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MODELLING AND EXPERIMENTAL INVESTIGATION OF TOOL WEAR IN ULTRA-PRECISION RASTER MILLING

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Ph.D

The Hong Kong Polytechnic University

2014
Modelling and Experimental Investigation of Tool Wear in Ultra-precision Raster Milling

Zhang Guoqing

A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy

June 2014
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Abstract

Abstract of thesis entitled "Modelling and Experimental Investigation of Tool Wear in Ultra-precision Raster Milling" submitted by ZHANG GUOQING in June 2014 for a doctor of philosophy degree at The Hong Kong Polytechnic University.

Ultra-precision raster milling (UPRM) is a typical intermittent cutting process used to fabricate non-rotational symmetric surface structures with nanometric surface roughness, which has become an essential method for producing precise optical products. However, since wear of the cutting tool in the UPRM process significantly affects the machined surface roughness, it is necessary to determine tool wear characteristics, tool wear effects on the surface roughness, and tool wear on-machine evaluation methods for UPRM.

This thesis provides an account of theoretical and experimental research into tool wear and machined surface roughness evaluation methods in UPRM, and is divided into four parts. In the first part, the research focuses on the exploration of tool wear characteristics and their effects on machined surface quality in UPRM. Each tool wear characteristic and its effect on the machined surface quality are discussed separately according to the observed tool wear characteristic: tool fracture, material welding, flank wear land formation, and sub-wear-land formation.

The second part of the thesis provides an account of tool wear evaluation methods based on cutting forces. An analytic cutting force model and a dynamic model are established to simulate the cutting force pulse and the free vibration of
dynamometer induced by the cutting force pulse. The relationship between cutting force and cutting parameters such as the feed rate and depth of cut, is presented and the power spectrum features of cutting forces at different tool wear stages are explored.

In the third part, tool fracture wear and its effects on the machined surface are evaluated on-machine by using cutting chips. During the UPRM process, tool fractures are directly imprinted both on the cutting chip surface and the machined surface as groups of ‘ridges’. Through inspection of the location and cross-sectional shape of these ‘ridges’ on a cutting chip surface, a virtual cutting edge of the diamond tool under fracture wear, and surface topography considering the effects of tool fracture wear, are developed. A mathematical model is developed to simulate the virtual cutting edge and surface topography with two geometric elements, semi-circle and isosceles triangle, used to approximate the cross-sectional shape of ridges. The mathematical model was also utilized to compute the surface roughness taking into consideration the effects of tool fracture wear.

In the fourth and final part, tool flank wear and its effect on machined surface quality are on-machine evaluated by using cutting chips. The occurrence of tool flank wear truncates the cutting chips at both the tool entry and tool exit sides of the cutting chips. The width of truncation positions of the cutting chip can be measured and used to calculate the width of flank wear land with the help of a mathematical model. The identified width of flank wear land is also used to calculate the surface roughness with the help of a mathematical model. It is found that with the progress of the tool flank
wear, the truncation position in the feed direction moves from two sides to the central position of the cutting chips, meanwhile, the surface roughness decreases at first and then increases significantly.

The originality and significance of this research lies in the provision of a novel method to on-machine evaluate tool wear and its effects on machined surface quality in UPRM. The study contributes to the body of knowledge by: (i) identifying tool wear characteristics and their effects on machined surface roughness in UPRM; (ii) analyzing the cutting force compositions in UPRM and indicating two power spectrum peaks that can be used to evaluate tool wear; and (iii) providing a new method for on-machine evaluation of tool wear characteristics (including both tool fracture wear and tool flank wear) and their effect on machined surface roughness by using cutting chips.
Publications Arising from the Thesis

Journal Papers


Conference Papers


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Chapter 1 Introduction

1.1 Background

1.1.1 Ultra-precision Raster Milling

Ultra-precision machining technology has been widely used in the manufacture of optical products for decades. As a key ultra-precision machining method, single point diamond turning is usually used to fabricate rotational symmetric components (Dow et al., 1991), while for the fabrication of non-rotational symmetric components or freeform surface, ultra-precision raster milling (UPRM) is usually employed (Cheng et al., 2008).

