NUMERICAL SIMULATION OF SINGLE POINT DIAMOND TURNING

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We certify that the project entitled "Numerical Simulation of Single Point Diamond Turning" is written by Teoh Yeong Chia. We have examined the final copy of this project and in our opinion; it is fully adequate in terms of scope and quality for the award of the degree of Bachelor of Engineering. We herewith recommend that it be accepted in partial fulfilment of the requirements for the degree of Bachelor of Mechanical Engineering with Manufacturing Engineering.

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STUDENT'S DECLARATION

I hereby declare that the work in this project is my own except for quotations and summaries which have been duly acknowledged. The project has not been accepted for any degree and is not concurrently submitted for award of other degree.

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To my Beloved Father and Mother

TEOH SEOW PENG
OOI GUIK HOON

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ABSTRACT

A coupled thermo-mechanical plane-strain large-deformation orthogonal cutting finite element model is presented in this thesis by using the ABAQUS finite element code to simulate the cutting mechanics of OFHC Copper in Single-Point Diamond Turning (SPDT). The simulations concern the study of stress and strain imparted in the workpiece during metal cutting process. Round edge cutting tool is used in this study since the tool edge radius has comparable size to the uncut chip thickness in SPDT. The tool is treated as perfectly rigid body where the cutting conditions and boundary conditions are prescribed at a reference point. Workpiece material is modeled as thermo-visco-plastic material that is considered dependent upon the plastic strain, the plastic strain rate and temperature variations. The flow stress calculation is expressed as the form of Johnson–Cook's constitutive equation that take into account the effect of the large strain, strain-rate and temperature associated with cutting on the material properties. To reduce computational time and cost, the workpiece is discretized by non-uniform mesh. Mesh distortion problem due to large deformation in front of tool tip during cutting simulation is solved using pure deformation technique. A more realistic and physically based chip formation can be achieved by using this method. Chip formation yield from the finite element method simulation of OFHC Copper is observed and it revealed good chip morphology that agrees well with the previous studies. The model is validated with the published report based on Von Mises Stress and found to be in good agreement also. This model is useful to economically analyze SPDT and thus to meet the need for improve productivity and quality of machining operations in SPDT.

ABSTRAK

Satu haba mekanikal terganding terikan satah ubah bentuk besar pemotongan ortogon model unsur terhingga telah diperkenalkan dalam tesis ini dengan kod unsur terhingga ABAQUS untuk simulasi mekanik pemotongan Kuprum OFHC dalam Pusingan Intan Mata Tunggal (SPDT). Simulasi adalah mengenai penyelidikan tegasan dan terikan yang terbentuk dalam benda kerja semasa proses pemotongan logam. Pinggir perkakas pemotongan yang bulat telah digunakan dalam penyelidikan ini sebab pinggir perkakas mempunyai saiz yang sesuai dibandingkan dengan ketebalan serpihan yang tidak dipotong dalam SPDT. Perkakas telah dianggap sebagai jasad tegar sempurna di mana keadaan pemotongan dan keadaan sempadan telah ditetapkan pada titik rujukan. Bahan benda kerja dipertimbangkan sebagai bahan termo-likat-plastik yang bersandar terhadap terikan plastik, kadar terikan plastik dan perubahan suhu. Penghitungan tegasan aliran telah dinyatakan dalam bentuk persamaan juzuk Johnson-Cook yang mengambil kira kesan terikan besar, kadar terikan dan suhu yang bersekutu dengan pemotongan terhadap ciri-ciri bahan. Bagi mengurangkan masa dan kos pengiraan, benda kerja tersebut telah didiskret oleh jejaring yang tidak seragam. Masalah herotan jejaring yang disebabkan oleh ubah bentuk besar di permukaan depan hujung perkakas semasa simulasi pemotongan telah diselesaikan dengan teknik ubah bentuk tulen. Satu pembentukan serpihan yang lebih praktikal dan fizikal boleh diperolehi dengan menggunakan kaedah ini. Pembentukan serpihan yang dihasilkan oleh simulasi Kuprum OFHC dengan kaedah unsur terhingga telah diperhatikan dan ia mendedahkan morfologi serpihan yang memuaskan malah sesuai dengan penyelidikan sebelum ini. Model telah disahkan dengan laporan yang diterbitkan berdasarkan Tegasan Von Mises dan didapati mencapai persetujuan juga. Model ini berkeupayaan untuk menganalisiskan SPDT secara ekonomik maka dapat memuaskan keperluan untuk mempertingkatkan produktiviti dan qualiti kendalian pemesinan dalam SPDT.

