
- Kalss W., Reiter A., Derflinger V., Gey C., and Endrino J.L. (2006). Modern coatings in high performance cutting applications, *International Journal of Refractory Metals and Hard Materials*, 24, 399-404.
- Katz Z., and Poustie A. (2001). On the hole quality and drill wandering relationship. *International Journal Advance Manufacturing Technology*, 17 ; 233-237
- Kitagawa T., Kubo A., and Maekawa K. (1997). Temperature and wear of cutting tools in high speed machining of Inconel 718 and Ti-6Al-6V-2Sn, *Wear*, 202, 142-148.
- Kivak T., Habali K., and Seker U. (2012). The effect of cutting parameters on the hole quality and tool wear during the drilling of Inconel 718. *Gazi University Journal of Science*. 25(2);533-540.
- Klocke F., Lung D., Cordes S.E., and Gerschwiler K. (2008). Performance of PVD coating on cutting tools for machining Inconel 718, austenitic steel and quenched and tempered steel. *Proceeding of the 7th International Conference Coatings in Manufacturing Engineering*. 1-3 October, Chalkidiki, Greece. pg; 101-108.
- Kurt M., Kaynak Y., and Bagci E. (2008). Evaluation of drilled hole quality in Al 2024 alloy. *International Journal of advance Manufacturing Technology*. 37; 1051-1060.

- Kurt M., Bagci E., and Kaynak Y. (2009). Application of taguchi methods in optimization of cutting parameters for surface finish and hole diameter accuracy in dry drilling processes. *International Journal of advance Manufacturing Technology*. 40; 458-469.
- Lawson J., and Erjavec J. (2001). *Modern statistics for engineering and quality improvement*. Duxbury
- Linberg R. A. (1990). *Processes and Materials of Manufacture*, 4th Edition, Prentice Hall Inc., New Jersey, USA.
- Liu G., He N., Ma, Z.L. and Li L. (2004). Cutting forces in the milling of Inconel 718, *Key Engineering Materials*, Vols. 259-260, 824-828.
- Lochner R.H., and Matar J.E. (1990). *Designing for quality; an introduction to the best of Taguchi and Western methods of statistical experiment design*. Chapman and Hall, New York.
- Loria E.A., (1988). The status and prospects of alloy 718. *Journal of Metallurgy*, 36 -41.
- Lou M.S., Chen J. C., and Li C. M. (1998). Surface roughness prediction technique for CNC end milling. *Journal of Industrial Technology*. 15; 1-6.
- Makiyama T., and Yamane Y. (2005). Drilling with MQL process. *Proceeding of 8th CIRP International Workshop on Modelling of Machining operations, May 10-11, Chemnitz-Germany*. 423-427.
- MacGinley T. and Monaghan J. (2001). Modelling the orthogonal machining process using coated cemented carbide coating tools, *Journal of Material Processing Technology*, 118; 293-300.
- Mitrofanov A.V., Babitsky V.I. and Silberschmidt V.V. (2004). Finite element analysis of ultrasonically assisted turning of Inconel 718, *Journal of Material Processing Technology*, 153-154; 233-239.
- Mohammed T.H. (2001). Hole quality in deep hole drilling. *Materials and manufacturing processes*. 16(2); 147-164.
- Monaghan J. and MacGinley T. (1999). Modelling the orthogonal machining process using coated carbide coating tools, *Computational Material Science*, 16; 275-284.
- Montgomery D.C. (2001). *Design and analysis of experiments*. Fifth edition. John Wiley & Sons, New York