UPRM is also called ultra-precision fly cutting because the diamond tool is installed on the spindle and rotates around the spindle axis circularly while the workpiece is fixed on the rotary table (see Figure 1.1). UPRM is widely used to produce components with non-rotational symmetric surface structures with a nanometric surface roughness without any post-polishing. UPRM with a single crystal diamond cutter can directly produce high quality surfaces and precise optical products (Zhang and To, 2013a). For example, freeform components and optical structures such as F-theta lenses, V-groove, pyramid structures can be directly milled with nanometric \((10^{-6}\text{mm})\) surface finishing and sub-micrometric \((10^{-4}\text{mm})\) form accuracy.

In UPRM, the feed direction and the step direction are perpendicular to each other at all times, hence the machined surface can be generated by the imprints of the diamond tool profile at a certain interval of feed rate as well as certain interval of step
distance. The two basic cutting strategies in the UPRM process are vertical and horizontal cutting, with their cutting direction perpendicular to each other.

![Figure 1.1 Schematic configuration of (a) Precitech Freeform 705G (Precitech Ltd.co. USA) and (b) Experimental setup](image)

To realize freeform cutting, the cutting machine should have at least three axes (Merdol and Altintas, 2008; Feng and Li, 2002) but usually has five axes so that it can cut complex components (Balasubramaniam, 2000; Lee and She, 1997; Xu et al., 2002). Freeform 705G is a UPRM machine, produced by Precitech in the USA, which can realize three-dimensional non-axisymmetric milling and grinding, as well as optional two-axis diamond turning. It can realize freeform and micro-structures cutting with sub-micro level form accuracy and nano level surface roughness.

### 1.1.2 Tool Wear

Tool wear reflects the cutting tools’ gradual failure during the metal cutting. In the metal cutting, with the growing cutting distance, the occurrence of tool wear is inevitable, even for a cutting tool made of very hard materials like diamond and cubic boron nitride. Tool wear form can be classified into 5 categories in conventional
cutting (Shaw, 1984): Nose wear, tool face wear, wear-land wear, cratering, and plastic flow.

According to ISO 3685:1993, flank wear is the most commonly used measure of tool wear and is classified by Stephenson and Agapiou (2006) into three stages: initial wear, steady wear, and severe wear (see Figure 1.2). The flank wear of a cutting tool is particularly important since it can depict the tool’s life.

![Flank tool wear curve](image)

Figure 1.2 Flank tool wear curve (Stephenson and Agapiou, 2006)

The occurrence of tool wear in the cutting increases cutting forces and cutting temperatures, and leads to poor machined surface finish and surface form accuracy (Choi, 2010; Masuda et al., 1989). Flank wear and micro-chipping increases the friction and contact area between cutting tools and workpiece, which results in the increase of cutting force. Flank wear affects the form accuracy of a component while micro-chipping increases the component’s surface roughness. It is therefore important to use lubricants and coolants to decrease cutting friction and temperature so as to reduce the occurrence of cutting tool wear.

In ultra-precision diamond machining, although diamond tools are extremely hard, the occurrence of tool wear is still inevitable (Lane et al., 2013; Ge et al., 2010;
Lane et al., 2010;). The crystallographic structure of diamond is a key factor in diamond tool wear because, as a single crystal, the yield strength of a diamond depends on its crystal orientation. Under the effect of outside pressure a diamond easily collapses along the surface parallel to the \( \{111\} \) plane, a phenomena known as octahedral cleavage; the mechanical aspect of diamond tool wear is thought to be caused by this phenomena.

From the foregoing discussion, it is concluded that better recognition of tool wear characteristics and a new method to realize on-machine evaluation of tool wear as well as the machined surface roughness are needed.

1.2 Research Objectives and Significance

This research explored tool wear characteristics and their effects on machined surface quality in UPRM. It also developed tool wear characteristics and machined surface roughness on-machine evaluation methods based on cutting force and cutting chips. The main objective of the study was to develop a novel and efficient method to evaluate and measure in-process tool wear in UPRM. The specific objectives of this study were to:

(1) Explore tool wear characteristics and their effects on the machined surface roughness in UPRM.