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LIST OF SYMBOLS

C	Specific heat
d, t_1	Depth of cut
E	Young’s modulus
f	Feed
K_r	Angle between cutting edge and cutting velocity
R_b	Tool edge radius
T_t	Material temperature
T_{melt}	Material melting temperature
T_{room}	Room temperature
U, V_c	Cutting speed
v	Poisson’s ratio
w	Width of cut
α	Thermal expansion coefficient
$\bar{\varepsilon}$	Equivalent total strain
$\dot{\bar{\varepsilon}}$	Equivalent total strain rate
$\dot{\bar{\varepsilon}}_0$	Initial strain rate
ρ	Material density
κ	Thermal conductivity
$\bar{\sigma}$	Flow stress

LIST OF ABBREVIATIONS

BUE	Built-up edge
CD	Computational domain
CAE	Computer-aided engineering
FE	Finite element
FEM	Finite element method
OFHC	Oxygen Free High Conductivity
PCD	Polycrystalline diamond
RP	Reference point
SPDT	Single-point diamond turning
2D	Two dimensional
3D	Three dimensional

CHAPTER 1

INTRODUCTION

This chapter gives a short description of the project background including several approaches. It then introduces objectives, scopes, problem statement of this project on numerical simulation of single-point diamond turning.

1.1 PROJECT BACKGROUND

Machining is one of the most common manufacturing processes for producing industrial pieces of desirable dimensions. Removal of unwanted material from a workpiece and obtain specified geometrical dimensions and surface finish is done by machining. Tool material selection, tool design, ensuring consistent dimensional accuracy and surface integrity of the finished product are important, especially in automated production and precision parts manufacturing (Shi et al., 2002). Those cutting condition and quality of machining operation can be determined by understanding the deformation characteristics of material removal process and the distributions of the process variables such as stresses and temperatures in machining (Pantalé et al., 2004).

Metal removal operations can be classified as conventional machining and ultra-precision machining by performance scales whether it is in macro or micro scales (Wu et al., 2005). The desired accuracy is so hard to obtain by conventional machining that ultra-precision machining technology is required for several industrial applications such as aerospace, automobile, artificial satellites, computer, lasers, optics components, quartz vibrators, semi-conductors, etc (Kim, J.-D and Kim, D.-S, 1997). In order to make cost-effective and quality assured precision parts, ultra-precision machining technology has been developed over recent years (Zong et al., 2006).

One of the ultra-precision machining technologies is Single-point diamond turning (SPDT), which possesses nanometric edge sharpness, from reproducibility, and wears resistance. SPDT has become increasingly important for the manufacture of optical quality components with micrometer to submicrometer form accuracy and surface roughness in nanometer range with the rapidly growing demand for precision components such as optoelectronics products (Wu et al., 2005).

There are considerable amount of research devoted to develop analytical, mechanistic and Finite Element Method (FEM) based numerical models to simulate metal cutting processes. This is due to finite element methods can be adapted to problems of great complexity and unusual geometry. Moreover, they are an extremely powerful tool in the solution of important problems in heat transfer, fluid mechanics, and mechanical systems also. (Hutton, 2004)

FEM based simulation models are primarily focus on conventional machining and prediction often goes to chip formation, computing distributions of strain, strain rate, temperatures and stresses on the cutting edge, in the chip and on the machined work surface among those researches have been performed (Pantalé et al., 2004 and Özel, 2006). Hence, accurate prediction from Finite Element (FE) simulations helps improve productivity and quality of machining operations (Özel, 2006).

1.2 PROBLEM STATEMENT

Single-point diamond turning is principally used in the manufacturing of high precision components with a surface finish of a few nanometers and with a tolerance which is in submicrometer range. The setup parameters for the diamond turning process are usually selected with the aid of trial cutting experiments conventionally, which are both time consuming and costly. The optimization for cutting parameters and prediction for machined surface quality are being necessary before perform the actual experiment to avoid these issues. Therefore, there is a need for the development of a simulation system which is capable of modeling the cutting process of single point diamond turning.

1.3 PROJECT OBJECTIVE

The objective of the project is to develop a numerical model to simulate the cutting mechanics of single-point diamond turning using finite element method.

