

MODELLING OF STAGNANT ZONE FORMATION ON DIAMOND CUTTING
TOOL WHEN TURNING TITANIUM ALLOY

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To
My late Parents,
who sent me to Rangoon Institute of Technology,
A bridge to study oversea

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ABSTRACT

Diamond tools are increasingly used in advanced manufacturing because of their unique properties such as high hardness and thermal conductivity, and low thermal expansion unbeatable by any other known material. Despite their importance in machining of precision parts, extensive research on diamond tool wear is still underway. Particularly, maintaining the cutting edge sharpness and prolonging tool life are very important for machining difficult-to-cut materials. It is believed that the existence of stagnant zone on the tool rake face during cutting can protect the cutting edge from rapid wear. In this research, a new analytical stagnant zone model is derived based on boundary layer theory in fluid mechanics. The stagnant zone model predicts the stagnant zone length on diamond tools when machining titanium alloy. The cutting tool stress and chip velocity distributions required for the analysis of the stagnant zone model were taken from Finite Element (FE) modelling and simulation of orthogonal machining. Machining of Ti-6Al-4V with polycrystalline diamond and diamond-coated tools were experimentally carried out to obtain cutting forces and stagnant zone information at various cutting conditions. Used tools and post-processed chips were investigated under scanning electron (SEM), field-emission scanning electron (FE-SEM) and optical microscopes. In FE modelling, input data such as material properties and the constants required in Johnson-Cook constitutive model were taken from the literature, and the friction data were calculated from experimentally measured forces. FE simulations were carried out for various cutting speeds, feeds, edge radius and surface roughness of the tool. The developed FE model is validated by comparing the predicted and experimental cutting forces. The predicted cutting forces are agreeable with the experiments. MATLAB is used to fit the equations that represent velocity and stress distribution as well as to calculate the stagnant zone length in the developed stagnant zone model. It is found that the predicted values are closed to the experimental results for both diamond tools. The average stagnant zone lengths formed at certain cutting conditions are between 0.1mm and 0.3mm. The used tool geometry, chip morphology and simulated shear strain, temperature, and velocity plots are also consistent with stagnant zone formation. The proposed stagnant zone model indicates that formation of stagnant zone is a function of cutting condition, tool geometry, the tool surface finish and material properties.

ABSTRAK

Penggunaan matalat intan meningkat dalam pembuatan termaju kerana keunikannya seperti kekerasan dan pengaliran haba yang tinggi, dan juga pengembangan haba yang rendah yang tiada tolak bandingnya dengan bahan yang lain. Disebalik kepentingannya dalam pemesinan komponen persis, kajian yang mendalam ke atas kehausan matalat intan masih sangat sedikit. Terutama sekali, pengekal ketajaman mata pemotong dan hayat alat adalah sangat penting untuk memesis bahan yang sukar dipotong. Adalah dipercayai bahawa kewujudan zon genang di atas permukaan sadak matalat semasa memotong boleh melindungi mata pemotong daripada kehausan cepat. Dalam kajian ini, satu model analisis zon genang yang baru telah diterbitkan berdasarkan kepada teori lapisan sempadan dalam mekanik bendalir. Model zon genang yang diterbitkan berupaya meramal panjang zon genang di atas matalat intan apabila memesis aloi titanium. Tegasan matalat dan taburan kelajuan tatal yang diperlukan untuk menganalisis model zon genang telah diperolehi dari pemodelan Unsur Terhingga dan hasil simulasi pemesinan secara ortogon. Ujikaji pemesinan Ti-6Al-4V dengan menggunakan matalat intan polihablur dan matalat tersalut intan pada beberapa keadaan telah dijalankan untuk mendapatkan daya pemotongan dan maklumat zon genang. Matalat yang telah digunakan dan tatal yang terhasil telah diperiksa di bawah mikroskop imbasan electron (SEM dan FE-SEM) dan optik. Dalam pemodelan FE, data masukan seperti sifat bahan dan angkatap yang diperlukan dalam model juzuk Johnson-Cook telah diperolehi dari kajian literatur, sementara data geseran pula dikira dari pengukuran daya. Simulasi FE telah dijalankan pada pelbagai kelajuan pemotongan, uluran, jejari dan kekasaran permukaan matalat. Model FE yang telah dibangunkan telah disahkan dengan membandingkan daya yang diramal dengan daya yang diperolehi dari ujikaji. Nilai daya pemotongan yang diramal adalah selaras dengan nilai ujikaji. MATLAB telah digunakan untuk memadankan persamaan yang mewakili taburan kelajuan dan tegasan. Ia juga digunakan untuk mengira panjang zon genang yang dihasilkan melalui model zon genang. Didapati bahawa nilai yang diramal adalah menghampiri kepada keputusan ujikaji bagi kedua-dua matalat intan. Purata panjang zon genang yang terbentuk pada keadaan pemotongan tertentu adalah di antara 0.1mm dan 0.3mm. Geometri matalat yang telah digunakan, morfologi tatal dan plot simulasi terikan ricih, suhu dan kelajuan juga konsisten dengan pembentukan zon genang. Model zon genang yang dicadangkan menunjukkan bahawa pembentukan zon tersebut adalah bergantung kepada keadaan pemotongan, geometri matalat, kemas permukaan matalat dan sifat bahan.

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LIST OF SYMBOLS / ABBREVIATIONS

α	-	Tool rake angle, Coefficient of thermal expansion
β	-	Tool clearance angle, Friction angle
ϕ	-	Shear angle
σ	-	Mean normal stress on the shear plane
σ	-	Mean normal stress on the tool face, Standard deviation
σ_n, σ_x	-	Normal stress distribution along the tool face
σ_{\max}	-	Maximum normal stress on the tool face
$\bar{\sigma}$	-	Flow stress, Effective stress
σ^*	-	Dimensionless pressure-stress ratio
τ	-	Mean shear stress on the shear plane
τ	-	Mean shear stress on the tool face, Fluid shear
τ	-	Shear stress distribution along the tool face
τ^*	-	Critical shear stress
τ_w	-	Wall shear stress
μ	-	Coefficient of friction, Viscosity
$\bar{\epsilon}_{pl}$	-	Effective plastic strain
$\Delta\bar{\epsilon}_p$	-	Incremental plastic strain
$\frac{\text{---}^f}{\epsilon^p}$	-	Failure strain, Fracture strain
$\dot{\epsilon}, \frac{\dot{\text{---}}}{\epsilon^p}$	-	Plastic strain rate
$\dot{\epsilon}_0, \frac{\dot{\text{---}}}{\epsilon_0}$	-	Reference strain rate
γ	-	Shear strain
$\dot{\gamma}$	-	Shear strain rate
δ, δ	-	Boundary layer thickness

δ_L	-	Boundary layer thickness at length L
δ_x	-	Boundary layer thickness at length x
δ^*	-	Boundary layer displacement thickness
θ	-	Boundary layer momentum thickness
η	-	Proportional distance
ψ	-	Stream function
ρ	-	Density
Δt	-	Incremental time
Δy	-	Distance between adjacent slip planes
A	-	Material constant
A_r	-	Real contact area
A_s	-	Sticking contact area, Area of seized contact
B	-	Material constant, Width of the tool
b	-	Width of the plate, Width of cut in orthogonal cutting
C	-	Material constant, Constant in MIE
\bar{C}	-	Mean value of C
dA	-	Elemental area
d	-	Width of cut in orthogonal cutting
D	-	Diameter of workpiece, Damage parameter
D_1	-	Constant in shear failure model
D_2	-	Constant in shear failure model
D_3	-	Constant in shear failure model
D_4	-	Constant in shear failure model
D_5	-	Constant in shear failure model
\mathcal{D}	-	Drag due to fluid interaction
\mathbf{D}	-	Total drag
\mathbf{D}'	-	Drag due to momentum change
E	-	Young's Modulus
F	-	Shear force along the tool face
F_P	-	Cutting force
F_Q	-	Feed force
F_S	-	Shear force along the shear plane
F_N	-	Normal force on the shear plane

