INFLUENCE OF PREHEATING ON CHATTER AND MACHINABILITY OF TITANIUM ALLOY-TI6A14V

BY

KAMARUDDIN KAMDANI

INTERNATIONAL ISLAMIC UNIVERSITY MALAYSIA

MAY 2005

INFLUENCE OF PREHEATING ON CHATTER AND MACHINABILITY OF TITANIUM ALLOY – Ti6Al4V

BY

KAMARUDDIN KAMDANI

INTERNATIONAL ISLAMIC UNIVERSITY
MALAYSIA

MAY 2005

INFLUENCE OF PREHEATING ON CHATTER AND MACHINABILITY OF TITANIUM ALLOY – Ti6Al4V

BY

KAMARUDDIN KAMDANI

A DISSERTATION SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN MANUFACTURING ENGINEERING

KULLIYYAH OF ENGINEERING
INTERNATIONAL ISLAMIC UNIVERSITY
MALAYSIA

MAY 2005

ABSTRACT

Numerous studies on machinability of titanium and its alloys have been conducted in the past few decades with the main objective of reducing cost of machining especially of aerospace alloys. Though classified as "difficult-to-cut" materials, titanium and its alloys are attractive materials due to their unique high strength-weight ratio, which is maintained up to elevated temperatures and their exceptional corrosion resistance. In this work, an experimental investigation of the influence of workpiece preheating using induction heating has been conducted for improvements of machinability of titanium alloy Ti-6Al-4V ASTM B348. The inserts used were uncoated cemented carbide filled into a 16 mm diameter end mill tool. The cutting speeds used in these experiments were 40, 80, 120 and 160 m/min; the depths of cut were 1 and 1.5 mm and the feed rates were 0.1 and 0.15 mm/rev. Thermo-couples were used in measuring the surface temperature of work material during machining. The experiments of end milling operation conducted on Vertical Machining Center (VMC) were designed to look into the effect of preheating on chip serration and chatter, cutting force and torque, tool wear and surface finish. A comparison of the above criteria for room temperature and preheated machining was made. The results show that preheating machining improves the machinability of titanium alloy. Increased plasticity of the work material during preheating reduces the frictional forces on the tool face and the fluctuation of cutting force and also contributes to improved damping capacity of the system. As a result preheated machining results in reduction in vibration amplitudes at resonance frequencies up to 67%. An increase in cutting force and torque mean value leads to the formation of relatively thicker chips, which in turn leads to an increase in chip-tool contact length. The hottest spot on the tool is thus shifted away from the cutting edge leading to a more favourable temperature distribution in the tool. More stable cutting, longer chip-tool contact length and favourable temperature distribution in the tool helps in reducing the dynamic stresses acting on the tool. This in turn reduces the enhances of micro and macro chipping of the tool. This leads to uniform and much lower tool wear up to three times reduction in flank wear has been achieved. Lower tools wear, helps in maintaining a sharp cutting edge at the nose section and the flank areas of the tool resulting in smoother surface roughness values during preheated machining.

ملخص البحث

في السنوات الماضية تمت كثير من الدراسات على قابلية التيتانيوم وسبائكه للتشغيل بهدف أساسى هو تخفيض تكلفة التشغيل لسبائك التيتانيوم المستخدمة في صناعة الفضاء. بالرغم من تصنيفها كمواد صعبة القطع , الا أن التيتانيوم وسبائكه كانت مواد جذابة لما لها من نسبة صلابة \ وزن عالية , وهى ميزة مستمرة حتي في درجات الحرارة العالية, وأيضاَ مقاومتها المتميزة للصدأ. في هذا البحث تم اختبار تجريبي على تأثير التسخين المبدئي علي الشغلة . تم التسخين باستخدام مسخَن حثَي لتحسين قابلية التيتانيوم Ti-6A1-4V ASTM B348 للتشغيل . أداة القطع المستخدمة كانت من الكاربايد السمنتي غير المطلى مركبة علي قاطع تفريز حدَي قطره 16 ملم . سرعات القطع المستخدمة في هذه التجارب تراوحت بين 40, 80, 120 و160 متر\الدقيقة . عمق القطع كان 0.1 و 0.15 ملم\الدورة. بينما كان مقدار التغزية 0.1 و 0.15 ملم\الدورة. تم استخدام مذدوجات حرارية لقياس درجة حرارة سطح الشغلة . التجارب على التفريز الحدَي تمت باستخدام مركز تشغيل رأسي (VMC) تم تصميمه ليمكن من النظر لأثر التسخين المبدئي على تدرَج الرائش و الأهتزاز, قوة القطع والعزم, تأكل القاطع ونعومة السطح. تمت مقارنة المعطيات السابقة في حالتي درجة حرارة الغرفة العادية و التسخين المبدئي. دلت النتائج علي أن التسخين المبدئي يحسن قابلية سبائك التيتانيوم على التشغيل. كما انه يزيد من لدونة المادة المشغولة مما يؤدى لنقص قوى الاحتكاك فى وجه اداة القطع والتذبذب فى قوة القطع كما يساهم ايضاَ فى تعزيز سعة الخمود للمنظومة. ونتيجة للتسخين المبدئي فقد انخفضت سعة الاهتزازات عند الرنين بحوالي 67%. الزيادة فى قوة القطع ومتوسط العزم ادتا لتكون رائش سميك نسبياَ, مما يؤدي بدوره لزيادة طول الاتصال بين الرائش واداة القطع. نتيجة للتسخين المبدئي تمت ازاحة اسخن نقطة باداة القطع بعيداَ عن حافة القطع مما نتج عنه توزيع جيد للحرارة فى اداة القطع. عملية قطع اكثر استقراراَ, اتصال بين الرائش والقاكع اطول, وتوزيع درجة الحرارة

بطريقة افضل على سطح اداة القطع ساعد فى تقليل الاجهادات الديناميكية المؤثرة على اداة القطع.هذا ادى بدوره لقلة محفزات تهتك اداة القطع علي المستويين الدقيق والكبير. هذا ادي لخفض وانتظام بري اداة القطع ونقص بري اداة القطع الجانبي بمعدل ثلاث مرات. قلة بري اداة القطع تساعد فى الحصول على حافة قطع حادة فى مقطع الانف والمقطع الجانبي من اداة القطع مما يؤدى لنعومة افضل للسطح عند استخدام التسخين المبدئي للشغلة.

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Master of Science in Manufacturing Engineering.

A.K.M. Nurul Amin
Supervisor

I certify that I have read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Master of Science in Manufacturing Engineering.

Ahmed A. Ibrahim S. Ashour
Internal Examiner

I certify that I have read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Master of Science in Manufacturing Engineering.

Imtiaz Ahmed Choudhury
External Examiner

This dissertation was submitted to the Department of Manufacturing and Material Engineering and is accepted as partial fulfilment of the requirements for the degree of Master of Science in Manufacturing Engineering.

for Shahjahan Mridha
Head, Department of
Manufacturing and Material
Engineering

This dissertation was submitted to the Kulliyyah of Engineering and is accepted as partial fulfilment of the requirements for the degree of Master of Science in Manufacturing Engineering.