(2) Explore the cutting force compositions in the UPRM process by building a model to predict and simulate the cutting force in UPRM, to detect the relationship between Power Spectral Density (PSD) of cutting force and tool wear characteristics.
(3) Provide a new tool fracture wear evaluation method based on cutting chips, by which the tool fracture wear characteristics and their influence on the surface roughness can be evaluated.

(4) Present a novel tool flank wear evaluation method, by which tool flank wear and their effects on the surface roughness can be evaluated based on the relations of tool flank wear and cutting chips.

The research is meaningful since it can be used to on-machine evaluate tool wear and their effects on machined surfaces without the need to stop the cutting process, and remedy a deteriorated surface in a timely manner so as to improve cutting efficiency. In addition, the data generated from the research in relation to tool wear and cutting force characteristics provides a reference for other intermittent machining processes.

1.3 Organization of the Thesis

The thesis focuses on methods for on-machine evaluation of tool wear and machined surface quality in UPRM and is organized into seven chapters as follows.

Chapter 1 indicates the motivation background, significance and objectives of the study. Chapter 2 gives a comprehensive literature review that summarizes previous research on relevant topics such as ultra-precision machining technologies, diamond tool wear characteristics, diamond tool wear mechanisms, tool wear monitoring methods, tool wear detection using cutting force, tool wear and chip morphology, and surface generation in UPRM. Chapter 3 explores tool wear characteristics and their effects on machined surface quality in UPRM, including the effect of the different tool
wear stages and patterns on the machined surface roughness, cutting chip morphology, and cutting force. Chapter 4 establishes a cutting force model and a dynamic vibration model for interpreting the cutting force composition in UPRM and for assessing the relations of cutting force and tool wear at different tool wear stages. Chapter 5 describes the development of a novel tool fracture wear evaluation method based on the fact that tool fracture wear is imprinted both on cutting chip surface and machined surface; mathematically simulated results of tool fracture wear and surface topography are verified by examining the cutting chips. Chapter 6 establishes a mathematical model to calculate the width of flank wear and the machined surface roughness based on the width of cutting chips, and verifies the predicted results with experimental results. Finally, Chapter 7 provides a conclusion to the study and some suggestions for further related study.
Chapter 2 Literature Review

2.1 Ultra-precision Machining Technologies

2.1.1 Overview

According to achievable accuracy, machining processes can be divided into three categories: conventional machining, precision machining, and ultra-precision machining. Among them, the ultra-precision machining process provides the best possible dimensional accuracy and surface roughness. Taniguchi (1983) defined ultra-precision machining as a process by which the highest surface finish and dimensional accuracy on the workpiece material are achieved at a given period. Therefore, ‘ultra-precision’ is a time dependent term and its meaning changes with the enduring pursuit for higher accuracy (Riemer, 2011). Figure 2.1 reveals the achievable machining accuracy evolution over the past decades.

![Figure 2.1 Achievable machining accuracy (Taniguchi, 1983)](image-url)
Ultra-precision machining technology has a technical tradition spanning over forty years. It generated from the US Government Weapons Laboratories in 1970’s (Saito et al., 2003). At that time, ultra-precision machining was limited to fabricating high-quality components for equipment used in advanced science, aerospace, and defense. Since the 1980’s, the technique has been used for the fabrication of precision medical components, as well for automotive, astronomy, illumination, optic, metrology, telecommunication, and electronic products. The ultra-precision machining process and the application of its technology to products are illustrated in Figure 2.2.

![Figure 2.2](image)

Figure 2.2 (a) Ultra-precision machining process (b) Application to products

Unlike conventional machining, diamond is used as the cutting tool material in the ultra-precision machining process due to its preferable material property. In ultra-precision diamond machining, a large number of engineering materials such as non-ferrous metal, ceramics, glasses plastics and even silicon can be machined (Choi et al., 2007; Yan et al., 2003; Endo et al., 1993). Surface structures like flat surface, freeform surface, v-groove, pyramid arrays can be fabricated during the cutting process (Kong and Cheung, 2012a; Kong and Cheung, 2011; Kim and Loh, 2007). Therefore, ultra-precision machining technology has become an essential method to
obtain products with very high quality surface finish both for military application and civilian application.