F_X	-	Force component in X-direction
i	-	Approaching angle, Angle of inclination
k	-	Thermal conductivity, Shear flow stress of chip
l	-	Sticking contact length, Characteristic length of plate
l_n, l_c	-	Total chip-tool contact length
L	-	Length of the plate
m	-	Strain rate sensitivity
n	-	Strain hardening index, Power law index
N	-	Spindle speed
N	-	Normal force along the shear plane
p	-	Pressure
R, R'	-	Resultant force in orthogonal cutting
R_a	-	Mean surface roughness
Re	-	Reynolds number
R_t	-	Maximum surface roughness
r	-	Cutting ratio, Cutting edge radius
t	-	Feed rate
t_1	-	Undeformed chip thickness, Depth of cut
t_2	-	Chip thickness
T	-	Temperature
T_m	-	Melting point
U, U_0, U	-	Upstream velocity, Cutting velocity
u, u_1	-	Velocity within the boundary layer, velocity component
V, V	-	Cutting speed, Upstream velocity
V_C	-	Chip velocity
V_S	-	Shear velocity
V_x, V_y	-	Velocity components in x and y-directions
v	-	Velocity within the boundary layer, velocity component
w	-	Width of workpiece in orthogonal cutting
x	-	Sliding contact length, Stagnant zone length
x_p	-	Predicted stagnant zone length
x_e	-	Experimental stagnant zone length
y	-	Distance from the surface
ALE	-	Arbitrary Lagrangian Eulerian

BUE	-	Built-up Edge
BUL	-	Built-up Layer
CI	-	Cutting interface
CNC	-	Computer Numerical Control
CVD	-	Chemical Vapour Deposited
EDAX	-	Energy Dispersive X-ray Analysis
FE	-	Finite element
FEM	-	Finite element method
FE-SEM	-	Field-emission Scanning Electron Microscope
HSS	-	High Speed Steel
ISO	-	International Standard Organization
MIE	-	Momentum Integral Equation
PCD	-	Polycrystalline diamond
SEM	-	Scanning electron microscope
SPDT	-	Single Point Diamond Turning
2D	-	Two dimensional

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CHAPTER 1

INTRODUCTION

1.1 Overview

Diamond has been increasingly used as cutting tools in advanced manufacturing such as high precision finishing, single point diamond turning, and ultraprecision machining. Due to its very strong chemical bonding of the structure, diamond has unique mechanical and elastic properties. Its hardness, molar density, and thermal conductivity are higher than those of any other known materials (Evans *et al.*, 1987; Davis, 1993). Such excellent properties of diamond are very important to make cutting tool with very sharp cutting edge that is crucial for machining ultra precision components. As the knowledge of the properties of diamond and the introduction of artifact diamond films have remarkably increased, the efficacious application of diamond to the technological requirements of the modern age is gaining momentum. Especially after single point diamond turning emerged as an economically viable technique for the machining of a range of components, the key ‘enabling technology’ has been availability of diamond tools with nearly ideal properties.

Primarily, achievable form and finish of a machined surface were related to the machine performance. Now advances in machine tool performance are such that tool-chip interactions become a limitation to further improvements in achievable form accuracy and surface finish. Tool-chip interaction directly influences the cutting tool condition during cutting which in turn affects the machined product quality. Therefore, a number of research groups have turned their attention to diamond

machining ‘chip science’. Much effort has been devoted to developing analytical models of metal cutting to understand the mechanics of chip formation with the objective of obtaining more effective cutting tools. Traditional ways are using great amount of experimentation and prototyping (Nishigushi *et al.*, 1988; Jared, 1999; Cook and Bossom, 2000; Manjunathaiah and Endres, 2000; Gubbles *et al.*, 2004).

In modern research technique, prediction by numerical simulation has been efficiently applied to predict material response with minimum amount of experiments. This method offers a great deal of advantages such as cost and time savings, accurate prediction of important process parameters without the actual machine tools or equipment and environmental safety. A more promising approach for developing a metal cutting model is provided by an advanced numerical discretization scheme such as finite element method (FEM). The application of this method to a variety of complex problems in solid mechanics has been well documented. The difficulty of reaching a better understanding of a particular machining process impelled researchers in the field to apply the finite element method in modelling of the process. More attention has been paid to FEM in the past decades in respect to its capability of numerically modelling different types of machining problems. The advantage of the (FEM) is that the entire complicated process can be automatically simulated using a computer (Shih, 1996a; Xie *et al.*, 1998; Movahhedy *et al.*, 2002; Wu *et al.*, 2005; Cakir and Isik, 2005).

Despite a number of simulation attempts reported in various papers, machining simulation has not become a common tool in industry due to the inherent complexity of the process which probably makes it one of the most challenging processes from the numerical point of view. It is also clear that more work still needs to be done in order to make the process responses such as cutting tool performance predictable close to reality and become parts of the computer integrated manufacturing system.

In many of these studies, various numerical codes were developed and used although some were not practical and not available commercially for the end user. Among these research efforts, the commercial FEM codes which have been

successfully used in chip formation simulation are NIKE-2D, ABAQUS, DYNA-3D, DEFORM-2D, FORGE-2D, MACH-2D and recently THIRD WAVE ADVANTEDGE (Jiang Hua, 2002; Sartkulvanich and Altan, 2005; Childs, 2006).

1.2 Research Background

Metal cutting is one of the most important material removal processes which produce desired shape and dimensions by removing unwanted material in the form of chips. Reasons for developing a rational approach to material removal are (Shaw, 1984 and 2005):

- To improve cutting techniques regardless of how much as even minor improvements in productivity are of major importance in high volume production.
- To produce products of greater precision and of greater useful life.
- To increase the rate of production and produce a greater number and variety of products with the tools available.

Rapid developments in tool material come together with the consideration of improving tool geometry and favourable tool wear. Diamond tool is one of the latest development in cutting tool technology. Modified Taniguchi chart (Figure 1.1) shows that since the diamond tool was introduced round about 1970, machining method and precision level have also improved (Taniguchi, 1994).

Single-crystal diamond is very expensive, but has been a perfect tool for ultraprecision machining. Ultraprecision machining using a single crystal diamond tool is generally termed single point diamond turning (SPDT). Now it has emerged as an economically viable technique for the fabrication of precision mechanical or optical parts of high geometrical and surface quality. Particularly due to the superior surface finish and form accuracy produced by SPDT, it is widely adopted for the manufacturing of precision lenses, laser mirrors, scanner mirrors, drums in photo copying machines and computer memory discs. This very precise way of fabricating

products can also reduce/eliminate the pollution compared to conventional manufacturing methods as the minimum amount of coolant or almost no coolant is needed to do the job (Weck *et al.*, 1988; Nakasuji *et al.*, 1990; Ueda *et al.*, 1991; Lucca *et al.*, 1993 and 1998; Beltrao *et al.*, 1999).

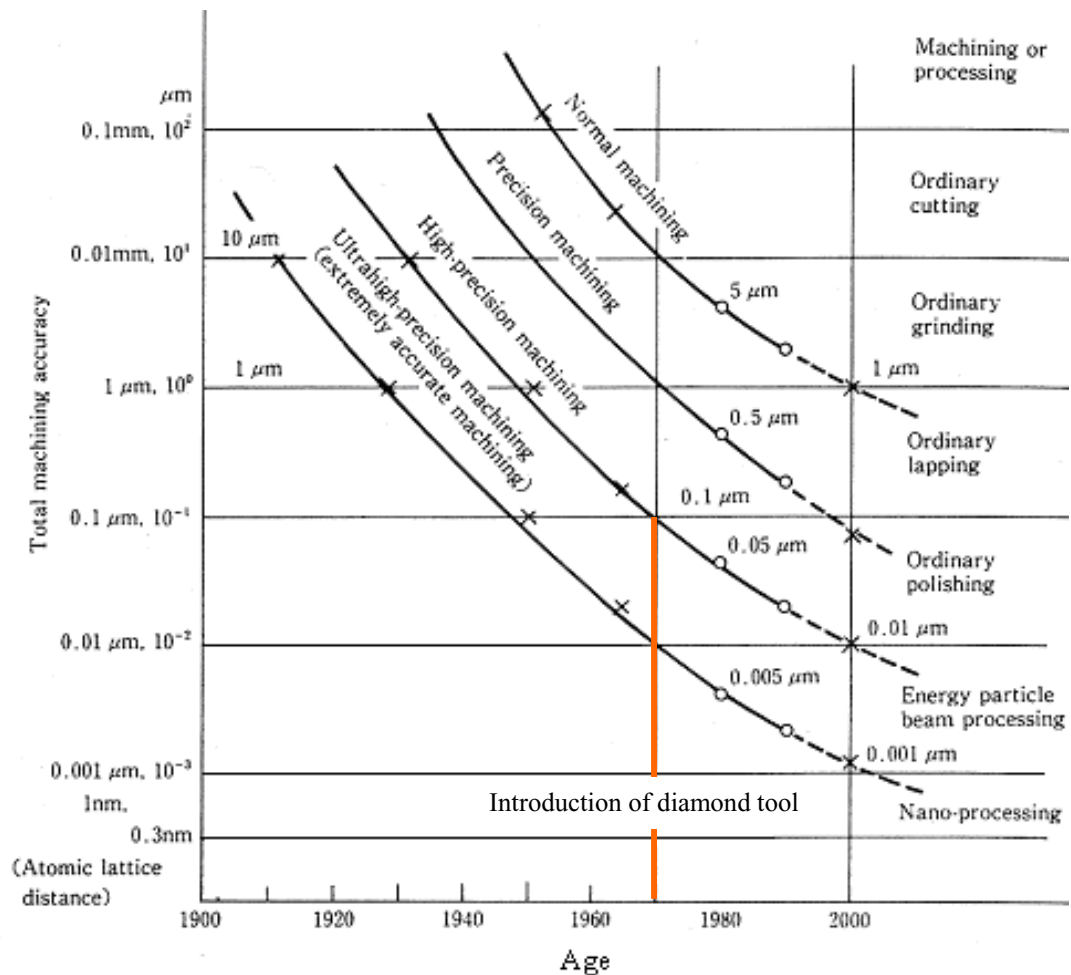


Figure 1.1 Modified Taniguchi's chart (Taniguchi, 1994).