Ahmad Faris Ismail
Dean, Kulliyyah of Engineering

DECLARATION

I hereby declare that this dissertation is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by giving explicit references and a bibliography is appended.

Name: Kamaruddin bin Kamdani

Signature.. Date 10/5/05..

INTERNATIONAL ISLAMIC UNIVERSITY MALAYSIA

DECLARATION OF COPYRIGHT AND AFFIRMATION OF FAIR USE OF UNPUBLISHED RESEARCH

INFLUENCE OF PREHEATING ON CHATTER AND MACHINABILITY OF TITANIUM ALLOY – Ti6Al4V.

No part of this unpublished research may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise without the prior written permission of the copyright holder except as provided below.

1. Any material contained in or derived from this unpublished research may only be used by others in their writing with due acknowledgement.

2. IIUM or its library will have the right to make and transmit copies (print or electronic) for institutional and academic purpose.

3. The IIUM library will have the right to make, store in a retrieval system and supply copies of this unpublished research if requested by other universities and research libraries.

Affirmed by Kamaruddin Kamdani

Signature 10/5/05

Date

I dedicate this work to my beloved parent, wife and children, Maisarah and 'Aqil.

ACKNOWLEDGEMENTS

Alhamdulillah, by the Grace of God, I have been endowed the strength to complete this work. I would like to extend my sincere thanks to Prof. Dr. A.K.M. Nurul Amin his supervisory guidance and support and the Kulliyyah of Engineering, International Islamic University Malaysia for providing me the instruments and facilities to accomplish my work. I would also like to express appreciation to Assoc. Prof. Dr. Imtiaz Ahmed Choudhury and Dr. Ahmed A. Ibrahim S. Ashour for thoroughly examining this work. Last, but certainly not least, my most heartfelt gratitude is reserved and long overdue to my wife and children for their undying patience, trust, and belief in my endeavor.

TABLE OF CONTENTS

CHAPTER 4: LITERATURE RIVIEW: INDUCTION HEATING

CHAPTER 5: EXPERIMENTAL TECHNIQUES

CHAPTER 6: RESULT AND DISCUSSION

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

N	Spindle speed [revolutions per minute] or [rpm]
f	feed rate [tooth/mm]
t_c	deformed chip thickness [mm]
t_u	undeformed chip thickness [mm]
t	depth of cut [mm]
v	cutting speed [m/min]
V_{chip}	Chip velocity in orthogonal cutting [m/min]
V_c	Cutting speed [m/min]
F_c	Tool cutting force (per unit width) in orthogonal cutting [N/mm]
F_t	Tool thrust force (per unit width) in orthogonal cutting [N/mm]
F_R	Resultant tool force (per unit width) in orthogonal cutting [N/mm]
F_s	Shear force on the shear plane in orthogonal cutting [N/mm]
F_{ns}	Normal force applying to the shear plane in orthogonal cutting [N/mm]
F_f	Friction force on the tool rake face in orthogonal cutting [N/mm]
F_n	Normal force on the tool rake face in orthogonal cutting [N/mm]
α	Rake angle [deg]
ϕ	Tool rotation angle[deg]
β	Friction angle in orthogonal cutting [deg]
τ_s	Shear stress on the shear plane [Mpa]
Ks	Shear stress [Mpa]
As	Area of cross section of the shear plane [mm^2]
Δh	Average amplitude of the serrated teeth (distance from top of saw teeth peak to bottom of serration)

h	Average maximum thickness of the chip (distance from the top saw tooth to flat area of the chip)
VMC	Vertical machining center
DAQ	Data acquisition card
DOC	Depth of cut [mm]
FFT	Fast Fourier Transform
VB	Flank wear
KT	Crater wear
VN	Notch at the depth of cut
cph	Closed-packed hexagonal
bcc	Body-centered cubic
PCD	Polycrystalline diamond
HSS	High speed steels
Ra	Average surface roughness

CHAPTER 1

INTRODUCTION

1.1 Introduction

For the past several years, titanium and its alloys have been experiencing extensive development stimulated by a series of their unique properties, which has placed titanium and its alloy in a prominent position among useful structural materials. The materials are used extensively in aerospace industry because of their excellent combination of high specific strength, which is maintained up to elevated temperature, their fracture resistant characteristics, and their exceptional resistance to corrosion (Ezugwu and Wang 1997; Boyer 1995). These materials are generally classified as the most difficult and expensive to machine materials. They are mainly used for making airframes and engine components in the aerospace industries. It has also been reported that the application of titanium alloys trends from military to commercial and from aerospace to industries, such as petroleum refining, chemical processing, surgical implantation, pulp and paper, pollution control, nuclear waste storage, food processing, automotive, sport good, electrochemical (including cathodic protection and extractive metallurgy) and marine applications (Ezugwu and Wang 1997). Ti-6Al-4V compromises about 45% to 60% among the titanium products in practical use (Yang and Liu 1999). It has become an established engineering material available in a range of alloys and in all the wrought forms such as billet, bar, plate, sheet, strip, hollows, extrusions, wire, etc. Despite the increased usage and production of titanium and its alloys, they are expensive when compared to many other metals because of the complexity of the extraction process, difficulty of melting and problems during fabrication and machining.

In the past decades, near net-shape methods such as die castings, isothermal forging and powder metallurgy have been introduced to reduce the cost of titanium components. However, most titanium parts are still manufactured by conventional methods at some stages during manufacture cycle. Machining is an important manufacturing process because it is almost always involved if precision is required; and the most cost effective process for small volume production. Improved fabrication methods could result in reduced scrap losses and fabricating time, thus reducing cost and increasing productivity. However the poor machinability of titanium and its alloys has led many large organizations (for example Rolls Royce, General Electric and DARPA) to invest considerable sums in exploring and developing new techniques to minimize machining costs while maintaining the quality requirements (Machado and Wallbank 1990).

Many researchers have actively carried out work with the main objectives to improve the machinability of titanium alloys and to provide end users with optimized cutting conditions (Machado and Wallbank 1990; Ezugwu and Wang 1997). Progress of the titanium alloy machining is hindered basically due to its high temperature strength, very low thermal conductivity, relatively low modulus of elasticity and high chemical reactivity. Although the cutting forces are low when cutting titanium alloys, tool life is usually short and permissible rates of metal removal are low (Trent 1991). Most of machining studies on titanium alloys are focused on turning operation, which involves continuous cutting. Unfortunately, the majority the data is not applicable to the milling operation where interrupted cutting takes place. Despite the fact that face milling is the second most important material removal process in aerospace industry, the research on face milling of titanium alloys has not been widely reported.