- Mustafa K., Eyup. B., and Yusuf K. (2009). Application of Taguchi method in the optimization of cutting parameters for surface finish and hole diameter accuracy in dry drilling process. *The International Journal of Advanced Manufacturing Technology*, vol. 40. issue 5-6. Pp 458-469.
- Myers R.H., and Montgomery D.C. (2002). *Response surface methodology: process and product optimization using designed experiments*. Second edition. John Wiley & Sons, New York
- National Center for Defense Manufacturing & Machining (NCDMM). (2000). *Inconel 713 Turbine Nozzle*, Technical Report, NCDMM Project No. 03-0011-10
- Ng E.G., Lee D.W., Dewes R.C. and Aspinwall D.K. (2000). Experimental evaluation of cutter orientation when ball nose end milling inconel 718, *Journal of Manufacturing Process*, 1-7.
- Noordin M.Y. (2003). *Performance Evaluation of Coated Carbide Cermet Tools When Turning Hardened Tool Steel*. PhD Thesis. Universiti Teknologi Malaysia.
- Obikawa T., Yamaguchi M., Funai K., Kamata Y., and Yamada S. (2012). Air jet assisted machining of nickel base superalloy. *International Journal of Machine Tools & Manufacture*. 61; 20-26.
- Olovsjo S., Wretland A., and Sjoberg G. (2010). The effect of grain size and hardness of Waspaloy on the wear of cemented carbide tools. *The International Journal of Advance Manufacturing Technology*. 50; 907-915.
- Olovsjo S., Wretland A., and Sjoberg G. (2010). The effect of grain size and hardness of Inconel 718 on the wear of cemented carbide tools. *Wear*. 268; 1045-1052.
- Olovsjo S., and Nyborg L. (2012). Influence of microstructure on wear behaviour of uncoated WC tools in turning of Alloy 718 and Waspaloy. *Wear*. 282-283; 12-21.
- Ozel T., and Ulutan D. (2012). Prediction of machining induced residual stresses in turning of titanium and nickel based alloys with experiments and finite element simulations. *CIRP Annals-Manufacturing Technology*. 61; 547-550.
- Rahman M., Seah W.K.H and Teo T.T. (1997). The machinability of Inconel 718, *Journal of Material Processing Technology*, 63 ; 199-204.

- Ralph W.C., Johnson W.S., Toivonen P., Makeev A., and Newman Jr J.C. (2006). Effect of various aircraft production drilling procedure on hole quality. *International Journal of Fatigue*, 28; 943-950.
- Roukema J. C. and Altintas Y. (2007). Generalized modeling of drilling vibrations. Part II: chatter stability in frequency domain. *International Journal of Machine Tools and Manufacture*. 47 ; 1474-1485.
- Sadat A.B. and Reddy M.Y. (1992). Surface Integrity of Inconel 718 nickelbase superalloy using controlled and natural contact length tools. Part 1: Lubricated, *Experimental Mechanics*, Vol.32, No.3; 343-348.
- Sadat A.B. and Reddy M.Y. (1993). Surface Integrity of Inconel 718 nickelbase superalloy using controlled and natural contact length tools. Part II: Lubricated, *Experimental Mechanics*, Vol.33, No.4; 343-348.
- Sanjay C., Neema M.L., and Chin C.W. (2005). Modelling of tool wear in drilling by statistical analysis and artificial neural network. *Journal of Material Processing Technology*, 170; 494-500.
- Schneider G. (2001). "Applied Cutting Tool Engineering." *Tooling and Production*, Vol. 65, No. 5, pp. 37-45.
- Satoshi EMA (2012). Effect of twist drill point geometry on torque and thrust. *Sci. Rep. Faculty of Education Gifu University*". 36. 165-174.
- Sharif S., Venkatesh V.C., and Rahim E.A. (2005). The effect of coatings on the performance of carbide tools when drilling titanium alloys Ti-6Al-4V. *Proceeding of 8th CIRP International Workshop on Modelling of Machining operations, May 10-11, Chemnitz-Germany*. 577-582.
- Sharif S. and. Rahim E. A. (2007). Performance of Coated and Uncoated Carbide Tools when Drilling of Titanium Alloy – Ti-6Al4V. *Journal of Materials Processing Technology*, Vol.185, Issues 1-3, pp 72 – 76.
- Sharman A.R.C, Dewes R.C. and Aspinwall D.K. (2001). Tool life when high speed ball nose end milling inconel 718TM, *Journal of Material Processing Technology*, 118; 29-35.
- Sharman A.R.C, Hughes J.J and Ridgway K. (2004). Workpiece surface integrity and tool life issues when turning inconel 718 nickel based super alloy. *Machining Science and Technology*, 8(3), 399-414.