Polycrystalline diamond (PCD) tools are cheaper than single crystal diamond tool. They are used in high precision finishing. The benefits of PCD have been observed in routine tooling types such as turning, milling and grooving. The PCD cutting edge has better ability to resist impact and fatigue damage because of fewer material imperfections under the surface. Their properties and performances under severe working conditions are generally considered to be outstanding and highly competitive in comparison to most ordinary wear-resistant materials (Sreejith *et al.*, 2000; Cook and Bossom, 2000; Andrewes *et al.*, 2000; Davim, 2002).

Diamond-coated tools are a much newer product and consist of a pure diamond coating as thick as 15-25 μm over a general-purpose carbide substrate. These tools can eliminate such problems encountered with uncoated cemented carbide tools as build-up edge formation, abrasive wear and work surface damage. Single crystal diamond and PCD have limitations, the most significant of which, besides the high cost, is the inability to create tools of complex geometries such as chip control geometry and rotary tools. These limitations can be overcome by the diamond-coated tools in a relatively simple and cost-effective manner (Bhat *et al.*, 1995; Oles *et al.*, 1996; Karner, 1996; Lahres and Jorgensen, 1997; Zalavutdinov *et al.*, 1998; Sun *et al.*, 2002; Polini *et al.*, 2002 and 2003).

Tool wear is an important factor influencing machined surface quality and manufacturing cost. Particularly wear of the diamond tool can affect the overall manufacturing cost significantly as a diamond tool costs much higher than a conventional tool. One of the various problems existing in industrial application of ductile regime turning involves edge wear of diamond tool. The problem becomes serious when machining large workpiece radius as tool wear dominates profiling errors and surface roughness as cutting distance increases (Nakasuji *et al.*, 1990; Yan *et al.*, 2002 and 2003; Davis *et al.*, 2003). Moreover, as the required precision level increases cutting edge sharpness becomes the more crucial. Therefore any research which contributes to prolonging of cutting edge of a diamond tool is benefited to manufacturing of high quality products.

There is still debate on the actual mechanism responsible for cutting edge chipping of diamond tool especially for a single crystal diamond. Cutting edge sharpness is very often demolished by edge chipping as it is major wear phenomenon during cutting. Due to characteristic length scales encountered in ultraprecision machining and the limited ability to resolve spatial dimensions at these scales, it has been difficult to bridge the understanding of wear phenomenon encountered in conventional cutting with those in ultraprecision machining (Lucca *et al.*, 1993 and 1998). Although there has been significant amount of wear study on PCD and diamond-coated tools, understanding of cutting edge condition during machining with these tools is lacking. Since the geometry of the contact zone between the tool and the work piece is extremely important for the attainment of plastic flow in

machining difficult-to-machined materials, knowledge of cutting edge condition during cutting is essential.

In relation to manufacturing processes, FEM has been extensively used by manufacturing community for modelling and simulation of metal forming and machining processes. These processes are among the most important processes widely used in various industries like automotive, aerospace or electronics. The machining process involves large deformation of the material at very high strain rates ($10^3 - 10^7$) with the strains being much greater than unity. The chip produced is in contact with the tool face in very high pressure and friction. Large plastic work and high friction generate an enormous amount of heat locally. Since all of these phenomena occur in a very tiny region around the cutting edge, the complexity of the process is evident. The stress, strain, strain rate and temperature variables are all dependent on the cutting parameters such as the cutting speed and feed rate as well as on geometrical features of the tool such as the rake angle and edge radius. To accurately obtain the flow model under these conditions makes the process complicated further. Moreover unlike many forming processes, there is cutting action in which the bulk of material is separated. This action is similar to phenomenon in elastic-plastic crack-propagation problems. Therefore the numerical simulation of chip formation during cutting process has been a challenging research topic (Shih, 1996; Xie *et al.*, 1998; Movahhedy *et al.*, 2002; Sartkulvanich and Altan, 2005).

From the point of view of numerical formulation, the FEM based on the updated-Lagrangian, and Eulerian as well as Arbitrary Lagrangian Eulerian formulations has been developed to analyze the metal cutting process in the past decade (Strenkowski and Carroll, 1985; Strenkowski and Moon, 1990; Shih, 1996a, b; Xie *et al.*, 1998; Movahhedy *et al.*, 2002). Several special FE techniques such as element deletion (Shih, 1996a; Huang and Black, 1996; Zhang, 1999), modelling of tool geometry including worn tool and edge radius effects (Komvopoulos and Erpenbeck, 1991; Li *et al.*, 2002; Movahhedy *et al.*, 2002, Özel, 2003), mesh rezoning (Shih, 1996b; Bäker *et al.*, 2002), friction modelling (Li *et al.*, 2002) have been implemented to improve the accuracy and efficiency of FE modelling. Three-dimensional modelling and modelling of tool wear and were successfully developed

by Guo and Liu (2002), Cheng (2003) and Yen *et al.* (2004) respectively. Detailed work material modelling, which includes the coupling of strain rate, strain hardening effect, temperature and microstructure has been applied to model the material deformation (Özel and Zeren, 2004 and 2005; Park *et al.*, 2004). In terms of chip types, continuous as well as serrated chips have been successfully simulated (Obikawa and Usui, 1996; Jiang Hua, 2002; Chen *et al.*, 2004; Childs, 2006). The FE simulation results have also been validated by experimental measurements (Zhang and Bagchi, 1994; Xie *et al.*, 1998; Mackerle, 1999; Klocke *et al.*, 2002; Jiang Hua, 2002; Chen *et al.*, 2004, Khadke *et al.*, 2005).

1.3 Problem Statements

Studies on tool wear have evolved a lot of improvement on the cutting tool geometry as well as on the machine tools performance. Improvement in machine tool rigidity together with better cutting tool properties and geometry enable some advanced materials be cut effectively but still in general at relatively slow pace. Rapid rise of temperature during cutting titanium alloys, for example, aggravates wear on the cutting tool. Despite many studies on the flank and crater wears, researchers pay very little attention on the small region on the rake face between the major cutting edge and crater boundary. This unworn region of about 0.75mm width was observed by numerous researchers (Venkatesh and Satchithanandam, 1980; Ranganatha, 1981; Sachithanandam, 1981) on the conventional cutting tools for almost two and half decades ago. Similar phenomenon was also reported recently by other researchers (Davim and Baptisa, 2000; Sahoo *et al.*, 2002; Yan *et al.*, 2003) but none of them paid serious attention to this peculiar region. Interestingly, this specific area is intact on the rake face for quite some time. As the crater wear get widen and deepen, this region gradually reduced and the cutting edge chipped off when crater groove meets the flank wear. It is believed that the tool edge collapses when this region completely demolished. To date, detail study related to this phenomenon hardly being found in the literature especially involving diamond cutting tools. Thus, the presence of this phenomenon and its mechanism still remain unexplained.