Ezugwu and Wang (1997) carried out a review study of machining of titanium and its alloys and they concluded that although many development in cutting tool material had taken place in the past decades, none of the cutting tool materials has been successful in improving the machinability of titanium alloys. Almost all tool materials developed so far, including coated carbides, ceramics, cubic boron nitride and diamond have shown great improvement in the machining of cast irons, steels and high temperature resistant alloys such as nickel based alloys. However when machining titanium alloys, these tool materials did not show promising results due to their reactivity with titanium alloys especially at high cutting speeds (Wang and Ezugwu 1997). It causes rapid wear at the flank and rake faces. The straight grade (WC/Co) cemented carbides are regarded as the most suitable tool material available for the machining of titanium alloys and have proved their superiority in almost all machining process involving titanium alloys (Ezugwu and Wang 1997).

When milling titanium alloys with carbide tools, chipping and flaking of the cutting edge are found to be the main cause of tool failure. These types of failure modes occur as the result of combination of various factors such as high cutting temperature, small chip-tool contact length and dynamic nature of the normal stresses acting on the tool during machining. For high cutting temperatures are attributed to high resistance of Titanium alloys to deform attain at elevated temperature and low thermal conductivity. On the other hand, a high dynamic normal stress is due to the formation of chip with serrated/saw teeth that causes high fluctuations of cutting force and unusually small chip-tool contact area on the rake face (Amin et al. 2004).

Chatter is undesirable because of its adverse effect especially on surface finish, machining accuracy and tool life. Talantov et al. (1980) and Amin (1983) established that chatter arises in the system when the frequency of the chip tooth serration coincides with any one of the natural frequencies of the system, e.g. the spindle and tool holder. Alternating phases of compression and adiabatic shear along a narrow rotating shear zone formed 'cyclic' or serrated teeth (Amin 1983). Chip tooth serration affect high dynamic loading on the tool causing catastrophic failure of the tool and high surface roughness during machining. Nakayama (1974) attributed the serrated tooth chip formation to the lack of ductility of the workpiece material causing heat concentrations and vibrations. He (Nakayama 1974) and Konig et al. (1993) in order to explain saw-toothed chip formation stated that the chip formation mechanism was based on exceeding the critical shear stress under compressive stress and shear loads.

In order to get better machining, many method of chatter control scheme had been implemented (Delio 1992). Amin and Talantov (1986) tried preheating of the work material to control chatter during turning of titanium alloy BT6 (USSR) but the furnace heating method employed in their work is not suitable for practical applications. Amin and Abdelgadir (2003) used induction heating method to improve machinability of medium carbon steel during end milling. The present work aims at investigating the influence of induction heating of the workpiece on chatter, surface roughness, tool wear and optimum temperature.

1.2 Aims and Objective

The aim of this project is to study the effect of preheating on end milling process of titanium alloy Ti-6Al-4V ASTM B348 using uncoated cemented carbide inserts. The specific objectives of this work are:

a) To determine suitable preheating temperature for different cutting condition.

b) To acquire, analyze and compare the vibration signals during machining at room temperature and under preheating condition.

c) To compare the cutting forces and torques developed during room temperature and preheated cutting.

d) To investigate the effect of preheating and cutting parameters on surface finish.

e) To conduct tool wear analysis to determine the intensities of tool wear during machining with and without preheating.

f) To analyze the worn tool using SEM (Scanning Electron Microscope).

g) To perform chip analysis at various conditions under an optical microscope.

1.3 Thesis Organization

This thesis has been organized into six chapters. The contents of each paper are summarized below.

Chapter one presents an introduction to the research works that have been conducted to improve machinability of titanium and its alloys.

In Chapter two, overview of the metal cutting process are present.

In Chapter three contain overview of milling process machining and machinability of titanium alloys are presented.

In Chapter four contain overview of induction heating principle and temperature distribution in the workpiece.

In Chapter five, experimental setup and equipment used in the experiment are described.

Chapter six presents the results and discussion. A thorough analysis is performed in this section.

In Chapter seven, conclusions and recommendations are presented.

CHAPTER 2

LITERATURE REVIEW: METAL CUTTING PROCESS

2.1 Introduction

Metal cutting is the explained as the removal of a thin layer of the work material by the action of a wedge-shaped tool, which has a straight cutting edge, and is constrained to move relative to the workpiece. The shavings removed during the metal cutting process are called chips. In machining process, the whole volume of metal removed is plastically deformed. The surface along which the chip flows is known as the rake face and the surface facing the new machined workpiece surface is known as flank surface. When the cutting edge of the tool is arranged to be perpendicular to the direction of relative work-tool motion, the cutting process is called an orthogonal cutting (Fig. 2.1 (a)). Since the orthogonal cutting is a two-dimensional process, it is easier to study the problem in theoretical or experimental work. The general case of cutting process, which has the work-tool arrangement other than the orthogonal cutting, is called an oblique cutting (Fig. 2.1 (b)). An oblique cutting is not easy to analyze, as it is a three-dimensional problem.

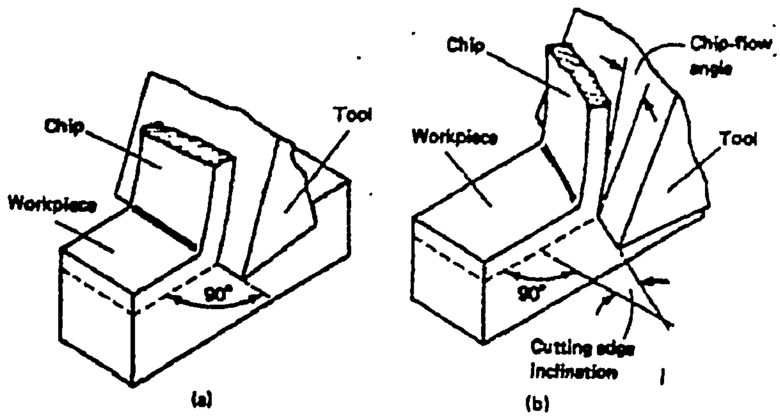

Fig. 2.1 Orthogonal and Oblique cutting. (a) Orthogonal cutting; (b) Oblique cutting (Boothroyd 1966).

The fundamental mechanics of metal cutting process has been well established. However, it is essential for every researcher in the field of metal cutting to understand the basic activities and changes that occur at the tool-work interface. Among major factors that should be considered in the metal cutting process are higher cutting speed, feed rate and thicker depth of cut. All these will lead to an ultimate goal of higher production output and lower production cost. Many new alloys are developed in order to meet the increasingly severe corrosive atmosphere, and condition of stress and temperature imposed by the requirements of modern day industries. These alloys are tougher and harder than the present generation materials and they are termed as "hard" or "difficult to machine" materials. However, materials scientists, metallurgists and engineers have to respond by developing cutting tool materials that can cut new materials at higher cutting speeds and feed rates, and greater depth of cuts. As a result, there will always be the need for the improvement in cutting tool materials, cutting fluids, workpiece materials and testing method. This will lead to a continual research to extend the state of understanding of the mechanics of metal cutting process.

