PERFORMANCE EVALUATION OF UNCOATED AND COATED CARBIDE TOOLS WHEN END MILLING OF TITANIUM ALLOY USING RESPONSE SURFACE METHODOLOGY

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PERFORMANCE EVALUATION OF UNCOATED AND COATED CARBIDE TOOLS WHEN END MILLING OF TITANIUM ALLOY USING RESPONSE SURFACE METHODOLOGY

AMRIFAN SALADIN MOHRUNI

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

Faculty of Mechanical Engineering
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MARCH 2008

I declare that this thesis entitled *"Performance Evaluation of Uncoated and Coated Carbide Tools when End Milling of Titanium Alloy using Response Surface Methodology"* is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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To my grandfathers, my parents, my brothers, my beloved wife and sons,
Alif Tias Mangkunegara, Anugerah Al-Amin Mangkunegara,
Noordin As-Shiddiq Mangkunegara and M. Rafif Al-Farouq Mangkunegara
for their supports and understandings

ACKNOWLEDGEMENTS

All praise to Allah, the Almighty, most Gracious and most Merciful, Who has created the mankind with knowledge, wisdom and power, for His guidance and help in giving me the strength and motivation to complete this thesis. A special thank you to all of my supervisors, Prof. Dr. Safian Sharif, Assoc. Prof. Dr. Noordin Mohd. Yusof and Prof. Dr. V.C. Venkatesh, for their continuous support, assistance and encouragement and for providing the opportunity to conduct this research during my pleasant stay at Production Laboratory, FKM, UTM.

I would like also to express my gratitude to all of the staff in the Production Laboratory at Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, especially to Mr. Sazali Ngadiman, Mr. Maizan Sulaiman, Mr. Aidid Hussin and Mr. Mahudin Abdul Rahim for their effort in assisting me in the various workshop and laboratory tasks.

I am indebted to Universiti Teknologi Malaysia for providing me financial support during the period of this research work and to the Ministry of Science Technology and Environment for awarding my supervisor the IRPA grant (vote: 74122), which has enabled the purchase of some of necessary research equipment and materials.

I cannot find any proper word to express my thanks to my parents for their endless love, support and prayer. Through their teaching and life, I learned to face the real life without fear and to understand the value of hard working and sharing to each other. I am also grateful to my beloved wife, Raden Ayu Erna Yuliwati for her patience, understanding, support and many sacrifices, and my four sons, Tias, Angga, Shiddiq and Afif for giving me smiles, hope and endless happiness.

ABSTRACT

Titanium alloys are being constituted in modern aerospace structure, marine, automotive and chemical industry due to their strength-to-weight ratio, excellent corrosion and fracture resistance and low modulus of elasticity. However, titanium and its alloys are considered very difficult-to-machine material due to its highly chemical reactivity and tendency to weld to the cutting tool. These result in edge chipping and rapid tool failure. Although in the past, many studies had been carried out to predict the tool performance during end milling operation in terms of primary machining parameters, the effect of tool geometry was not taken into consideration. Therefore, an effort has been made in this research to evaluate the influence of tool geometry (radial rake angle), feed and cutting speed when end milling titanium alloy, Ti-6Al-4V. Machining trials were performed under flood condition with a constant axial and radial depth of cut. The cutting tools used were uncoated solid carbide tools grade K30 and coated with a physical vapor deposition (PVD) TiAlN and Supernitride. Tool performance of the above mentioned tools were investigated under various cutting conditions, while the surface roughness of the milled parts and cutting forces were measured. The performance of cutting tools was described using response surface methodology. It was found that, the cutting speed, feed rate and radial rake angle have a significant effect on various responses investigated such as tool life, surface roughness and cutting forces. The developed mathematical models were validated statistically using analysis of variances (ANOVA), which can be used for predicting the optimum cutting conditions within the limits of the factors investigated. In general, coated solid carbide tools performed better than the uncoated tools when end milling Ti-6Al-4V.