Wear mechanism on the cutting tool always linked to attrition/adhesion, abrasion, oxidation, diffusion, plastic deformation or combination of one of those. It is very rare that the state of stress at the tool-chip interface is being exploited for explaining the wear mechanism; partly because of difficulty to get accurate stress information during cutting. Usually, the cutting forces that are captured using dynamometer during actual machining process are used to evaluate indirectly the magnitude of stresses. This method becomes very costly and less practical when both the cutting tool and work piece materials are expensive which definitely limits the number of trials. Therefore, software based finite element (FE) method is commonly being applied nowadays to model the process and solves complex engineering problems without wasting a lot of pricey resources. Since early 1980s, finite element modelling has been used in the metal cutting field to simulate chip formation, tool wear, cutting forces, temperature in both chip and cutting tool etc. However, limited FE studies have been observed on the cutting stresses especially on the diamond tool. Most stress studies were focused on the chip rather than on the cutting tool. No direct comparison has been reported on the stress patterns obtained from FE results to the empirical models proposed by Zorev (1963) and Trent (2000). Literature also showed that stagnant zone phenomenon on the cutting tool has been neglected within research communities despite its importance preserving the cutting edge from wear. As such no concerted effort has been reported to relate this phenomenon to the stress state at the chip-tool interface either by conventional or numerical formulation methods.

1.4 Objectives

The objectives of the research are as follows:

1. To investigate the range of stagnant zone retention length on the polycrystalline diamond and diamond-coated cutting tools when machining Ti-6Al-4V at various machining conditions
2. To predict cutting tool stresses during orthogonal cutting of Ti-6Al-4V with diamond tool using finite element method

3. To propose an analytical stagnant zone model that predicts stagnant zone length on diamond tool.

1.5 Scope

The research is conducted within the following limits:

1. Work piece understudy is limited to titanium alloy (Ti-6Al-4V). Actual experimental trials are conducted at the cutting speed in the range from 60m/min to 150m/min and feed rate 0.1 to 0.2mm/rev.
2. CNC Turning centre (MAHO 500E) is used for turning titanium alloy (Ti-6Al-4V) to investigate the intact zone on the diamond tools which is the indicator of stagnant zone formation, while cutting force experiments are carried out on the conventional Harrison 500 heavy duty lathe.
3. Polycrystalline diamond and diamond-coated inserts are used in the study. The geometry of the insert is limited to TPGN160308 (ISO code).
4. ABAQUS version 6.5 is employed for modelling the cutting process and analysis of stress-strain, material flow and temperature distribution.
5. Used tool and chip morphology are characterized with field emission scanning electron microscope (FE-SEM), contact stylus profilers, and optical microscopes.

1.6 Rationale and Motivation

Stagnant zone is a desirable phenomenon as cutting edge sharpness is maintained by its presence. The sharpness of diamond tool is one of the most important factors to reduce damaged layer remaining at the machining surface. While diamond tools often face problem of edge wear, which results difficulties of shearing at cutting edge during machining, this problem could be overcome if the stagnant zone survived. Retention of this zone could possibly prolong the tool life as it preserves the tool edge from breakage easily. As such the occurrence of stagnant

zone on a diamond tool is worth to be investigated as it has great potential of saving tooling cost. Furthermore, the investigation of the stagnant zone formation on diamond tool when machining titanium alloy would provide a basis to understand stagnant zone phenomenon in diamond turning of difficult-to-cut materials.

It has also been understood that knowledge of stress and stress distribution at the tool-work interface is useful in many ways, which should be the basis of analysis of cutting tool condition during cutting and thus provides avenue for detailed analysis of tool failure, the properties required for the tool materials and the influence of tool geometry on cutting performance.

1.7 Summary of Research Methodology

Figure 1.2 shows the schematic diagram summarizing the three main activities involved in this research with the inputs required, i.e. 1) Preliminary experimental trials, 2) Finite element modelling and 3) Development of stagnant zone model.

The main objective of the preliminary experimental trials (activity 1) is to provide basic information in terms of cutting forces and the stagnant zone length at various machining conditions. In the FE modelling (activity 2), tool and workpiece properties and friction data are required to predict material behaviour during cutting. The cutting forces obtained from the experimental trials are used to validate the finite element model. In these experimental trials also, the actual stagnant zone lengths are measured on the used tool and these are used to compare with the predicted results obtained from proposed stagnant zone model. In activity 3, outputs from finite element simulation are utilized in order to develop an analytical stagnant zone model. Later, verification of the stagnant zone model is done by comparing the experimental and predicted stagnant zone lengths. Detail procedures for these activities are explained in Chapter 3.

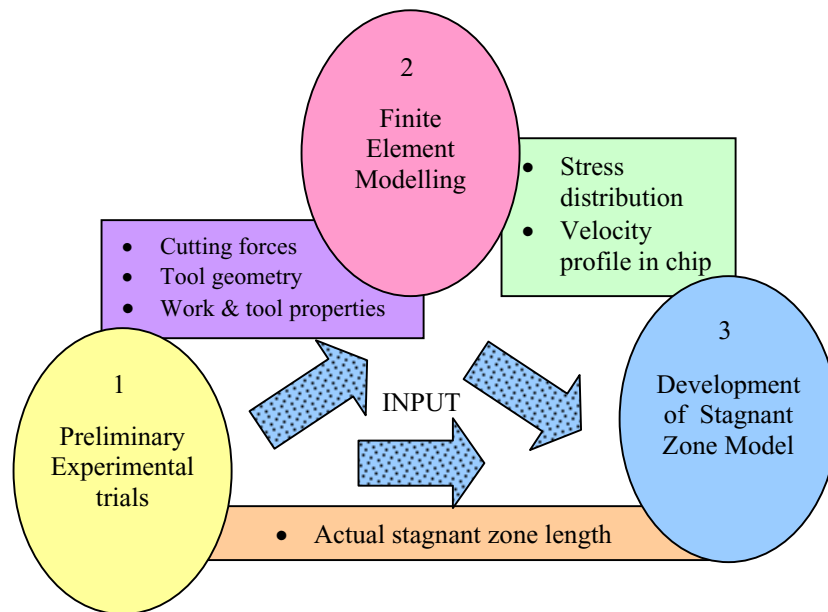


Figure 1.2 Schematic diagram summarizes three main activities involved in the research.

1.8 Structure of the Thesis

This thesis comprises of seven chapters. The first chapter is introduction. It overviews the application and importance of diamond tools in machining and finite element modelling in solving complex engineering problems, discusses background of metal cutting field in general, problem statements, research objectives, scope, rationale and motivation and summary of research methodology. Chapter 2 focuses on the literature reviews. This chapter highlights the background knowledge on the metal cutting principles, critical reviews on the chip-tool interface and finite element studies in the metal cutting field, and overview on the boundary layer theory in fluid mechanics. Detail procedure to run experimental trials, finite element modelling and simulation of cutting process flow chart and steps in developing of stagnant zone analytical model are described in Chapter 3. Results and discussion are presented in the three separated chapters, i.e Chapter 4, 5 and 6. Chapter 4 concentrates on the results of preliminary experimental trials. This chapter provides inputs required by the finite element and stagnant zone models. Chapter 5 presents finite element modelling results which comprise of the investigation of material model, the choice

of FE machining model based on model validation results, the effect of machining parameters on process responses such as material behaviour, stress-strain in chips, cutting tool stresses and cutting temperatures. Chapter 6 reports on the development of stagnant zone analytical model which is based on the boundary layer theory. It also discusses the validation process and prediction of stagnant zone length at various machining conditions. Chapter 7 summarizes the conclusions, outlines the significant contributions from the findings and finally suggests recommendation for future works.

REFERENCES

- ABAQUS. *User's Manual Version 6.5*. USA.: ABAQUS Inc. 2004
- Anagonye, A. and Stephenson, D. A. Modelling Cutting Temperatures for Turning Inserts with Various Tool Geometries and Materials. *Transactions of the ASME*, 2002. 124: 544-552.
- Andrewes, J. E. C., Feng, H. –Y. and Lau, W. M. Machining of an Aluminum/SiC Composite using Diamond Inserts. *Journal of Materials Processing Technology*, 2000. 102: 25-29.
- Armarego, E. J. A. and Brown, R. H. *The Machining of Metals*. Englewoods Cliffs, N. J.: Prentice-Hall. 1969
- Bäker, M., Rösler, J. and Siemers, C. A Finite Element Model of High Speed Metal Cutting with Adiabatic Shearing. *Computers and Structures*, 2002. 80: 495-513.
- Bailey, J. A. Friction in Metal Cutting–Mechanical Aspects. *Wear*, 1975. 31: 243-275.
- Barry, J., Byrne, G. and Lennon, D. Observations on Chip Formation and Acoustic Emission in Machining Ti–6Al–4V Alloy. *International Journal of Machine Tools & Manufacture*, 2001. 41: 1055–1070.
- Beltrao, P. A., Gee, A. E., Corbett, J., Whatmore, R. W., Goat, C. A. and Impey, S. A. Single Point Diamond Machining of Ferroelectric Materials. *Journal of the European Society*, 1999. 19: 1325-1328.
- Bhat, D. G., Johnson, D. G., Malshe, A. P., Naseem, H., Brown, W. D., Schaper, L. W. and Shen, C. –H. A Preliminary Investigation of the Effect of Post-deposition Polishing of Diamond Films on the Machining Behaviour of Diamond-coated Cutting tools. *Diamond and Related Materials*, 1995. 4: 921-929.
- Bhaumik, S. K., Divakar, C. and Singh, A. K. Machining Ti -6Al-4V Alloy with a wBN-cBN Composite Tool. *Materials & Design*, 1995. 16: 221-226.
- Bil, H., Kilic, S. E. and Takkaya, A. E. A Comparison of Orthogonal Cutting Data from Experiments with Three Different Finite Element Models. *International Journal of Machine Tools and Manufacturing*, 2004. 44: 933-944.
- Blasius, H. http://en.wikipedia.org/wiki/Blasius_boundary_layer 1908