2.2 Metal Cutting Process

The objective of metal cutting is to maximize metal removal rates while maintaining a desirable surface finish quality, and dimensional accuracy of the machined components. However, machining at high speeds will increase chip disposal problems, tool wear, forces and power consumption.

In the machining process, the tool is forced to move through the workpiece so that a chip of material is removed from the surface. The contact conditions between the tool and the workpiece are very complicated. According to Shaw (1984):

a. The heat produced in the tool-chip interface comes primarily from heat generated by the mechanical deformation of the chip. Besides, heat also comes from friction between the chip and the tool rake face, and a small amount from the rubbing action on the tool tip.

b. In cutting steel, a major amount of the heat is removed by the chip and some is absorbed by the workpiece and the rest is conducted through the tool.

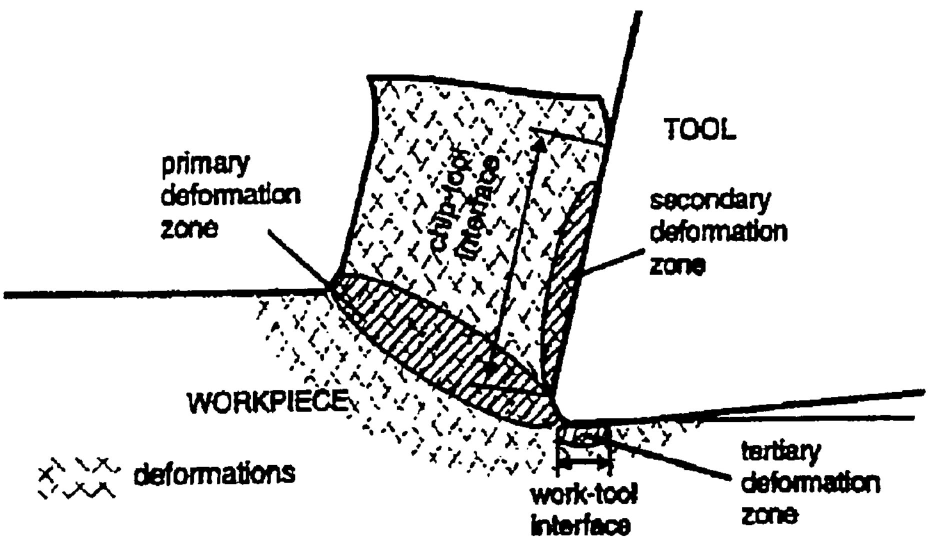

Fig 2.2 Deformation zones in orthogonal cutting (Ozel et al.1998).

As illustrated in Figure 2.2, there are local deformation zones where the severe deformations and high strain rates take place:

a. From the tip of the tool to the intersection of the chip and free surface of uncut workpiece, there is a shear zone where deformation takes place. This region is known as the primary deformation or shear zone. The shear stress is constant on the tool rake face until a certain point at which the chip starts to slide on the tool rake face.

b. The secondary deformation or shear zone is at the chip-tool interface in which plastic deformation due to both upsetting of advancing tool to the chip being formed and frictional stress occurs.

Many researchers have reported their findings to explain the complex behavior at the tool-workpiece interface. The best way to explain the behavior of the chip formation process is by limiting the scope of study to two-dimensional orthogonal cutting. The first complete analysis, resulting in a so-called shear angle solution was published by Ernst and Merchant (1941). In their analysis the chip is assumed to behave as a rigid body, which is held in equilibrium by the action of the forces, transmitted across the chip-tool interface and shear plane. It is assumed that the resultant tool force is transmitted across the chip-tool interface only and there will be no force acting on the tool edge or flank. The major drawback of those models was the infinite acceleration of the chip flow on the shear plane. Some improvements to Merchant's model were made by Lee and Schaffer (1951), in which the workpiece material was assumed as a rigid body plastic and slip line field analysis was used to model the shear zone. Later, cutting models that included friction, material behavior at high strains, strain-rates and temperature were presented (Zorev 1963).

2.2.1 Discontinuous Chip

This type of chip is formed when cutting brittle materials or ductile materials at very low cutting speeds and high feeds. During the deformation of a chip, the material undergoes severe strain. Fracture occurs in the primary deformation zone when the chip is only partly formed. This fracture has caused the chip to segment. When this type of segmented chip is associated with brittle material, the surface finish is fair, the tool life is acceptable and the power consumption is relatively low. However, when the discontinuous chip is formed during the cutting ductile materials, it may give poor surface finished, excessive tool wear and short tool life (Boothroyd 1975).

2.2.2 Continuous chip without built-up-edge

The formation of continuous chip without built-up-edge is a result of machining ductile materials under a steady state condition at high cutting speeds. This type of chip is formed by continuous deformation of metal without fracture at the tool cutting edge, followed by steady flow of the chip on the tool rake face. It is unlikely for the materials to adhere to the tool, since there is minimum friction taking place at the interfaces during machining. The chip may experience some cracking, but it is not serious enough to cause any fracture. High cutting speeds, polished tool faces, and an efficient lubricating system are among factors for the formation of this type of chip. Normally, the continuous chip formation produces a very smooth machined surface.

2.2.3 Continuous chip with built-up-edge

This type of chip is formed in the similar way as the previous one, but in this case the chip flow encounters an excessive frictional resistance at the cutting edge and at the tool rake face. This type of chip is normally formed when machining at relatively low cutting speeds. The friction between the chip and the tool is so large that the chip material welds itself to the tool face. As successive chips move along the face, some of the pre-welded metal breaks off and moves away with the following chip, while new fragmentation and welding take place due to increased friction. The friction leads to the building up of layer upon layer of chip material on the tool face.

2.3 Forces in Metal Cutting

For the past decade metal cutting researchers have investigated the forces in metal cutting to develop a better understanding of cutting phenomena. Knowledge of the cutting forces involved in machining is required by the machine tool manufacturers to estimate the power requirements and to design sufficiently rigid and vibration-free machines. Dynamometers had been developed for measuring tool forces at the cutting tool with considerable precision and accuracy.

The cutting forces, which act in particular directions relative to the tool and workpiece in a single point turning tool, are resolved into three components: feed force (F_t), which is acting on the tool in the direction parallel to the direction of feed, radial force (F_s), which is acting to push the tool away from the work, and cutting force (F_c), which is acting on the rake face of the tool in the direction of the cutting velocities. These three components are shown in Figure 2.3 and they can be measured by a well-designed force-tool dynamometer. In the case of orthogonal cutting, only cutting force, F_c, and feed force, F_t, components are usually considered. These forces are an important aspect in machining due to their relation with chip formation during the cutting process. In a cutting process, there are three important zones to be considered.

Zone one is the shear plane area where the chip is separated from the workpiece by plastic flow. It is assumed that the shearing takes place on this plane to form the chip.