Ultra-precision machining technology includes two key machining technologies:

(1) Single-point diamond turning (SPDT)

(2) Ultra-precision raster milling (UPRM)

### 2.1.2 Single-point Diamond Turning (SPDT)

According to Ikawa et al. (1991), single-point diamond turning (SPDT) is a machining process taking use of a single crystal diamond tool, which possesses nanometric edge sharpness, wear resistance, and form reproducibility. In single-point diamond turning, the workpiece is rotating with the chunk while the diamond tool is fixed on the tool holder. SPDT is widely used to manufacture high-quality symmetric optical components with a range of non-ferrous materials like aluminum, copper, brass, electroless nickel and so on. The machined surface finish of these workpiece materials can get to nanometric range without the need for any additional polishing (Cheung and Lee, 2001). Optical components produced by SPDT are widely used in telescopes, microscopes, lasers, and scientific research instruments.

However, it is hard for SPDT to fabricate optical components with micro-lens array on the machined surface or freeform surface. In this situation, fast tool servo (FTS) and slow tool servo (STS) are used to realize this operation. The FTS is an assistive technology for SPDT whereby a controller provides tool position commands for the FTS at frequencies up to several kHz. The axial position of the tool is real-time calculated with the use of high-resolution linear position feedback of the translational
slide and the angular feedback of the spindle. As is shown in Figure 2.3, the FTS systems can be used for diamond turning of complex surface structures such as lens arrays, off-axis aspheres, micro prisms, and torics (Lu et al., 2014; Yu et al., 2012).

![Figure 2.3](image)

Figure 2.3 (a) FTS system (b) the micro-lens array machined by this system

The slow tool servo (STS) is another assistive technology for single point diamond turning (Yin et al., 2011). The STS depends on the slide of machine tools to drive the tool holder synchronous with the cross slide and rotation of the spindle, which creates a system that can perform large departures at slower speeds (see Figure 2.4). Differs from the FTS, in the STS, the tool position is calculated and commanded as motion in three-coordinated-axis on the controller. STS has the capability to fabricate complex surface structures, such as aspheres, torics and large sagitta workpieces, without the need to incorporate any additional devices to the standard two-axes lathe.
2.1.3 Ultra-precision Raster Milling (UPRM)

Ultra-precision raster milling (UPRM) is another machining method to fabricate precise products that can be used to fabricate non-rotational symmetric components with sub-micron surface accuracy and nano metric surface roughness. Previous studies related to UPRM mainly focused on surface generation (Cheng et al., 2008), error compensation (Kong and Cheung, 2012b) and the effects of spindle vibration on the surface topography (Zhang and To, 2013b). However, there has apparently been no research on the evaluation of tool wear and its effect on surface roughness.

In the UPRM process, contact between the workpiece and diamond tool is discontinuous and is closely related to the depth of cut and swing distance. In general, the cutting angle $\alpha$ is a mere 1~3 degree in every rotary circle (360 degree), while in most sections of the rotary circle the spindle is idling. Therefore, ultra-precision raster milling process is a typical intermittent cutting process (Zhang et al., 2014a). The intermittent cutting process will apply cyclic cutting and thermal impact stresses onto
the diamond tool. Thus, the diamond tool’s cutting condition and stress state in UPRM is greatly different from those in conventional cutting and single point diamond turning with continuous contact between the diamond tool and workpiece. Also the property of discontinuous cutting in UPRM make the cutting tool more difficult to be monitored compared to conventional cutting and single-point diamond turning (Yin et al., 2009). Therefore, it is meaningful to develop a new method to on-machine evaluate tool wear and its effect on the machined surface roughness.

2.2 Diamond Tool Wear Characteristics

2.2.1 Tool Wear Characteristics

The study of tool wear is an essential topic in ultra-precision machining. A better understanding to the wear mechanism of cutting tools is key to suppressing wear and enhancing tool life (Goel et al., 2013). In addition, cutting tools are the direct executor to form a desired surface topography. In the surface forming process the tool profile is directly imprinted on the machined surface, hence the wear of cutting tools can affect the machined surface quality.