- Boothroyd, G. *Fundamentals of Metal Machining and Machine Tools*. Washington, D. C.: McGraw-Hill. 1975
- Boothroyd, G. and Knight, W. A. *Fundamentals of Machining and Machine Tools*. 2nd. ed. NY, USA.: Marcel Dekker. 1989
- Born, D. K. and Goodman, W. A. An Empirical Survey on the Influence of Machining Parameters on Tool Wear in Diamond Turning of Large Single-Crystal Silicon Optics. *Precision Engineering, Journal of the International Societies for Precision Engineering and Nanotechnology*, 2001. 25: 247–257.
- Cakir, M. C. and Isik, Y. Finite Element Analysis of Cutting Tools Prior to Fracture in Hard Turning Operations. *Materials and Design*, 2005. 26: 105-112.
- Ceretti, J. E., Fallbehmer, P., Wu, W. T. and Altan, T. Application of 2D FEM on Chip Formation in Orthogonal Cutting. *Journal of Material Processing Technology*, 1996. 59: 169-181.
- Chambers, A. R. The Machinability of Light Alloy MMCs. *Composites*, 1996. Part A 27A: 143-147.
- Che-Haron, C. H. Tool Life and Surface Integrity in Turning Titanium Alloy. *Journal of Material Processing Technology*, 2001. 118 (1-3): 231-237.
- Chen, L., El-Wardany, T. I. and Harris, W. C. Modelling the Effects of Flank Wear-land and Chip Formation on Residual Stresses. *Annals of the CIRP*, 2004. 53 (1): 95-98.
- Cheng, K., Luo, X., Ward, R. and Holt, R. Modelling and Simulation of Tool Wear in Nanometric Cutting. *Wear*, 2003. 255: 1427-1432.
- Childs, T. H. C. and Mahdi, M. I. On the Stress Distribution between the Chip and Tool during Metal Turning. *Annals of the CIRP*, 1989. 38(1): 55-58.
- Childs, T. H. C. and Maekawa, K. Computer-aided Simulation and Experimental Studies of Chip Flow and Tool Wear in the Turning of Low Alloy Steels by Cemented Carbide Tools. *Wear*, 1990. 139: 235-250.
- Childs, T. H. C. Material Properties Needs in Modelling Metal Machining. *Machining Science and Technology*, 1998. 2 (2): 303-316.
- Childs, T. H. C. Numerical Experiments on the Influence of Material and Other Variables on Plane Strain Continuous Chip Formation in Metal Machining. *International Journal of Mechanical Sciences*, 2006. 48: 307-322.

- Choi, I-H. and Kim, J-D. Development of Monitoring System on the Diamond Tool Wear. *International Journal of Machine Tools &Manufacture*, 1999. 39: 505-515.
- Cook, M. W. and Bossom, P. K. Trends and Recent Developments in the Material Manufacture and Cutting Tool Application of Polycrystalline Diamond and Polycrystalline Cubic Boron Nitride. *International Journal of Refractory Metals & Hard Materials*, 2000. 18: 147-152.
- Davim, J. P. Diamond Tool Performance in Machining Metal–Matrix Composites. *Journal of Materials Processing Technology*, 2002. 128: 100–105.
- Davim, J. P. and Baptist, A. M. Relationship between Cutting Force and PCD Cutting Tool wear in Machining Silicon Carbide Reinforced Aluminum. *Journal of Materials Processing Technology*, 2000. 103: 417-423.
- Davis, D. W., Walter, M., Takahashi, M. and Masaki, T. Machining and Metrology Systems for Free-form Laser Printer Mirrors. *SADHANA, Academy Proceedings in Engineering Sciences, Special Issue on Precision Machining*, 2003. 28: 925-932.
- Davis, R. F. *Diamond Films and Coating*. NY, USA.: Noyes Publications. 1993
- Deuerler, F., Gruner, H., Pohl, M. and Tikana, L. Wear Mechanisms of Diamond-coated tools. *Surface and Coatings Technology*, 2001. 142-144: 674-680.
- Deuerler, F., Lemmer, O., Frank, M., Pohl, M. and Hebing, C. Diamond Films for Wear Protection of Hard Metal Tools. *International Journal of Refractory Metals & Hard Materials*, 2002. 20: 115–120.
- Durante, S., Rutelli, G., and Rabezzana, F. Aluminum-based MMC Machining with Diamond-coated Cutting Tools. *Surface and Coating Technology*, 1997. 94-95: 632-640.
- EL-Zahry, R. M. On the Hydrodynamic Characteristics of the Secondary Shear Zone in Metal Machining with Sticking-Sliding using the Boundary Layer Theory. *Wear*, 1987. 115: 349-359.
- Evans, C., Polvani, R., Postek, M. and Rhorer, R. Some Observations on Tool Sharpness and Sub-surface Damage in Single Point Diamond Turning, In-Process Optical Metrology for Precision Machining. *SPIE*, 1987. 802: 52-66.
- Fang, F. Z. and Chen, L. J. Ultra Precision Cutting for ZKN7 Glass. *Annals of the CIRP*, 2000. 49(1): 17-20.

- Fang, F. Z. and Venkatesh, V. C. Diamond Cutting of Silicon with Nanometric Finish. *Annals of the CIRP*, 1998. 47(1): 45-49.
- Fang, N., Jawahir, I. S. and Oxley, P. L. B. A Universal Slip-Line Model with Non-unique Solutions for Machining with Curled Chip Formation and a Restricted Contact Tool. *International Journal of Mechanical Sciences*, 2001. 43: 557-580.
- Finnemore, E. J. and Franzini, J. B. *Fluid Mechanics with Engineering Applications*. 10th. ed. NY, USA.: McGraw-Hill Series. 2002
- Goldstein, S. *Modern Development in Fluid Dynamics*. NY, USA.: Oxford University Press. 1938
- Gubbels, G. P. H., van der Beek, G. J. F. T., Hoep, A. L., Delbressine, F. L. M. and van Halewijn, H. Diamond Tool Wear when Cutting Amorphous Polymers. *Annals of the CIRP*, 2004. 53 (1): 447-450.
- Guo, Y. B. and Liu, C. R. 3D FEA Modelling of Hard Turning. *Journal of Manufacturing Science and Engineering, ASME*, 2002. 124: 189-199.
- Hamann, J. C., Le Maître, F. and Guillot, D. Selective Transfer Built-up Layer Displacement in High-Speed Machining – Consequences on Tool Wear and Cutting Forces. *Annals of the CIRP*, 1994. 43(1): 69-72.
- Hartung, P. D. *Tool Wear in Titanium Machining*. M.Sc. Thesis. Massachusetts Institute of Technology; 1980
- Hirao, M., Thusty, J., Sowerby, R. and Chandra, G. Chip Formation with Chamfered Tools. *Journal of Engineering for Industry. ASME*, 1982. 104: 339-342.
- Hobbs, J. W., Greene, R. J. and Patterson, E. A. A Novel Instrument for Transient Photoelasticity. *Society for Experimental Mechanics*, 2003: 403-409.
- Hooper, R. M., Henshall, J. L. and Klopfer, A. The Wear of Polycrystalline Diamond Tools used in the Cutting of Metal Matrix Composites. *International Journal of Refractory Metals & Hard Materials*, 1999. 17: 103-109.
- Horia, K., Kasai, T. and Ogata, Y. A Study on Damaged Layer Remaining in Diamond Mirror Cut Surface. *Annals of the CIRP*, 1992. 41(1): 137-140.
- Huang, J. M. and Black, J. T. An Evaluation of Chip Separation Criteria for the FEM Simulation of Machining. *Journal of Manufacturing Science and Engineering*, 1996. 118: 545-553.
- ISO 3685 –1977/BS 5623:1979