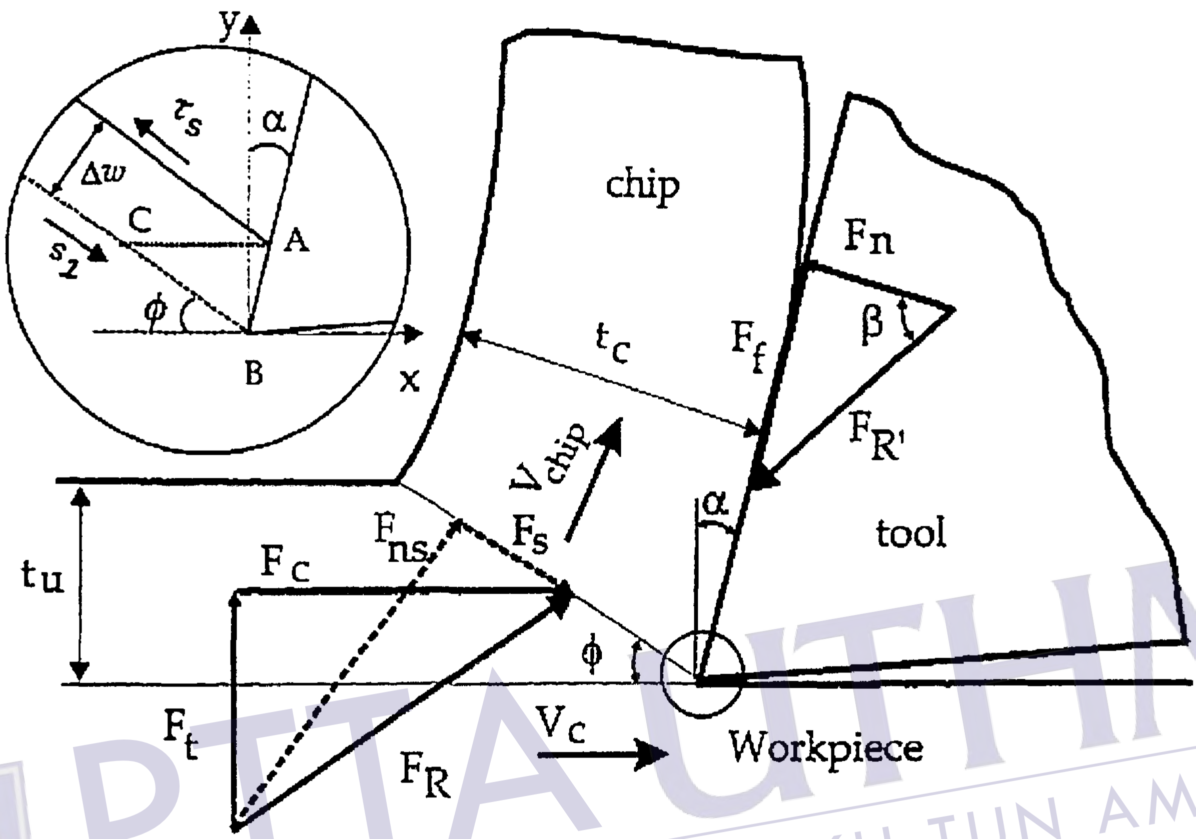

Fig. 2.3 Shear plane model and force diagram in orthogonal cutting (Boothroyd 1966).

The force acting on the shear plane, F_s, is calculated from the measured forces and the shear plane angle:

$$F_s = F_c \cos\phi - F_f \sin\phi \tag{2.1}$$

Therefore, the shear stress required for the chip formation is

$$k_s = F_s / A_s \tag{2.2}$$

where A_s is the area of shear plane. In the orthogonal cutting, this area can be defined as

$$A_s = \frac{t_u \omega}{\sin \phi} \tag{2.3}$$

Zone two is the area of contact between the moving chip and the tool face. In this region there is a considerable amount of friction and heat generation taking place. Owing to the extreme conditions of shear strain, strain rate, temperature and temperature gradient in this region, an area of seizure is formed (Boothroyd 1975). Zone three is the machined surface whose quality is determined by the conditions at the other two previous zones. It has been established by the past researchers that the cutting forces are directly proportional to the contact length between the chip and tool face (Boothroyd 1975). This means that the materials producing discontinuous chips will generate lower cutting forces. When the cutting speed increases, the shear plane angle will also increase. The tool forces will increase as the tool is worn out. This is due to an increase in the area of contact.

2.4 Tool Materials

The use of high carbon steel could be considered the starting point of modern cutting technology. It was then followed by the use of high speed steel (HSS) at the beginning of century. However hardness values of these tool materials are not sufficient to withstand the hardness and toughness of the newly developed work materials. The invention of cemented carbide tools has enabled the cutting of steels and other materials at higher speed. Ceramic, Cubic Boron Nitride and diamond tools were manufactured in the later period to cope with the demand for much tougher and harder wor p ece mater a s. These robust tool materials were developed in a attempt to increase the productivity, reliability and better accuracy in the metal industry cutting. A cutting tool material should be able to withstand the intense conditions, which are imposed on them during cutting operations. The efficiency of machine tools and tool wear and failure are among the major factors limiting the increase of the metal cutting productivity and eventually low production costs.

2.4.1 Tool material Requirements

The pressures of technological change and economic competition have led to the need for new developments on tool materials. Tools materials must be strong and have high wear resistance for better efficiency in machining. The physical and metallurgical requirement of good cutting tools material were given by Trent (1991), and Mill and Redford (1983) as the following:

a. High yield strength at cutting temperatures
b. High fracture toughness
c. High wear resistance
d. High fatigue resistance
e. High thermal capacity and conductivity
f. Low solubility in the workpiece material
g. High thermal shock resistance
h. Good oxidation resistance

The best tool material may not be one, which gives longest life, or with cheapest price, rather it is the one that performs a given job to the desired accuracy and efficiency at a reasonable cost. According to Shaw (1997), the most satisfactory tool will usually be the one corresponding to the minimum total cost of performing a required operation to the specified accuracy of the workpiece.

2.4.2 Major Class of Cutting Tool Materials

The major types of cutting tool materials, listed in order of hot hardness and wear resistance are:

a. Single-crystal diamond

b. Polycrystalline diamond and Cubic Boron Nitride

c. Ceramics

d. Cemented carbides

e. High speed steels (HSS)

f. Carbon steels

As mentioned above, we can see that cutting tool materials are many and varied. It is not the intention of this study to look into all the types of cutting tool materials but rather concentrate on the performance of carbide tools. Detail discussion of this tool is outlined in the following section.

2.4.3 Cemented Carbide Tools

Cemented carbide tools are the most utilized tool materials in today industries and have dominated the metal removal market since their first introduction. The production of cemented carbides involves the binding of carbide particles with binder metals such as cobalt. They are manufactured by using the powder metallurgy technologies involving production of the hard carbide particles, compacting and sintering at high temperatures. Cemented carbides are manufactured in a variety of compositions with varying properties to meet a wide range of applications. The quality of a cemented carbide is to a great extend determined by the proportion of WC to Co. The percentage of WC in cemented carbide ranges between 56% and 93%, with Cobalt (Co) taking up the balance. Coarser grain WC is better for shock resistance and finer grain WC will increase the hardness and wear resistance. The grain size of WC goes from 0.5 to 5 μm. A harder product is produced with more WC, whilst more Co results in a tougher product. WC-Co carbide cutting tools, however, are not suitable for machining steel due to the greater tendency for the formation of a crater on the rake face of the tool (Thomas and Mick 1983, Shaw 1997). This due to the metal and carbon atoms diffusing into the steel which are then carried away by the chip. Consequently, rapid wear in the chip/tool contact area takes place resulting in early tool failure.