Diamond tool wear characteristics present different patterns when cutting different workpiece materials. For example, Oomen and Eisses (1992) studied the wear behavior of diamond tools whilst cutting some nonferrous metals like copper, aluminum, and electroless nickel et al. They found that the workpiece material seriously affected the wear behavior of diamond tools and that all types of diamond show nearly the same wear degree when machining aluminum. However, much
subtler wear characteristics were found when machining copper and electroless nickel. Li et al. (2005) revealed that tool wear started with the occurrence of Nano-scale grooves on the tool clearance face when cutting silicon wafer. Ge et al. (2010) indicated that chipping, microwear, abrasive wear, chemical wear, and cleavage were the dominant wear characteristics for a single crystal diamond tool when turning SiCp/2009 Al matrix composite. Goel et al. (2012) revealed that during the single point diamond turning of silicon, a relatively high tool flank temperature causes more wear on the flank face as comparing to the rake face of cutting tool. In addition, they found that the wear mechanism of diamond tools as cutting silicon is chemical wear and the subsequent abrasion. Yan et al. (2003) conducted research on the diamond tool wear characteristics when cutting single-crystal silicon and found that the tool wear when cutting silicon include two types: (1) microchippings that occur in the brittle mode cutting, and (2) gradual wear including crater wear and flank wear land that occurs in the ductile mode cutting. However, according to ISO 3685:1993, diamond tool wear is typically evaluated by counting the width of the tool’s flank wear land (VB) (Cardenas et al., 2007). In ultra-precision machining, different rates of diamond tool wear depend on the chemical and physical properties of the workpiece material. Diamond tool wear mechanisms can be either chemical or abrasive, or their combination. Lane et al. (2010) conducted research to explore the wear characteristics of a diamond tool when cutting 6061 aluminum and 1215 steel. In their experiment, the diamond tool wear was evaluated using the deposition method induced by electron beam. Experimental results show that the wear land angle when diamond turning of
6061 aluminum and 1215 steel is different: the wear land angle is parallel to the machined surface for 6061 aluminum; however, for 1215 steel, the wear land has an angle with respect to the machined surface instead of being parallel to it.

During UPRM process, the diamond tool rotates relative to the spindle at a high speed, cutting into and out of workpiece surface intermittently. The cutting tool material and cutting mechanism in the UPRM process can delay the occurrence tool wear since the diamond material has excellent mechanical properties e.g. low friction coefficient and extreme hardness, and the discontinuous cutting reduces the contact time between the diamond tool and workpiece thereby helping with heat dispersion and suppressing the occurrence of tool wear (Song et al., 2009). Until now, little attention has been paid to tool wear in UPRM. Yin et al. (2009) conducted the most comprehensive research to date into the tool wear characteristics in UPRM and concluded that fractures or micro chipping is the predominant tool wear characteristics due to the impact effects of the UPRM process. However, their research focused on the early stage of tool wear only whereas the research that formed the basis of this thesis found other tool wear characteristics as a result of investigating all the stages of tool ware in UPRM.

2.2.2 Effect of Tool Wear on the Machined Surface Roughness

In the ultra-precision machining process, cutting tools are the direct executors to form a desired surface topography. The tool nose geometry can be directly imprinted on the machined surface. Therefore, the occurrence of tool wear can definitely affect the machined surface quality. With the tool wear progress, some micro chippings or
craters occur on the cutting edge, and a ploughing process rather than the cutting process happens. This will change the tool nose geometry and be imprinted on the machined surface to deteriorate the machined surface roughness.