- Iwata, K., Osakada, K. and Terasaka, Y. Process Modelling of Orthogonal Cutting by the Rigid-Plastic Finite Element Method, *ASME Journal of Engineering Materials and Technology*, 1984. 106: 132-137.
- Iwata, K. and Ueda, K. Fundamental Analysis of the Mechanism of Built-up Edge Formation Based on Direct Scanning Electron Microscope Observation. *Wear*, 1980. 60: 329-337.
- Jackson, P. S. and Wight, P. K. Application of Plastic Boundary Layer Theory to Metal Machining. *Transactions of the ASME*, 1982. 104: 358-362.
- Jared, B. H. and Dow, T. A. Investigation and Prediction of Chip Geometry in Diamond Turning. *Precision Engineering*, 2000. 24: 88-96.
- Jawahir, I. S. The Tool Restricted Contact Effect as a Major Influencing Factor in Chip Breaking: An Experimental Analysis. *Annals of the CIRP*, 1988. 37(1): 121-126.
- Jawaid, A., Che-Haron, C. H. and Abdullah, A. Tool Wear Characteristics in Turning of Titanium Alloy Ti-6246. *Journal of Material Processing Technology*, 1999. 92-93: 329-334.
- Jawaid, A., Sharif, S. and Koksai, S. Evaluation of Wear Mechanisms of Coated Carbide Tools When Face Milling Titanium Alloy. *Journal of Material Processing Technology*, 2000. 99: 266-274.
- Jiang Hua, M. S. *Chip Mechanics and its Influence on Chip Segmentation and Tool Wear*. Ph.D. Thesis. Ohio State University; 2002
- Karner, J., Pedrazzini, M., Reineck, I., Sjostrand, M. E. and Bergmann, E. CVD Diamond Coated Cemented Carbide Cutting Tools. *Material Science and Engineering*, 1996. A209: 405-413.
- Khadke, A., Ghosh, S. and Li, M. Numerical Simulations and Design of Shearing Process for Aluminium Alloys. *Transactions of the ASME*, 2005. 127: 612-621.
- Kim, K. W. and Sin, H.-C. Development of a Thermo-Viscoplastic Cutting Model using Finite Element Method. *International Journal of Machine Tools Manufacturing*, 1996. 36(3): 379-397.
- Kita, Y., Ido, M. and Kawasaki, N. A Study of Metal Flow Ahead of Tool Face with Large Negative Rake Angle. *Journal of Engineering for Industry. ASME*, 1982. 104: 319-325.

- Klocke, F., Markworth, L. and Messner, G. Modeling of Ti-6Al-4V Machining Operations. *Proceedings of 5th CIRP International Workshop on Modeling of Machining Operations*. May 20-21, 2002. West Lafayette, USA: CIRP. 63-70.
- Komanduri, R. and Brown, R. H. On the Mechanics of Chip Segmentation in Machining. *Journal of Engineering for Industry, ASME*, 1981. 103: 33-51.
- Komanduri, R. and Von Turkovich, B. F. New Observations on the Mechanism of Chip Formation when Machining Titanium Alloys. *Wear*, 1981. 69: 179-188.
- Komanduri, R. Some Clarifications on the Mechanics of Chip Formation When Machining Titanium Alloys. *Wear*, 1982. 76: 15-34.
- Komanduri, R., Schroeder, T., Hazra, J., von Turkovich, B. F. and Flom, D. G. On the Catastrophic Shear Instability in High-speed Machining of an AISI4340 Steel. *Journal of Engineering for Industry. Transactions of the ASME*, 1982. 104: 121-131.
- Komvopoulos, K. and Erpenbeck, S. A. Finite Element Modelling of Orthogonal Metal Cutting. *Journal of Engineering for Industry. ASME*, 1991. 113: 253-267.
- König, W. and Neises, A. Wear Mechanisms of Ultrahard, Non-metallic Cutting Materials. *Wear*, 1993. 162-164 (1):12-21.
- Kopac, J., Korosec, M. and Kuzman, K. Determination of Flow Stress Properties of Machinable Materials with Help of Simple Compression and Orthogonal Machining Test. *International Journal of Machine Tools & Manufacturing*, 2001. 41: 1275-1282.
- Lahres, M. and Jorgensen, G. Properties and Dry Cutting Performance of Diamond-coated Tools. *Surface and Coating Technology*, 1997. 96: 198-204.
- Lee, D. The Effect of Cutting Speed on Chip Formation under Orthogonal Machining. *Journal of Engineering for Industry. ASME*, 1985. 107: 55-63.
- Li, K., Gao, X.-L. and Sutherland, J. W. Finite Element Simulation of the Orthogonal Metal Cutting Process for Qualitative Understanding of the Effects of Crater Wear on the Chip Formation Process. *Journal of Material Processing Technology*, 2002. 127: 309-324.
- Li, X. Development of a Predictive Model for Stress Distributions at the Tool-Chip Interface in Machining. *Journal of Material Processing Technology*, 1997. 63: 169-174.

- Lin, Z. C. and Lin, S. Y. A Coupled Finite Element Model of Thermo-Elastic-Plastic Large Deformation for Orthogonal Cutting. *Journal of Engineering Material Technology. ASME*, 1992. 114: 218-226.
- Lin, Z.-C. and Lo, S.-P. A Study of the Tool-Chip Interface Contact Problem under Low Cutting Velocity with an Elastic Cutting Tool. *Journal of Material Processing Technology*, 1997. 70: 34-46.
- Lin, Z.-C. and Lo, S.-P. A Study of the Machined Workpiece and Tool under Different Low Cutting Velocity with an Elastic Tool. *International Journal of Mechanical Science*, 1998. 40(7): 663-681.
- Lucca, D. A., Chou, P. and Hocken, R. J. Effect of Tool Edge Geometry on the Nanometric Cutting of Ge. *Annals of the CIRP*, 1998. 47(1): 475-478.
- Lucca, D. A., Seo, Y. W. and Komanduri. R. Effect of Tool Edge Geometry on Energy Dissipation in Ultra Precision Machining. *Annals of the CIRP*, 1993. 42(1): 83-86.
- Macdougall, D. A. S. and Harding, J. A Constitutive Relation and Failure Criterion for Ti6Al4V alloy at Impact Rates of Strain. *Journal of the Mechanics and Physics of Solids*, 1999. 47: 1157-1185.
- Mackerle, J. Finite Element Analysis and Simulation of Machining: A Bibliography (1976-1996). *Journal of Material Processing Technology*, 1999. 86: 17-44.
- Majumdar, P. Jayaramachandran, R. and Ganesan, S. Finite Element Analysis of Temperature Rise in Metal Cutting Processes. *Applied Thermal Engineering*, 2005. 25: 2152-2168.
- Manjunathaiah, J and Endres, W. J. A New Model and Analysis of Orthogonal Machining with an Edge-Radius Tool. *Transaction of ASME*, 2000. 122: 384-390.
- Mamalis, A. G., Horvath, M., Branis, A. S., and Manolakos, D. E. Finite Element Simulation of Chip Formation in Orthogonal Metal Cutting. *Journal of Material Processing Technology*, 2001. 111: 19-27.
- Marmy, P., Leguey, T., Belianov, I. and Victoria, M. Tensile and Fatigue Properties of Two Titanium Alloys as Candidate Materials for Fusion Reactors. *Journal of Nuclear Materials*, 2000. 283-287: 602-606.
- Marusich, T. D. and Ortiz, M. Modelling and Simulation of High-Speed Machining. *International Journal for Numerical Methods in Engineering*, 1995. 38 (21): 3675-3694.