2.4.4 Classification of Cemented Carbide Tools

There are a number of systems of classifying cemented carbides tools. The two most popular classification systems used by manufacturers and users are:

a. The International Organization for Standardization (ISO) System

In 1964, the ISO issued Recommendation R513, which is widely used in Europe and appears to be gaining acceptance in the United States. In this system, all the grades are divided into three groups:

P-grade (color code: blue): Also known as the steel cutting grade. Highly alloyed tungsten carbide grades for machining ferrous metals such as steel.

M-grade (color code: yellow): This is an intermediate grade which compromises of alloyed tungsten carbide grades with less TiC than P-grades. They are used for a wide range of applications in both P-grade and K-grade categories. Materials machined under this grade include ductile irons, hard steels and high temperature alloys.

K-grade (color code: red): Tungsten carbides belonging to this grade are used for cutting cast iron, non-ferrous metals and non-metallic materials. The K-grade tools normally composed of WC-Co. Also known as straight tungsten carbide and cast iron cutting grade.

b. The United States (US) Designation

This is an application-oriented system in the U.S. to assist in the selection of proper grades of cemented carbides. This is the simplest system based on relative performance. The system employs eight numbers, namely, C-1 to C-8. The grades C-1 to C-4 are for machining cast iron, non-metallic materials and materials that produce short chips such as the non-ferrous alloy, while the grades C-5 to C-8 are steel cutting grades containing TiC, TaC and NbC. In going from C-1 (roughing cuts) to C-4 (finishing cuts), and C-5 (roughing cuts) to C-8 (finishing cuts), the cobalt content decreases and hence the shock resistance decreases.

2.5 Tool Wear Mechanism

Wear is basically removal of material from the body of the tool and is a result of process parameters existing at the tool-workpiece interface due to relative motion and cutting conditions. There are various mechanisms and modes of tool wear that have been observed in metal cutting. The investigations of machining wear due to cutting speed and temperature shows that tool wear is due to a complex combination of wear modes and highly sensitive to cutting conditions (Fig 2.4).

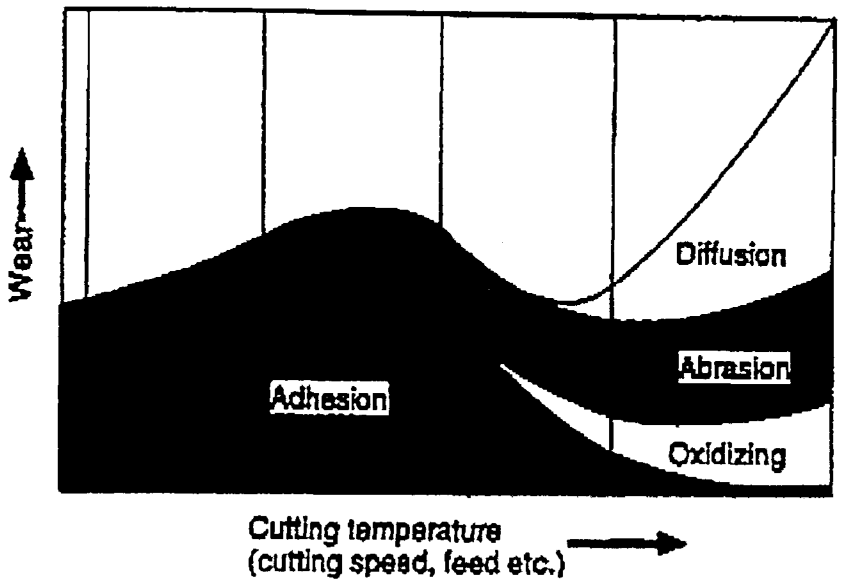

Fig. 2.4 Schematic diagram of the tool wear mechanisms appearing at different cutting temperatures corresponding to cutting speed and feed (Konig 1984).

2.5.1 Sliding Tool Wear Mechanisms

Sliding wear mechanisms include abrasive wear, adhesive wear and delamination wear. Abrasive wear is caused by the contact of a tool body with a particle, where the particle slides over the body and the movement causes material loss. Adhesive wear occurs between two surfaces rubbing against each other as a result of formation and breakage of the interfacial bonds. Delamination wear is another mechanism of wear when chips are sliding against tool surfaces at low speeds, which do not generate very high contact temperature. In this process large tool particles are removed in the form of layers by the process of plastic deformation of the surface layer (Suh 1973).

2.5.2 Non-Sliding Tool Wear Mechanisms

Non-sliding wear mechanisms include solution wear, diffusion wear, electrochemical wear and oxidation wear and become dominant with the chemical instability where cutting temperatures are very high, up to 1600°C as in high speed machining (Schulz and Hock 1995). Solution and diffusion wear is a result of a tendency in workpiece and tool material to dissolve in each other to form a solution. The rate of the solution is dependent on cutting temperature at the interface (Suh 1986). The wear due to diffusion is more dependent on the chemical properties of the material rather than its mechanical strength or hardness. Electrochemical wear is caused by a thermoelectric electromotive force generated at the work-tool junction during the cutting process. The e.m.f. causes electric currents to flow and results in the passage of ions from the tool to the workpiece (Moore 1975). Oxidation wear is a result of the chemical bonding of atoms of tool material with oxygen. Oxidation in metal cutting occurs in the area where the chips are generated at elevated temperatures, usually above 700 °C (Konig 1979).

2.6 Tool Life Criteria

Tool life is defined as the cutting time before the tool fails. The tool life is often measured in seconds or minutes and it is based on several criteria such as (Venkatesh and Chandrasekaran 1987):

a. Time taken for catastrophic failure.

b. Time between regrinds of a tool.

c. Time taken for specified amount of wear is observed on the tool.

The International Standards Organization (ISO) has suggested a procedure for tool life testing. The ISO recommended the following criteria for rejecting sintered-carbide tools:

a. Flank wear, $VB_{ave} = 0.3$ mm, or

b. $VB_{max} = 0.6$ mm if the flank is irregularly worn, or

c. Crater wear, $KT = 0.06 + 0.3f$, where f is the feed.

From previous machining test carried out by several researchers, the wear criteria set by ISO is too small. However, in this current machining test, the ISO standard was still used as a guideline for making decision on determining the tools wear. Thus, the criteria listed below were used for determining the effective tool life of a sintered-carbide tool (Jawaid 1982):

a. When the average flank wear, VB = 0.4 mm, or

b. When the maximum flank wear, $VB_{max} = 0.7$ if the flank is irregularly worn, or

c. When the notch at the depth of cut, VN = 1.00 mm, or

d. When the crater wear depth reached 0.14 mm.