ABSTRAK

Aloi titanium digunakan di dalam struktur bidang aerospace moden, marin, automotif dan industri kimia, disebabkan oleh kadar berat dan kekuatannya, ketahanan terhadap kakisan dan keretakan serta modulus elastik yang rendah. Walau bagaimanapun titanium dan aloinya dikategorikan sebagai bahan yang sukar untuk dimesin, disebabkan oleh kereaktifan kimia yang tinggi, dan becenderungan untuk terkimpal ke matalat dengan pantas. Walaupun pada masa yang lalu telah banyak kajian dilakukan untuk menjangka prestasi matalat semasa proses kisar hujung terhadap parameter permesinan utama, kesan dari geometri matalat tidak pernah dipertimbangkan. Oleh itu, usaha telah dibuat dalam penyelidikan ini untuk menilai pengaruh geometri matalat pemotong (sudut sadak jejarian), uluran dan kelajuan pemotongan ketika pengisaran hujung aloi titanium, Ti-6Al-4V. Percubaan permesinan telah dilakukan di bawah keadaan basah serta kedalaman pemotongan tujah dan jejarian yang tetap. Matalat pemotong yang digunakan adalah matalat karbida padu tanpa salut dengan gred K30 dan matalat bersalut PVD-TiAlN dan Supernitride. Kebolehan matalat pemotong yang disebut di atas diselidiki di bawah pelbagai keadaan pemotongan, sementara kekasaran permukaan benda kerja dan daya pemotong diukur. Kebolehan matalat pemotong digambarkan menggunakan kaedah permukaan respon (RSM). Didapati kelajuan pemotongan, kadar uluran dan sudut sadak jejarian mempunyai kesan yang besar terhadap tindak balas yang diselidiki seperti hayat matalat, kekasaran permukaan dan daya potong. Model matematik yang dibangunkan, disahkan secara statistik menggunakan analisa varian (ANOVA) dan ianya dapat digunakan untuk menjangkakan keadaan pemotongan optimum di dalam julat faktor yang diselidiki. Secara umumnya matalat bersalut menunjukkan prestasi yang lebih baik berbanding matalat tidak bersalut ketika pengisaran hujung Ti-6Al-4V.

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LIST OF ABBREVIATIONS

ANOVA	-	Analysis of Variance
CCD	-	Central Composite Design
CIMS	-	Computer Integrated Manufacturing Systems
CVD	-	Chemical Vapor Deposition
FMS	-	Flexible Manufacturing Systems
DOE	-	Design of Experiments
HIP	-	High Isostatic Presses
HIS	-	High Ionization Sputtering
LOF	-	Lack of Fit
LSM	-	Least Squares Method
MSE	-	Mean Squares Errors
MSR	-	Mean Squares Regression
PVD	-	Physical Vapor Deposition
RSM	-	Response Surface Methodology
SSE	-	Sum of Squares Errors
SSR	-	Sum of Squares Regression
SST	-	Sum of Squares Total
SN_{TR}	-	Supernitride
TRS	-	Transfer Rupture Strength
TiAlN	-	Titanium Aluminum Nitrate

LIST OF SYMBOLS

α	-	Distance of Stars Points from Center.
β	-	Model Parameter
γ	-	Radial rake Angle
ξ	-	Natural Independent Variables
ε’	-	Multiplicative Random Errors.
k	-	Number of Independent Variables (Factors)
C	-	Model Parameter
F_c	-	Calculated Cutting Force
R_s	-	Measured Response
x_i	-	Coded Variables

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CHAPTER 1

INTRODUCTION

1.1 Overview

This research is carried out to evaluate the machining performance of uncoated and coated physical vapor disposition (PVD) TiAlN and Supernitride (SN_{TR}) solid carbide tools when end milling titanium alloy. The research involves the development of mathematical models for tool life, surface roughness and cutting force, which describe the relationship between the independent variables and the machinability parameters. The results obtained from this research will provide the suitable cutting conditions and cutting tool geometry when machining titanium alloy Ti-6Al-4V.