- Merchant, M. E. Mechanics of Metal Cutting Process. I. Orthogonal Cutting and a Type 2 Chip. *Journal of Applied Physics*, 1945. 16 (5): 267-275.
- Monaghan, J. and MacGinley, T. Modelling the Orthogonal Machining Process using Coated Carbide Cutting Tools. *Computational Material Science*, 1999. 16: 275-284.
- Moriwaki, T. and Shamoto, E. Ultraprecision Diamond Turning of Stainless Steel by Applying Ultrasonic Vibration. *Annals of the CIRP*, 1991. 40(1): 559-562.
- Moriwaki, T., Sugimura, N. and Luan, S. Combined Stress, Material Flow and Heat Analysis of Orthogonal Micromachining of Copper. *Annals of the CIRP*, 1993. 42(1): 75-78.
- Movahhedy, M., Gadala, M. S. and Altintas, Y. Simulation of the Orthogonal Metal Cutting Process Using an Arbitrary Lagrangian-Eulerian Finite Element Method. *Journal of Material Processing Technology*, 2000. 103: 267-275.
- Movahhedy, M., Altintas, Y., and Gadala, M. S. Numerical Analysis of Metal Cutting with Chamfered and Blunt Tools. *Transactions of the ASME*, 2002. 124 (2002) 178-188.
- Nabhani, F. Machining of Aerospace Titanium Alloys. *Robotic and Computer-Integrated Manufacturing*, 2001. 17(1-2): 99-106.
- Nakasuji, T., Kodera, S., Hara, S., Matsunaga, H., Ikawa, N. and Shimada, S. Diamond Turning of Brittle Materials for Optical Components. *Annals of the CIRP*, 1990. 39(1): 89-92.
- Narutaki, N. and Murakoshi, A. Study on Machining of Titanium Alloys. *Annals of the CIRP*, 1983. 32(1): 65-69.
- Ng, E. –G., El-Wardany, T. I., Dumitrescu, M. and Elbestawi, M. A. Physics Based Simulation of High Speed Machining. *Proceedings of 5th CIRP International Workshop on Modelling of Machining Operations*. May 20-21, 2002. West Lafayette, USA: CIRP. 1-19.
- Nishiguchi, T., Maeda, Y., Masuda, M., Sawa, M. and Uehara, K. Mechanism of Micro Chip Formation in Diamond Turning of Al-Mg Alloy. *Annals of the CIRP*, 1988. 37(1): 117-120.
- Obikawa, T. and Usui, E. Computational Machining of Titanium Alloy – Finite Element Modelling and a Few Results. *Transactions of the ASME*, 1996. 118: 208-215.

- Obikawa, T., Kaseda, C., Matsumura, T., Gong, W. G. and Shirakashi, T. Tool Wear Monitoring for Optimizing Cutting Conditions. *Journal of Materials Processing Technology*, 1996. 62: 374-379.
- Oldroyd, J. G. Two Dimensional Plastic Flow of a Bingham Solid, a Plastic Boundary Layer Theory for Slow Motion. *Proceedings of Cambridge Philosophical Society*, 1947. 43: 383 – 395.
- Oles, E. J., Inspektor, A., Bauer, C. E. The New Diamond-coated Carbide Cutting Tools. *Diamond and Related Materials*, 1996. 5: 617-624.
- Optiz, H. Werkstattstch. *U. Maschinenbau*, 1956. 46: 210.
- Oxley, P. L. B. Metallic Friction under Near-Seizure Conditions. *Wear*, 1980. 65: 227-241.
- Oxley, P. L. B. *Mechanics of Machining*. Ellis Horwood Series in Mechanical Engineering, England.: John Wiley & Sons. 1989
- Özel, T. Modeling of Hard Part Machining: Effect of Insert Edge Preparation in CBN Cutting Tools. *Journal of Materials Processing Technology*, 2003. 141: 284-293.
- Özel, T. and Zeren, E. Determination of Work Material Flow Stress and Friction for FEA of Machining using Orthogonal Cutting Test. *Journal of Materials Processing Technology*, 2004. (153-154): 1019-1025.
- Özel, T. and Zeren, E. Finite Element Modeling of Stresses Induced by High Speed Machining with Round Edge Cutting Tools. *Proceedings of IMECE'05, 2005 ASME International Mechanical Engineering Congress & Exposition*. November 5-11, 2005. Orlando, Florida: ASME. 1-7.
- Özel, T. and Zeren, E. A Methodology to Determine Work Material Flow Stress and Tool-Chip Interfacial Friction Properties by Using Analysis of Machining. *Journal of Manufacturing Science and Engineering, ASME*, 2006. 128: 119-129.
- Pantalé, O., Bacaria, J.-L., Dalverny, O., Rakotomalala, R. and Caperaa, S. 2D and 3D Numerical Models of Metal Cutting with Damage Effects. *Computer Methods in Applied Mechanics and Engineering*, 2004. 193: 4383-4399.
- Park, S., Kapoor, S. G. and DeVor. E. R. Mechanistic Cutting Process Calibration via Microstructure-level Finite Element Simulation Model. *Transaction of the ASME*, 2004. 126: 706-709.

- Paul, E., Evans, C. J., Mangamelli, A., McGlaufflin, M. L. and Polvanit, R. S. Chemical Aspects of Tool Wear in Single Point Diamond Turning. *Precision Engineering*, 1996. 18:4-19.
- Polini, R., Bravi, F., Casadei, F., D'Antonio, P. and Traversa, E. Effect of Substrate Grain Size and Surface Treatments on the Cutting Properties of Diamond Coated Co-Cemented Tungsten Carbide Tools. *Diamond and Related Materials*, 2002. 11: 726-730.
- Polini, R., Casadei, F., D'Antonio, P., and Traversa, E. Dry Turning of Alumina Composites with CVD Diamond Coated Co-cemented Tungsten Carbide Tools. *Surface and Coatings Technology*, 2003. 166: 127–134.
- Prandtl, L and Tietjens, O. E. *Fundamentals of Hydro- and Aeromechanics*. NY. USA.: McGraw-Hill. 1934
- Prandtl, L. *Essentials of Fluid Dynamics*. NY, USA.: Hafner Publishing. 1952
- Qi, H. S. and Mills, B. Formation of a Transfer Layer at the Tool-chip Interface during Machining. *Wear*, 2000. 245: 136–147.
- Ranganatha, B. J. *Study of Tool Materials Containing TiC*. Ph.D. Thesis. Indian Institute of Technology; 1981
- Reineck, I., Sjöstrand, M. E., Karner, J., and Pedrazzini, M. HCDCA Diamond-coated Cutting Tools. *Diamond and Related Materials*, 1996. 5: 819-824.
- Riberio, M. V., Moreira, M. R. V. and Ferreira, J. R. Optimization of Titanium Alloy (6Al- 4V) Machining. *Journal of Material Processing Technology*, 2003. 143-144: 458-463.
- Robert, W. F., Alan, T. M. and Philip, J. P. *Introduction to Fluid Mechanics*, 6th. ed. USA.: Wiley & Son. 2004
- Sachithanandam, M. *Study of Tool Wear, Tool Failure and Tool Life Criteria on Different Cutting Tool Materials*. Ph.D Thesis. Indian Institute of Technology; 1981
- Sahoo, B., Chattopadhyay, A. K. and Chattopadhyay, A. B. Development of Diamond Coated Tool and its Performance in Machining Al-11%Si Alloy. *Material Science Bulletin*, 2002. 25 (6): 487-491.
- Sartkulvanich, P. and Altan, T. Effect of Flow Stress and Friction Models in Finite Element Simulation of Orthogonal Cutting – A Sensitivity Analysis. *Machine Science and Technology*, 2005. 9: 1-26.

- Schimmel, R. J., Endres, W. J. and Stevenson, R. Application of an Internally Consistent Material Model to Determine the Effect of Tool Edge Geometry in Orthogonal Machining. *Transactions of the ASME*, 2002. 124: 536-543.
- Sharif, S. *Face Milling of Titanium Alloys using Coated and Uncoated Carbide Tools*. Ph.D. Thesis. Coventry University; 1999
- Shaw, M. C. *Metal Cutting Principle*. NY, USA.: Oxford University Press. 1984
- Shaw, M.C. Precision Finishing. *Annals of the CIRP*, 1995. 44(1): 343-348.
- Shaw, M. C. *Metal Cutting Principle*, 2nd. ed. NY, USA.: Oxford University Press. 2005
- Shi, G., Deng, X. and Shet, C. A Finite Element Study of the Effect of Friction in Orthogonal Metal Cutting. *Finite Elements in Analysis and Design*, 2002. 38: 863-883.
- Shih, A. J. Finite Element Simulation of Orthogonal Metal Cutting. *Transactions of the ASME*, 1995. 117: 84-93.
- Shih, A. J. Finite Element Analysis of Orthogonal Metal Cutting Mechanics. *International Journal of Machine Tools Manufacturing*, 1996a. 36(2): 255-273.
- Shih, A. J. Finite Element Analysis of the Rake Angel Effects in Orthogonal Metal Cutting. *International Journal of Mechanical Science*, 1996b. 38: 1-17.
- Shimada, S., Inamura, T., Higuchi, M., Tanaka, H. and Ikawa, N. Suppression of Tool Wear in Diamond Turning of Copper under Reduced Oxygen Atmosphere. *Annals of the CIRP*, 2000. 49 (1): 21-24.
- Shimada, S., Tanaka, H., Higuchi, M., Yamaguchi, T., Honda, S. and Obata, K. Thermo-Chemical Wear Mechanism of Diamond Tool in Machining of Ferrous Metals. *Annals of the CIRP*, 2004. 53(1): 57-60.
- Shinozuka, J., Obikawa, T. and Shirakashi, T. Chip Breaking Analysis from the Viewpoint of the Optimum Cutting Tool Geometry Design. *Journal of Materials Processing Technology*, 1996. 62: 345-351.
- Singamneni, S. B. A Mixed Solution for the Three-Dimensional Temperature Distribution in Turning Inserts using Finite and Boundary Element Techniques. *Journal of Materials Processing Technology*, 2005. 166: 98-106.
- Spurk, J. H. *Fluid Mechanics: Problems and Solutions*. Berlin, Heidelberg, New York.: Springer-Verlag. 1997