In the past, many researchers have used different values of criteria to determine the tool life of cutting tools when machining titanium alloys. These values were decided based on various factors such as range of cutting speeds and feed rates tested, type of operations, type of inserts used and the overall costs of the experiment. Ezugwu and Machado (1988) suggested in the face milling of titanium alloys (Ti-6Al-4V) that the tools would be rejected according to the following condition:

a. When the maximum flank on any of the inserts was in excess of 0.76 mm and/or

b. When severe flaking occurred or

c. Premature failure of any of the inserts occurred.

CHAPTER 3

LITERATURE REVIEW: MACHINABILITY OF TITANIUM AND ITS ALLOY

3.1 Introduction

The consumptions of titanium and its alloys in the non-aeronautics sector are approximately 20 to 25% of world consumption and are growing by 9% each year. Some of the major factors that contribute to the high demand of these alloys are excellent combination of high specific strength (strength to weight ratio) which maintained at elevated temperature, fracture resistance characteristics, exceptional corrosion resistance, immune to almost every medium, longer service life and compatibility with composite structures (Ezugwu and Wang 1997, Donachie 2000). Titanium is nonmagnetic, has good heat transfer properties and its coefficient of thermal expansion is somewhat lower than steel and less than half of aluminum. Although the melting point of titanium is in excess of 1660 °C, it performs best up to 538 °C (Donachie 2000). Titanium alloys can be cast, rolled, forged, welded and formed in a variety of shapes and forms (Chen 1982). Despite the increased usage and production of titanium and its alloys, they are relatively more expensive than other materials, such as iron, copper and aluminum. Hence the advantages of using titanium must be balanced against its added cost.

3.2 Metallurgy of Titanium Alloys

Pure titanium undergoes an allotropic transformation at 882 °C (1797 °F), changing from the low temperature close-packed hexagonal (cph) α-phase to the high temperature body-centered cubic (bcc) β-phase. Alloying elements in titanium alloys tend to stabilize either the α-phase or the transformed β-phase that changes the transformation temperature, and the shape and extent of the α - β field (Flower 1995). Elements that raise the transformation temperature are α-stabilizers, these include (Al), oxygen (O), nitrogen (N) and carbon (C), of which Al is the most effective α - strengthening element at ambient and elevated temperature up to 550 °C. One of the important additional advantages of Al is its low density. O, N, and C are thought to be impurities in commercial alloys. However, O is used as a strengthening agent to provide several grades of commercially pure titanium that offers various combinations of the strength and workability (Flower 1995). Although the additions of Sn or Zr strengthen α-phase, these elements have little influence on the transformation temperature because they exhibit extensive solubility in α- and β-titanium and are known as 'Neutral elements'.

Elements that decrease the transformation temperature are β-stabilizers, these being two types, β-isomorphous and β-eutectoid (Flower 1995). The most important β-isomorphous alloying additions are molybdenum (Mo), vanadium (V) and niobium (Nb). These elements are mutually soluble with β-titanium, increasing addition of the solute element that progressively depress the β to α transformation up to ambient temperature. β-eutectoid elements have restricted solubility in β-titanium and form intermetallic compounds by eutectoid decomposition of the β-phase. The two most important examples of such elements used in commercial alloys are copper (Cu) and silicon (Si).

BIBLIOGRAPHY

Abdelgadir, M. 2001. The effect of preheating of work material on chatter of VMC and machinability of work materials. Masters Dissertation. International Islamic University Malaysia.

Amin, A.K.M.N.. 1983. Investigation of the mechanism of chatter formation during the metal cutting process. *Mech. Engg. Res. Bulletin* 6. (1): 11-18.

Amin, A.K.M.N., Abdelgadir, M. and Kamaruddin, K. 2004. Effect of workpiece preheating on machinability of titanium alloy. *Proc. of 3rd Int. Conf. AMT. Malaysia*: 145-152.

Amin, A.K.M.N. and Talantov, N.V. 1986. Influence of the instability of chip formation and preheating of work on tool life in machining high temperature resistant steel and titanium alloys. *Mechanical Engineering Research Bulletin* 9(1): 52-62.

Amin, A.K.M.N. and Abdelgadir, M. 2003. The effect of preheating of work material on chatter during end milling of medium carbon steel on a VMC. *Transactions of the ASME* 125: 674-680.

Boothroyd, G. 1975. *Fundamentals of metal machining and machine tools*. McGraw-Hill.

Boothroyd, G. 1966. *The Fundamentals of Metal Machining*. Edward Amold, London.

Boyer, R.R. 1995. Titanium for aerospace: Rationale and applications. *Advance Performance Materials*: 349-368.

Brookes, C.A. James, R.D. and Nabhani, F. 1999. Turning aerospace titanium alloys. *Industrial Diamond Review* 3:107-139.

Che-Haron, C.H., Jawaid, A. and Sharif, S. 1998. Evaluation of wear mechanisms of carbide tools in machining of titanium alloys. *Proc. of 4th Int. Conf. AMPT. Malaysia*: 811-818.

Chen, C.C.1982. Recent advancements in titanium near net-shape technology. *J. of Metals* 34(11): 30-35.

Cook, N.H. 1953. Chip formation in machining titanium, *Proc. Of the Sym. On Mach. and Grinding of Titanium*. Watertown Arsenal, Massachusetts: 1-7.

Dearnley, P.A. and Gearson, A.N. 1986. Evaluation of principal wear mechanism of cemented carbides and ceramics used for machining titanium alloy IMI 318. *Materials Science and Technology* 2: 47-58.

Delio. 1992. Method of controlling chatter in a machine tool. *United States Patent No. 517358.*

Donachie Jr., M.J. 2000. *Titanium – A Technical Guide 2nd Edition.* ASM International.

Donachie Jr., M.J., Ed. 1983. *Titanium and Titanium Alloys: Source Book.* American Society of Metals.

Ernst, H. and Merchant, M.E. 1941. Chip formation, friction and high quality machined surfaces, Surface Treatment of Metals. *American Society of Metals* 29:299.

Ezugwu, E.O. and Machado, A.R. 1988. Face milling of aerospace materials. *Proc. Of the 1st. Int. Conf. On the Behaviour of Materials in Machining*: 3.1-3.11.

Ezugwu, E.O. and Wang, Z.M. 1997. Titanium alloys and their machinability – A Review. *Journal of Materials Processing Technology* 68: 262-274.

Ezugwu, E.O. and Pashby, I.R. 1991. The Milling of Titanium and Nickel Base Superalloys With TiN/Steel Composite End Mills. *2nd International Conf. On The Behaviour of Materials in Machining*: 96-102.

Ezugwu, E.O., Da Silva, R.B., Bonney, J. and Machado, A.R. 2005. Evaluation of the performance of CBN tools when turning Ti-6Al-4V alloy with high pressure coolant supplies. *Int. Journal of Mach. Tools & Manufacture*: 1-6.