Therefore, the study of tool wear and its effects on surface finish is an essential topic in the field of ultra-precision machining (Kılıçkap et al. 2005; Ozel and Karpat, 2005; Benardos and Vosniakos, 2003). A good understanding of tool wear effect on surface finish is essential to improving machined surface quality (Karim et al., 2013). The occurrence of tool wear has multiple effects during the cutting process. For example: tool flank wear effect on thermal damage, cutting mechanics and heat transfer in finish hard tuning was explored by Wang et al. (1999); and Liu et al. (2004) concluded from their research that tool nose radius affects residual stress distribution significantly in hard turning of bearing steel JIS SUJ2, especially at the early stage of the cutting process. Certainly, tool flank wear can affect the surface finish during the cutting process.

Most previous studies focused on the tool wear effect on machined surface roughness. For example: Grzesik (2008) carried out a study to explore the effects of tool wear on machined surface roughness by using different ceramic cutting tools in hard turning; Penalva et al. (2002) studied the influence of tool wear on the machined surface quality in hard turning and concluded that plastic deformation of the cutting tool exists in the early stages while gradual abrasion recedes the cutting edge, both of which are replicated on the roughness profile; Pavel et al. (2005) confirmed that a negative flank wear is imprinted on the machined surface in continuous and
interrupted hard turning, and observed that a strong correlation is existed between the evolution of notch wear and the evolution of surface roughness; Li et al. (2008) found from milling OFHC Copper with 0.1 mm diameter micro end mills that tool wear can significantly affect the machined surface roughness, and that in some cases the Ra values increase several times with progressive tool wear; Nabil and Mabrouk (2006) found that, when turning AISI 1045 carbon steel, standard deviations related to surface roughness and tool flank wear grows exponentially with respect to cutting time; Jia and Zhou (2012) found from a series of experiments that flank wear is dominant in diamond cutting of glass, that wear land is observed as micro-grooves and craters on the rake face of the cutting tool, that surface roughness under the occurrence of tool wear increases fast as the cutting mode transfer from ductile cutting to brittle cutting, and that the main tool wear mechanisms in diamond turning of glass are summarized as diffusion, thermo-chemical action, and abrasive wear; Ozel et al. (2005) proposed a predictive model for tool wear and surface quality and utilized artificial neural network to predict surface roughness and tool flank wear at variety of cutting conditions in finished hard turning; Zeng et al. (2009) utilized real surface characterization, a real auto-correlation function (AACF), and pattern analyses to predict and monitor the influence of tool wear on the workpiece surface; and Ali et al. (2010) developed an artificial neural network (ANN) model to predict surface roughness and tool wear in relation to cutting parameters.
2.3 Diamond Tool Wear Mechanisms

2.3.1 Mechanical Tool Wear Mechanisms

In the diamond cutting process, the degree of diamond tool wear is closely related to the workpiece material. Materials suitable for diamond cutting are currently limited to nonferrous materials such as copper, aluminum, and electroless nickel. However, for cutting some other materials like ferrous materials, silicon, silicon carbide etc., the diamond tool wear is not neglected. Diamond tool wear during the cutting of different materials may be caused by different wear mechanisms, which can be classified into two types: mechanical wear and thermal-chemical wear.

A lot of research has been conducted into the mechanical wear of diamond tools. Yan et al. (2003) classified mechanical tool wear as gradual wear and micro-chippings, and presented that the dominant wear mechanism depends on the undeformed chip thickness. Yen et al. (2004) reviewed prior work related to the modeling of tool wear with different empirical and theoretical models, which revealed various wear mechanisms, including abrasive, adhesive and diffusive wear. Zhou et al. (2006) proposed that microchipping and cleavage were the dominant tool wear mechanisms in diamond turning. Goel et al. (2013) conducted a molecular dynamics simulation to explore diamond tool wear mechanisms when cutting single crystal silicon using the single point diamond turning (SPDT), and found from the radial distribution that the silicon carbide was formed at the contact interface thereby indicating wear of the diamond tool. Uddin et al. (2004) investigated the wear patterns of single point diamond tools and effects of the crystallographic orientation of diamond through
experimental method, and indicated that: (i) gradual wear mainly occurs on the tool’s flank face; (ii) a smooth wear mark was seen on the tool’s rake face; and (iii) the machining data indicate that tool wear resistance and tool life were bigger as the rake face’s crystallographic orientation of diamond tool was \{1 1 0\} compared to \{1 0 0\} or \{1 1 1\}.