- Sharman A. R. C., Amarasinghe A., and Ridgway K (2008). Tool life and surface integrity aspects when drilling and hole making in Inconel 718, *Journal of Material Processing Technology*, 200; 424-432.
- Shaw M.C., (2007). Metal cutting principles. Clarendon Press Oxford, ISBN 0198590202.
- Subhas B.K., Bhat R., Ramachandra K., and Balakrishna H.K. (2000). Simultaneous optimization of machining parameters for dimensional instability control in aero engine gas turbine components made of inconel 718 alloy, *Journal of Manufacturing Science and Engineering*, Vol. 122-3; 586-590.
- Subhas B.K., Bhat R., Ramachandra K., and Balakrishna H.K. (2000). Dimensional instability studies in machining of inconel 718 nickel based superalloy as applied to aerogas turbine components, *Journal of Engineering for Gas Turbines and Power*, 122-1; 55-61.
- Smith W.F and Hashemi J. (2006). *Foundations of Materials Science and Engineering*. McGraw Hill International Edition. New York.
- Thangaraj A. and Langenstein M. (1990). "An Investigation Into the Relationships Between Hole Quality and Drilling Forces." *Proceedings of Manufacturing International, Part 4, Advances in Materials and Automation*, Vol. 4, ASME, New York, pp. 149-157.
- Thomas A., El-Wahabi M., Cabrera J.M., and Prado J.M. (2006). High temperature deformation of Inconel 718, *Journal of Material Processing Technology*, 177, 469-472.
- Tonshoff H. K., Spintig W., and Konig W. (1994). "Machining of Holes Developments in Drilling Technology." *CIRP Annals*, Vol. 43, No. 2.
- Ulutan D. and Ozel T. (2011). "Machining induced surface integrity in titanium and nickel alloys: A review", *International Journal of Machine Tools and Manufacture*, Vol. 51, 250-280.
- Venkatesh V.C. "Diffusion Wear of High Speed Steel Tools." *Proceedings of the 7th International M.T.D.R Conference*, University of Birmingham, September 1966, pp. 401-413.
- Wang Z.Y. and Rajurkar K.P. (2000). Cryogenic machining of hard to cut materials, *Wear*, 239 ; 168-175.

- Wang Z.Y. Rajurkar K.P., Fan J., Lei S., Shin Y.C. and Petrescu G. (2000). Hybrid machining of Inconel 718, *International J. of Machine Tools & Manufacture*, 43; 1391-1396.
- Wei X. (2002). Experimental study on the machining of a shaped hole in Ni-based super heat resistant alloy, *Journal of Material Processing Technology*, 29, 143-147.
- Xue C. and Chen W. (2011). Adhering layer formation and its effect on the wear of coated carbide tools during turning of nickel based alloy. *Wear*. 270; 895-902.
- Yamamoto K., Kuroda M, Omokawa H. and Itakura K. (2001). *High efficiency cutting of super heat resistant alloy*, Mitsubishi Heavy Industries Ltd, Technical Review, Vol. 38 No.1.
- Zhong S., Gang L., and Ming C. (2007). Development and experiment of new AlTiN coated drills for high efficiency dry drilling of 40 Cr. *Transaction of Nanjin University of Aeronautics and Astronautics*. 24(2); 106-111.
- Zhou J.M., Bushlya V., Peng R.L., Johansson S., Avdovic P., and Stahl J-E. (2011). Effect of tool wear on subsurface deformation of nickel-based superalloy. *Procedia Engineering*. 19. 407-413.