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 keunikan sifatnya seperti kekerasan dan pengaliran haba yang tinggi, dan juga pengembangan haba yang rendah yang tiada tolok bandingnya dengan bahan yang lain. Disebalik kepentingannya dalam pemesinan komponen persis, kajian yang mendalam ke atas kehausan matalat intan masih sangat sedikit. Terutama sekali, pengekalan ketajaman mata pemotong dan hayat alat adalah sangat penting untuk memesin 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 memesin 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, kemasan 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
$\overline{\sigma}$	-	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
$\overline{\varepsilon}_{pl}$	-	Effective plastic strain
$\Delta\overline{\varepsilon}_p$	-	Incremental plastic strain
$\overline{\varepsilon^p}^f$	-	Failure strain, Fracture strain
$\dot{\varepsilon}$, $\overline{\dot{\varepsilon}^p}$	-	Plastic strain rate
$\dot{\varepsilon}_0$, $\overline{\dot{\varepsilon}_0}$	-	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
As	-	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
$\overline{C}$	-	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
$\boldsymbol{D}$	-	Total drag
$\boldsymbol{D'}$	-	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 sentivity
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
R_e	-	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
Vx, 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).

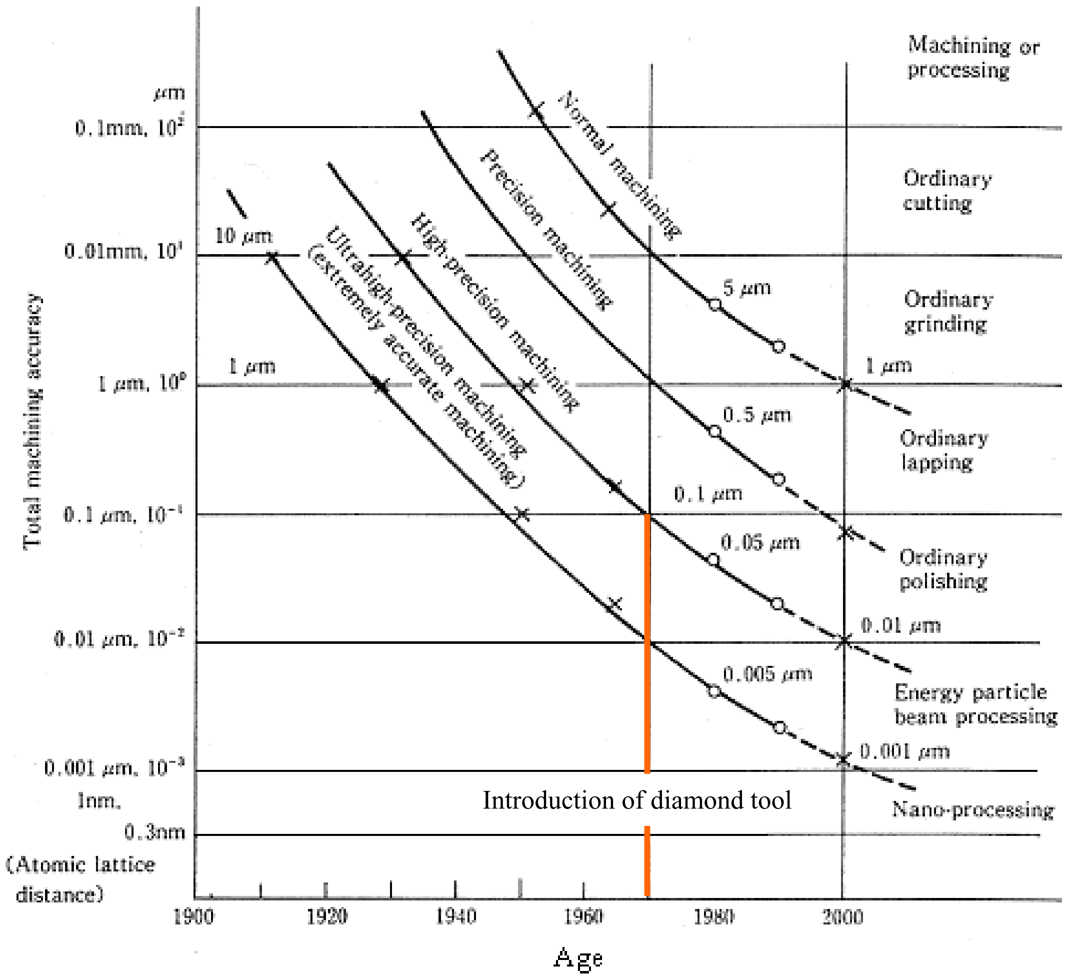

Figure 1.1 Modified Taniguchi's chart (Taniguchi, 1994).

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.

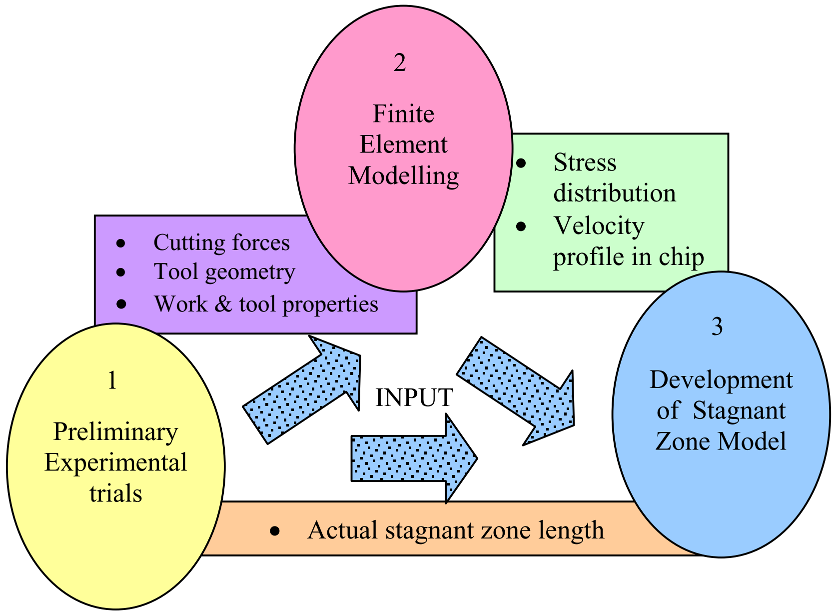

Figure 1.2 Schematic diagram summarizes three main activities involved in the research.

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.

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