2.3.2 Thermal-Chemical Tool Wear Mechanisms

Paul et al. (1996) ascribed the diamond tools’ thermal-chemical wear to the missing of unpaired “d” electrons in the material being cut. Their hypothesis is utilized to explain the tool wear results as cutting alloys, metals, and "electroless" nickel, which is shown in Table 2.1 above. The hypothesis was further verified by the

<table>
<thead>
<tr>
<th>Element</th>
<th>Melting point, °C</th>
<th>Crystal structure</th>
<th>Microhardness, Brinell, kg/mm²</th>
<th>No. of unpaired d-shell electrons</th>
<th>Diamond turnable?</th>
<th>Yes/No</th>
<th>Refs</th>
</tr>
</thead>
<tbody>
<tr>
<td>In Indium</td>
<td>157</td>
<td>t</td>
<td>10</td>
<td>0</td>
<td>Y</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Sn Tin</td>
<td>232</td>
<td>f</td>
<td>9</td>
<td>0</td>
<td>Y</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Pb Lead</td>
<td>373</td>
<td>f</td>
<td>0.022</td>
<td>5</td>
<td>Y</td>
<td>6,7</td>
<td></td>
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<tr>
<td>Zn Zinc</td>
<td>420</td>
<td>h</td>
<td>51</td>
<td>0</td>
<td>Y</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Pu Plutonium</td>
<td>640</td>
<td>m</td>
<td>0</td>
<td>Y</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mg Magnesium</td>
<td>649</td>
<td>h</td>
<td>30</td>
<td>48</td>
<td>Y</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Al Aluminum</td>
<td>660</td>
<td>f</td>
<td>25</td>
<td>0</td>
<td>Y</td>
<td>6,7</td>
<td></td>
</tr>
<tr>
<td>Ge Germanium</td>
<td>937</td>
<td>d</td>
<td>721</td>
<td>0</td>
<td>Y</td>
<td>6,7</td>
<td></td>
</tr>
<tr>
<td>Ag Silver</td>
<td>962</td>
<td>f</td>
<td>96</td>
<td>0</td>
<td>Y</td>
<td>6,7,46</td>
<td></td>
</tr>
<tr>
<td>Au Gold</td>
<td>1064</td>
<td>f</td>
<td>96</td>
<td>0</td>
<td>Y</td>
<td>6,7,46</td>
<td></td>
</tr>
<tr>
<td>Cu Copper</td>
<td>1083</td>
<td>f</td>
<td>76</td>
<td>0</td>
<td>Y</td>
<td>46</td>
<td></td>
</tr>
<tr>
<td>U Uranium</td>
<td>1132</td>
<td>o</td>
<td>245</td>
<td>1</td>
<td>N</td>
<td>47</td>
<td></td>
</tr>
<tr>
<td>Mn Manganese</td>
<td>1244</td>
<td>b</td>
<td>384</td>
<td>5</td>
<td>N</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Be Beryllium</td>
<td>1277</td>
<td>h</td>
<td>60</td>
<td>0</td>
<td>Y</td>
<td>**,†,‡,46</td>
<td></td>
</tr>
<tr>
<td>Si Silicon</td>
<td>1410</td>
<td>d</td>
<td>1211</td>
<td>0</td>
<td>Y†</td>
<td>x,5,7,y</td>
<td></td>
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<tr>
<td>Ni Nickel</td>
<td>1453</td>
<td>f</td>
<td>189</td>
<td>2</td>
<td>N</td>
<td>23,47</td>
<td></td>
</tr>
<tr>
<td>Co Cobalt</td>
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<td>h</td>
<td>100</td>
<td>247</td>
<td>N</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>Fe Iron</td>
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<td>b</td>
<td>50</td>
<td>4</td>
<td>N</td>
<td>47,y,‡</td>
<td></td>
</tr>
<tr>
<td>Ti Titanium</td>
<td>1660</td>
<td>h</td>
<td>75</td>
<td>142</td>
<td>N</td>
<td>23,47,y</td>
<td></td>
</tr>
<tr>
<td>Cr Chromium</td>
<td>1857</td>
<td>b</td>
<td>63</td>
<td>250</td>
<td>N</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>V Vanadium</td>
<td>1890</td>
<td>b</td>
<td>248</td>
<td>3</td>
<td>N</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>Rh Rhodium</td>
<td>1966</td>
<td>f</td>
<td>2</td>
<td>N</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ru Ruthenium</td>
<td>2310</td>
<td>h</td>
<td>3</td>
<td>N</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nb Niobium</td>
<td>2468</td>
<td>b</td>
<td>75</td>
<td>128</td>
<td>N</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Mo Molybdenum</td>
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<td>b</td>
<td>162</td>
<td>192</td>
<td>N</td>
<td>23,47</td>
<td></td>
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<tr>
<td>Ta Tantalum</td>
<td>2996</td>
<td>b</td>
<td>70</td>
<td>3</td>
<td>N</td>
<td>47</td>
<td></td>
</tr>
<tr>
<td>Re Rhenium</td>
<td>3180</td>
<td>h</td>
<td>250</td>
<td>319</td>
<td>N</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>W Tungsten</td>
<td>3410</td>
<td>b</td>
<td>348</td>
<td>4</td>
<td>N</td>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>
machining of several high purity elements. Shimada et al. (2000) suggested that the tool wear in the diamond turning of copper is effective to be suppressed by using a reduced oxygen atmosphere, while Attanassio et al. (2008) studied the diffusive wear in 3D simulation of turning steel.