1.4 PROJECT SCOPES

Project scopes are guidelines to help in achieving the objective and goals of the project. The project scopes are marked out as below:

1. Numerical model will be developed using ABAQUS FE code.
2. Model geometry of the numerical model is limited to 2D orthogonal cutting.
3. Material model used is based on Johnson-Cook's model and properties will be taken from published report.
4. Simulation of cutting mechanics will be based on adaptive meshing approach and pure deformation technique.
5. Simulation will be done in ABAQUS FE environment.
6. Analysis will be focused on stress and strain field.

1.5 THESIS STRUCTURE

This thesis consists of five chapters. Chapter 1 is the introduction, Chapter 2 reviews some related literature, Chapter 3 focuses on project methodology, Chapter 4 displays the outcomes of FE modeling and FE simulation followed by discussion, and lastly Chapter 5 that summarizes all main research points of this thesis.

1.6 SUMMARY

Chapter 1 has been discussed generally about project background, problem statement, objective and the scopes of the project which have been mark out in order to achieve the objective as mention. Hence, this chapter has great importance in functioning as fundamentals of this project and guidelines to complete the project research.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The purpose of this chapter is to provide a review of past research efforts related to orthogonal cutting, turning, single-point diamond turning and finite element analysis. A review of other relevant research studies is also provided. Substantial literature has been studied on model geometry, material model and properties, and finite element analysis of single-point diamond turning cutting mechanics. There are information can be found on method to develop numerical model also. The review is done to offer insight to how past research efforts have laid the groundwork for subsequent studies, including the present research effort. The review is detailed so that the present research effort can be properly tailored to add to the present body of literature as well as to justly the scope and direction of the present research effort.

2.2 TURNING

Turning is one of the typical machining processes that remove unwanted material in which the work piece is rotated with utilization of a single point tool by producing chips. It is accomplished by using lathe as machine tool. The adjustable variables for turning process are the cutting speed V_c (f.p.m. or m.s^{-1}) which is velocity of the cutting tool travel to the left as the work piece, the feed f (i.p.r. or mm.rev^{-1}) that refer to the distance of the tool travels horizontally per unit revolution of the work piece, and the depth of cut d (in or mm) where the cutting tool is set. To a good approximation, the chip is produced in plane strain and hence the width of chip is equal to the undeformed chip width since the depth of cut (*d*) is usually at least five times the feed (*f*) (Kalpakjian, and Schmid, 2006). Figure 2.1 illustrates main features of a typical turning process where workpiece, cutting tool, and machining parameters are shown.

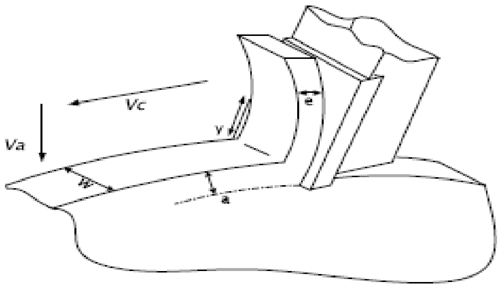

Figure 2.1: Turning process (Pantalé et al., 2004).

2.3 SINGLE POINT DIAMOND TURNING

Single Point Diamond Turning (SPDT) also known as diamond turning is categorized under ultra-precision machining. As shown in Figure 2.2, the machining system principally consists of aerostatic spindle and rigidly supported diamond tool used as the cutting tool. Diamond tool has a polished cutting edge with a radius in few nm. SPDT has become an essential process in the design and manufacture of high-technology products that require high surface quality lately (Ramesh et al., 2001). Surface generation in SPDT is a complicated process that comprises of burnishing, elastic recovery, plastic deformation, and materials swelling. Material factors in SPDT have a larger influence on the cutting process unlike conventional machining as the depth of cut is often less than the grain size of materials (Kong et al., 2006).

The machine tools for SPDT are built with very high precision and high machine, spindle, and workholding-device stiffnesses. Figure 2.3 shows SPDT system with major components that would make it ideally rigid and ultra-precise cutting. Ultra-precision machines are located in a dust-free environment where temperature is regulated within a fraction of one degree especially parts which are made of structural material with low thermal expansion and good dimensional stability. (Kalpakjian, and Schmid, 2006)

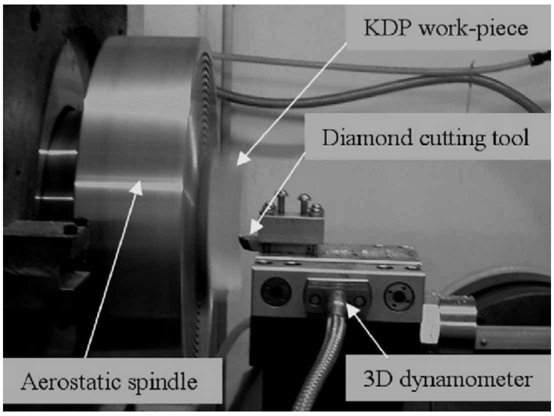

Figure 2.2: Ultra-precision turning system (Zhao et al., 2008).