Field, M., Zlatin, Noeman, and Jameson, R.T.1965. Titanium Alloys. *Metal Progress*: 85-89.

Flower, H.M. 1995. High Performance Materials in Aerospace, Chapman and Hall, London.

Freeman, R.M. 1974. The Machining of Titanium and Some of Its Alloys. Ph.D. Thesis. University of Birmingham.

Hartung, P.D. and Kramer, B.M. 1982. Tool Wear in Machining Titanium. *Annals of the CIRP* 31: 75-80.

Jawaid, A. 1982. Ph.D. Thesis. Warwick University.

Kahles, J.F., Field, M., Eylon, D., and Froes, F.H. 1985. Machining of Titanium Alloys. *Journal of Metals* 34:30-35.

Kramer, B. 1985. On Tool Materials for High Speed Machining. *Trans of ASME. J. of Engg. For Industry* 107: 99-106.

Komanduri, R. 1982. Some Clarification on The Mechanics of Chip Formation when Machining Titanium Alloys. *Journal of Sc. and Tech. Of Friction, Lubrication and Wear* 76(7): 15-34.

Komanduri, R. and Turkovich, B.F. 1981. New Observations on The Mechanics of Chip Formation when Machining Titanium Alloys. *Journal of Sc. and Tech. Of Friction, Lubrication and Wear* 69(2): 179-188.

Komanduri, R. and Reed Jr, W.R. 1983. Evaluation of Carbide Grades and a New Cutting Geometry for Machining Titanium Alloys. *Wear* 92:113-123.

Konig, W. 1979. Applied Research on the Machinability of Titanium and its Alloys. *AGARD Conf. Proc. Adv. Fabrication Processes.* 256: 1.1-1.10.

Konig, W. 1978. Applied Research on the Machinability of Titanium and its Alloys. *AGARD Conf. Proc. – Adv. Fabrication Processes* 256: 1.1-1.10.

Konig, W. Berktold, A. and Koch, F.K. 1993. Turning versus Grinding – A comparison of surface integrity aspects and attainable accuracies. *Annals of the CIRP* 42: 39.

Lee, E.H and Shaffer, B.W. 1951. The Theory of Plasticity Applied to a Problem of Machining. *Journal of Applied Mechanics* 18: 405-413.

Machado, A.R., and Wallbank, J. 1990. Machining of Titanium and its Alloys – A Review. *Proc. Instn. Mech. Engrs.* 204: 53-60.

Mills, B. and Redford, A.H. 1983. *Machinability of Engineering Materials.* Applied Science Publisher.

Moore, D.F. 1975. *Principles and Applications of Tribology.* Pergamon Press, Great Britain.

Nakayama, K. 1974. The formation of saw-toothed chip in metal cutting. *Proc. Int. Conf. on Prod. Eng.*: 572.

Narutaki, N. and Murakoshi, A. 1983. Study on Machining of Titanium Alloys. *Annals of the CIRP* 32: 65-69.

Ozel, Tugrul; Roriguez, Ciro A.; Lucchi, Marco; Altan, Taylan. 1998. Prediction of Chip Formation and Cutting Forces in flat end milling: Comparison of process simulations with experiments. *Tech. Paper- Society of Manuf. Engineers*: 1-6.

Schulz, H. and Hock, St. 1995. High Speed Milling of Dies and Molds – Cutting Conditions and Technology. *Annals of the CIRP* 44(1): 35-38.

Shaw, M.C. and Vyas, A. 1993. Chip Formation in the Machining of Hardened Steel. *Annals of the CIRP* 42(1): 29-33.

Shaw, M.C. 1984. *Metal Cutting Principles.* Oxford University Press, London.

Shaw, M.C. 1997. *Metal Cutting Principles.* Reprinted London: Oxford University Press.

Shaw, M.C. Dirke, S.O. Smith, P.A. Cook, N.H. Loewen, E.O. and Yang. C.T. 1954. Machining Titanium. *MIT Report*. Massachusetts Institute of Technology. Cambridge. MA.

Siekman, H.J. 1955. How to Machine Titanium. *The Tool Engineer*: 78-82

Smallman, R.E. and Bishop, R.J. 1995. *Metals and Materials*. 1st Edition Butterworth Heinemann, London.

Smart, E.F. and Trent, E.M. 1975. Temperature Distribution in Tools Used for Cutting Iron, Titanium and Nickel. *Int. J. Prod. Res.* 13(3): 265-290.

Suh, N.P. 1973. The Delamination Theory of Wear. *Wear* 25: 111-124.

Suh, N.P. 1986. *Tribophysics*. New Jersey. Prentice Hall inc.

Talantov, N.V. Amin, A.K.M.N. and Chereomushnikov, N.P. 1980. Temperature deformation laws of chatter formation during metal cutting process. *Abstracts of the paper presented at the 5th Soviet National Conference*: 92.

Thomas, J.D. and Mick, C. 1983. *Tool and Manufacturing Engineers Handbook – Vol. 1 Machining 4th Edition*. Society of Manufacturing Engineers.

Trent, E.M. 1991. *Metal Cutting 3rd Edition*. Oxford: Butterworth-Heinemann.

Vaughn, R.L. 1966. Modern Metals Machining Technology. *ASME Journal of Engineering for Industry*: 65-71.

Venkatesh, V.C., and Chandrasekaran, H. 1987. *Experimental Technique in metal cutting*. Prentice Hall of India, New Delhi.

Wang, M. and Zhang, Y.Z. 1988. Diffusion Wear in Milling Titanium Alloy. *Material Science and Technology* 4: 548-553.

Wang, M. and Zhang, Y.Z. 1988. Investigation on the Tool Wear Mechanisms in Milling of Titanium Alloys. *16th NAMRC: North American Manufacturing Research Conference* 62: 190-194.

Wang, Z.M. and Ezugwu, E.O. 1997. Performance of PVD of PVD-Coated Carbide Tools when Machining Ti-6Al-4V. *Tribology Transaction* 40: 81-86.

Wang, Z.G., Wong, Y.S. and Rahman, M. 2005. High-speed milling of titanium alloys using binderless CBN tools. *Int. Journal of Mach. Tools & Manufacture* 45: 105-114.

Wiliams, J.C., *Titanium Alloys: Production, Behaviour and Application*, IN Flower. H.M., Ed. 1995. *High Performance Materials in Aerospace*. Chapman Hall: 85-134.

Yang, Xiaoping and Liu, C.R. 1999. Machining Titanium and its Alloys. *Machining Science and Technology* 3:107-139.

Zin, S. and Semiatin, S.L. 1995.*Elements of Induction Heating: Design, Control and Applications*. ASM International.

Zorev, N.N. 1963. Inter-Relationship Between Shear Processes Occurring Along Tool Face and Shear Plane in Metal Cutting. *Int. Research in Prod. Engg*. ASME: 42-49.