- Sreejith, P. S., Krishnamurthy, R., Malhotra, S. K. and Narayanasamy, K. Evaluation of PCD Tool Performance during Machining of Carbon/phenolic Ablative Composites. *Journal of Materials Processing Technology*, 2000. 104: 53-58.
- Stevenson, M. G., Wright, P. K. and Chow, J. G. Further Developments in Applying the Finite Element Method to the Calculation of Temperature Distributions in Machining and Comparisons with Experiment. *Journal of Engineering for Industry. ASME*, 1983. 105: 149-154.
- Strenkowski, J. S. and Carroll, J. T. A Finite Element Model of Orthogonal Metal Cutting. *Journal of Engineering for Industry. ASME*, 1985. 107 (1985), 347-354.
- Strenkowski, J. S. and Moon, K. –J. Finite Element Prediction of Chip Geometry and Tool/workpiece Temperature Distributions in Orthogonal Metal Cutting. *Journal of Engineering for Industry. ASME*, 1990. 112: 313-318.
- Sun, F. H., Zhang, Z. M., Chen, M. and Shen, H. S. Fabrication and Application of High Quality Diamond-coated Tools. *Journal of Materials Processing Technology*, 2002. 129: 435-440.
- Taniguchi, N. The State of the Art of Nanotechnology for Processing of Ultraprecision and Ultrafine Products. *Precision Engineering*, 1994. 16(1): 5-24.
- TIMET AUTOMOTIVE. *Technical data*. USA. 2002
- Trent, E. M. Metal Cutting and the Tribology of Seizure: I Seizure in Metal Cutting. *Wear*, 1988a. 128: 29-45.
- Trent, E. M. Metal Cutting and the Tribology of Seizure: II Movement of Work Material over the Tool in Metal Cutting. *Wear*, 1988b. 128: 47-64.
- Trent, E. M. Metal Cutting and the Tribology of Seizure: III Temperature in Metal Cutting. *Wear*, 1988c. 128: 65-81.
- Trent, E. M. and Wright, P. K. *Metal Cutting*. 4th. ed. M.A.: Butterworth-Heinemann. 2000
- Uddin, M. S., Seah, K. H. W., Li, X. P., Rahman, M. and Liu, K. Effect of Crystallographic Orientation on Wear of Diamond Tools for Nano-scale Ductile Cutting of Silicon. *Wear*, 2004. 257(7-8): 751-759.
- Ueda, K. and Manabe, K. Rigid-Plastic FEM Analysis of Three-Dimensional Deformation Field in Chip Formation Process. *Annals of the CIRP*, 1993. 42(1): 35-38.

- Ueda, K., Amano, A., Ogawa, K., Takamatsu, H., Sakuta, S. and Murai, S. Machining High-Precision Mirrors Using Newly Developed CNC Machine. *Annals of the CIRP*, 1991. 40(1): 555-558.
- Usui, E. and Shirakashi, T. Analytical Prediction of Cutting Tool Wear. *Wear*, 1984. 100: 129-151.
- Venkatesh, V. C., Radhakrishnan, V. and Chandramowli, J. Wear Propagation in Cutting Tools. *Annals of the CIRP*, 1969. 17: 317-323.
- Venkatesh, V. C. and Satchithanandam, M. A Discussion on Tool Life Criteria and Total Failure Causes. *Annals of the CIRP*, 1980. 29(1): 19-22.
- Venkatesh, V. C. and Chandrasekaran, S. *Experimental Technique in Metal Cutting*. India.: Prentice Hall. 1987
- Venkatesh, V. C. and Enomoto, S. *Finishing Methods using Defined Cutting Edges*. ASM Handbook 5, OH.: ASM International. 1994
- Von Kármán, T. Turbulence and Skin Friction. *Journal of Aerospace Society*, 1934. 1: 1-18.
- Von Kármán, T. <http://www-history.mcs.st-andrews.ac.uk/References.html>. 1963.
- Wada, R., Kodama, H., Nakamura, K., Mizutani, Y. and Shimura, Y. Wear Characteristics of Single Crystal Diamond Tool. *Annals of the CIRP*, 1980. 29(1): 47-52.
- Weck, M., Hartel, R. and Modemann, K. Performance Assessment in Ultraprecision Micromachining. *Annals of the CIRP*, 1988. 37(1): 499-502.
- Wern, C. W., Ramulu, M. and Shukla, A. Investigation of Stresses in the Orthogonal Cutting of Fiber-reinforced Plastics. *Experimental Mechanics, SAGE Social Science Collections*, 1995.: 33-41.
- Wright, P. K., Horne, J. G. and Tabor, D. Boundary Conditions at the Chip-Tool Interface in Machining: Comparisons between Seizure and Sliding Friction. *Wear*, 1979. 54: 371-390.
- Wu, H. Y., Lee, W. B., Cheung, C. F., To, S. and Chen, Y. P. Computer Simulation of Single-point Diamond Turning Using Finite Element Method. *Journal of Material Processing Technology*, 2005. 167: 549-554.
- Wu, J. -S., Dillon, O. W. and Lu, W. -Y. Thermo-viscoplastic Modelling of Machining Process Using a Mixed Finite Element Method. *Journal of Engineering for Industry. ASME*, 1996. 118: 470-481.

- Xie, J. Q., Bayoumi, A. E. and Zbib, H. M. FEA Modelling and Simulation of Shear Localized Chip Formation in Metal Cutting. *International Journal of Machine Tools & Manufacture*, 1998. 38: 1067-1087.
- Yan, J., Syoji, K. and Tamaki, J. Some Observations on the Wear of Diamond Tools in Ultra-Precision Cutting of Single-Crystal Silicon. *Wear*, 2003. 255: 1380-1387.
- Yan, J., Syoji, K., Kuriyagawa, T. and Suzuki, H. Ductile Regime Turning at Large Tool Feed. *Journal of Materials Processing Technology*, 2002. 121: 363-372.
- Yen, Y.-C., S. Jorg, Lilly, B. and Altan, T. Estimation of Tool Wear in Orthogonal Cutting using the Finite Element Analysis. *Journal of Materials Processing Technology*, 2004. 146: 82-91.
- Young, D. F., Munson, B. R. and Okiishi, T. H. *A Brief Introduction to Fluid Mechanics*. 3rd. ed. NY, USA.: John Wiley & Sons. 2002
- Yuan, Z. J., He, J. C. and Yao, Y. X. The Optimum Crystal Plane of Natural Diamond Tool for Precision Machining. *Annals of the CIRP*, 1992. 41(1):605-608.
- Zalavutdinov, R. K., Gorodesky, A. E., Zakharov, A. P., Lakhokin, Y. V., Ralchenko, V. G., Samokhvalov, N. V., Aikin, V. N. and Pjyanov, A. I. Diamond-coated Cemented Carbide Cutting Inserts. *Diamond and Related Materials*, 1998. 7: 1014-1016.
- Zareena, A. R., Rahman, M. and Wong, Y. S. Binderless CBN Tools, a Breakthrough for Machining Titanium Alloys. *Journal of Manufacturing Science and Engineering. ASME*, 2005. 127: 277-279.
- Zhang, B. and Bagchi, A. Finite Element Simulation of Chip Formation and Comparison with Machining Experiments. *Journal of Engineering for Industry. ASME*, 1994. 116: 289-297.
- Zhang, H. T., Liu, P. D. and Hu, R. S. A Three-zone Model and Solution of Shear Angle in Orthogonal Machining. *Wear*, 1991. 143: 29-43.
- Zhang, L. On the Separation Criteria in the Simulation of Orthogonal Metal Cutting Using the Finite Element Method. *Journal of Material Processing Technology*, 1999. 80-90: 273-278.
- Zorev, N. N. Inter-relationship between Shear Processes Occurring along Tool Face and Shear Plane in Metal Cutting. *International Research in Production Engineering ASME*, 1963. : 42-49.