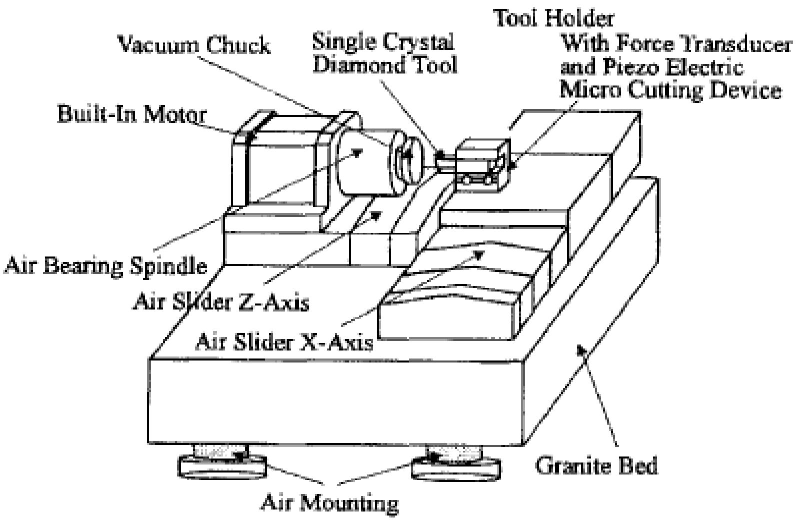

Figure 2.3: Single point diamond turning system (Kim, J.-D and Kim, D.-S, 1997).

2.4 CHIPS FORMATION IN MACHINING

There are four main types of chips commonly produced during machining and observed in practice, namely continuous chips, built-up edge chips, serrated chips and discontinuous chips. All chips have two surfaces (Shaw, 2005). One of the surfaces of a chip which has been in contact with the rake face of the tool has a shiny and burnished appearance caused by rubbing as the chip moves up the tool face. However, another surface from the original surface of the work piece has a jagged, rough appearance caused by the shearing mechanism. (Kalpakjian and Schmid, 2006)

Continuous chips are common when ductile materials are machined at high cutting speeds and/or high rake angles, as shown in Figure 2.4. A narrow shear zone known as primary shear zone is where the material deformation takes place. A secondary shear zone may develop by continuous chips caused by high friction at the tool-chip interface. The secondary shear zone becomes thicker as the friction increases. (Boothroyd and Knight, 1989)

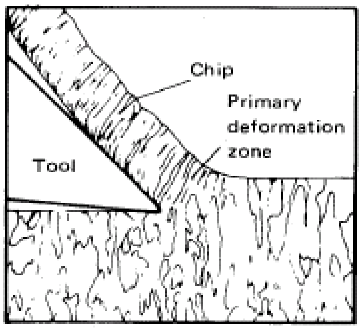

Figure 2.4: Continuous chip (Boothroyd and Knight, 1989).

A built-up edge (BUE) chip is formed when small particles of ductile material adhere to the edge of the cutting tool while the chip shears away, as shown in Figure 2.5. This happened as the result of the high temperature, pressure, and friction resistance to the flow of the chip along the chip-tool interface. BUE grows larger and becomes unstable as the cutting process continues. Eventually it breaks apart where some fragments adhere to the tool-side of the chip; the rest is deposited randomly on the work piece cut surface.

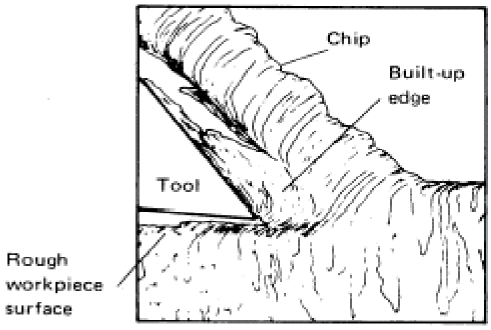

Figure 2.5: Built-up edge chip (Boothroyd and Knight, 1989).