1.2 Background of the Problem

The development of better and more advanced materials is crucially important for the advancement in technology. This is especially true in high technology industries like aerospace, defense, nuclear power engineering etc. The trend in the aerospace industry in the recent past has been towards the development of materials for constructions that are:

(i) of greater strength
(ii) resistant to oxidation, particularly at high temperature
(iii) exhibit small deformations at high temperatures
(iv) of lighter weight
(v) not brittle at low temperature

One of the advanced materials such as titanium alloys have been introduced to meet these requirements. Hence, nowadays the demand on machining this advanced material increases rapidly. Even though new cutting tools like coated carbides, ceramics, diamond etc. have been developed, titanium alloys are still considered "difficult to machine" materials due to rapid failure of the faults (Kramer, 1987; Komanduri *et.al.*, 1981; Hartung *et.al.*, 1982).

1.3 Statement of the Problem

It was often thought that coatings offer better productivity advantages to carbide tools when machining steels and aluminium. However, most of the coatings developed so far including diamonds, ceramics and CBN are highly reactive with titanium alloys, causing rapid wear on the cutting tools (Kramer, 1987; Komanduri *et.al.*, 1981; Hartung *et.al.*, 1982).

The most recent coating material TiAlN has proven to offer higher hardness, increased toughness and improved wear resistance. TiAlN coated tools are also much more chemically stable and therefore suitable for high speed machining (Erkens, 2003, 2004).

Nevertheless, the suitability of TiAlN coated tools when machining titanium alloys is yet to be investigated. This work is aimed to evaluate the performance of TiAlN and Supernitride coated tools as compared to uncoated carbide (WC/Co) tools when end milling titanium alloy, Ti-6Al-4V.

The basic aim of tool performance assessment is the provision of sufficient technological data to ensure the efficient use of machine tools and other manufacturing resources. The tool performance data system is essential for the selection of cutting conditions during process planning and it has become an important component in the implementation of Flexible Manufacturing System (FMS) and Computer Integrated Manufacturing Systems (CIMS).

Computerized tool performance data systems have been classified into two general types:

(i) Simple data retrieval system
(ii) Mathematical model system

The simple data retrieval systems are based on the systematic collection and storage of large quantities of data from laboratory and industry resulting in so called “tool performance or machining data banks” and simply the retrieving system recommended the cutting speeds, feed rates and cost information for any specific cutting operation (Balakrishan and Deviries, 1983, 1985; Alauddin, 1997).

The mathematical model systems attempt to predict the optimum cutting conditions for a specific operation. The machining responses data such as tool-life, surface roughness, cutting forces, power, etc., are used as the primary data. Then mathematical models of these machining responses are developed as a function of the machining variables using a model building module, the model parameters and other relevant economic factors being used to derive the optimum set of cutting conditions (Wu, 1964; Taraman, 1974; El-Baradie, 1994).

1.4 Objective of the Study

The objective of this study comprising the following:

(i) To develop a mathematical model for tool life, surface roughness and cutting force of uncoated and coated carbide tools when end milling titanium alloy, Ti-6Al-4V.

(ii) To determine the optimum machining conditions in end milling of a titanium alloy, Ti-6Al-4V using uncoated and coated carbide tools.

(iii) To evaluate the effect of cutting conditions on tool life, surface roughness and cutting force of uncoated and coated carbide tools in end milling of titanium alloy, Ti-6Al-4V.

1.5 Significance of the Study

Most published research works on the development of mathematical model systems are concerned mainly on turning process, whilst end milling has received little attention due to the complexity of the process and the high cost involved.

Currently, reports on end milling of Ti-6Al-4V using the new hard coatings such as TiAlN and Supernitride are still lacking. Hence, this work is undertaken to carry out the investigation.

1.6 Scope of the Study

The scope of this research was focused on end milling of Ti-6Al-4V using three types of cutting tools, they are uncoated carbide and two coated carbide tools (TiAlN and SN_{TR}). The processes were conducted under various independent variables which include cutting speed, feed rate and coatings materials and tool geometries. At the end of the study the performance of each cutting tool was compared by means of response surface methodology, the mathematical models (empirical equations) for tool life, surface roughness and cutting force were developed. Ultimately, the optimum cutting conditions for carbide tool in end milling of Ti-6Al-4V were established.

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APPENDIX A
List of Publications

1. Mohruni, A. S., Sharif, S., Noordin, M. Y., Venkatesh, V. C. (2008) Mathematical Modeling of Cutting Force in End Milling Ti-6Al-4V using TiAlN coated Carbide Tools. *Proceeding of International Conference on Mechanical and Manufacturing Engineering (ICME).* 21-23 May. Johore Bahru: (Accepted for Publication).

2. Mohruni, A. S., Sharif, S., Noordin, M. Y., Venkatesh, V. C. (2007). Application of Response Surface Methodology of Tool Life Predicition Models when End Milling Ti-6Al4V. *Proceeding of 10th International Conference on Quality in Research (QIR)*. 4-6 December. ISSN: 1411-1284, Jakarta, Indonesia: IMM 20, 1-6.

3. Mohruni, S., Sharif, S., Noordin, M. Y., Venkatesh, V. C. (2007) Optimization of Surface Roughness when End Milling Ti-6Al4V using TiAlN Coated Tool. *Proceeding of 10th International Conference on Quality in Research (QIR)*. 4-6 December. ISSN: 1411-1284, Jakarta, Indonesia: IMM 15, 1-6.

4. Sharif, S., Rahim, E. A., Mohruni, A. S., Jawaid, A. (2007). Effect of Edge Geometry on PVD-TiN Coated Carbide Tools when Face Milling Titanium Alloy, Ti-6246. *The 4th International Conference on Leading Edge Manufacturing in 21st Century (LEM 21)*, 7-9 November. Fukuoka, Japan: 41-46.

5. Mohruni, A. S., Sharif, S., Noordin, M. Y., Venkatesh, V. C. (2006). Investigation of Optimum Cutting Condition when End Milling Titanium Alloy Ti-6Al-4V. *Proceeding of 9th International Conference on Quality in Research (QIR).* 6-7 September. ISSN: 1411-1284, Jakarta, Indonesia: IMM 01, 1-4.

6. Mohruni, A. S., Sharif, S., Isa, M. (2006). Surface Integrity Evaluation of Uncoated and TiCN coated Carbides Tools when End Milling of Titanium Alloy Ti-6Al-4V. *National Scientific Meeting of Indonesians Engineering Lecturer.* 5-6 September. Jakarta, Indonesia: C4, 24-29.

7. Sharif , S., Mohruni, A. S., Noordin, M. Y., Venkatesh, V. C. (2006). Optimum Surface Roughness Prediction Model when End Milling Titanium

Alloy (Ti-6Al-4V). *International Conference on Manufacturing Science and Technology (ICOMAST)*. 28-30 August. Melaka, Malaysia: 55-58.

8. Mohruni, A. S., Sharif, S., Noordin, M. Y. (2006). Cutting Force Predictions Model in End Milling titanium Alloy, Ti-6Al-4V. *1st Regional Postgraduate Conference on Engineering and Science (RPCES)*. 26-27 July. Johor Bahru, Malaysia: 337-342.

9. Sharif, S., Mohruni, A. S., Noordin, M. Y. (2006). Modeling of Tool Life when End Milling on Titanium Alloy (Ti-6Al-4V) using Response Surface Methodology. *International Conference on Manufacturing and Material Processing (ICMM)*. 14-16 March. Kuala Lumpur, Malaysia: 127-132.

10. Rahim, E. A., Sharif, S., Ahmad, Z. A., Mohruni, A. S. and Syed, I. A. (2005). Machinability Investigation when Drilling Titanium Alloys. *The 3rd International Conference on Leading Edge Manufacturing in 21st Century (LEM21)*. 19-22 October. Nagoya, Japan: 553-557.

11. Sharif, S. and Mohruni, A. S. (2005). Performance Evaluation of TiCN Coated Carbide Tools when End Milling of Titanium Alloy Ti-6Al4V. *Proceedings of the 8th International Conference on Quality in Research, (QIR)*. 9-10 August. ISSN : 1411-1284. Jakarta, Indonesia: ME15-MPSDO-01, 1–5

12. Sharif, S., Mohruni, A. S., Noordin, M. Y., Venkatesh, V. C. (2008). Application of Response Surface Methodology for Optimization of Surface Roughness Model in End Milling Titanium Alloy (Ti-6Al-4V). *International Journal of Machining Science and Technology.* (Accepted for Publication).