In ultra-precision machining technology, steel (one of the ferrous materials) is the best common mold die material. However, the tool wear between diamond tool and steel workpiece is severe. Some researchers ascribe this phenomenon to the affinity between diamond and steel. However, this cannot essentially interpret the reason why diamond tool wear happens when cutting ferrous material. Although much research has been undertaken on this topic, it is still not clear why the diamond tool will be worn when cutting ferrous material. However, there is agreement that the diamond tool wear when cutting ferrous materials can be seen as an integration of mechanical wear, thermal-chemical wear, and diffusion, with thermal-chemical wear dominant. Tanaka (1973) found that in the single crystal cutting of steel, the diamond exhibits an increasing wear rate with the decrease of carbon content in the workpiece, and that the highest wear rate found was in the cutting of pure iron although it is softer than the carbon steel. The results reveal that mechanical wear mechanisms are not dominant when diamond cutting ferrous material. Shimada et al. (2004) conducted an erosion experiment to simulate the diamond tool wear process when machining ferrous metals. The results reveal that due to the interaction with the iron surface, dissociation of carbon atoms on the diamond surface is the dominant wear mechanism at a cutting temperature higher than 1000K. However, at a cutting temperature lower
than 900K, due to oxidization of diamond accompanied by that of iron oxide, the wear mechanism is classified into the removal of carbon atoms. Narulkar et al. (2009) proposed a diamond tool wear mechanism involving the transformation of diamond into graphite and the carbon diffusion into iron workpiece being cut. The forgoing discussion suggests that the thermal-chemical wear mechanism is dominant when diamond cutting ferrous materials.

2.3.3 Tool Wear Suppressing Methods

Researchers have tried different methods to reduce diamond tool wear when cutting ferrous materials. Nitriding is an effective method that modifies the workpiece material by a thermochemical process to bond the unpaired electrons in the “d” shell of the iron, which are thought to be responsible for the diamond tool wear. Nitriding produces a thin film beneath the surface of the workpiece in which the iron atoms and the nitrogen atoms will build iron nitride to form a compound layer at the surface where all the iron is bonded to nitrogen; the chemical reactive electrons in the “d” shell of iron are bonded to these nitrides and so diamond tool wear is considerably reduced when cutting steel. Wang et al. (2011) utilized plasma nitriding treatment to reduce the rapid tool wear in diamond cutting of steel and found that severe chemical tool wear was suppressed significantly after plasma nitriding treatment. After cutting, a surface roughness of 20 nm root-mean-square (RMS) with mirror-quality was achieved under the cutting distance about 5.4 km. Intermittent cutting process is another method to suppress tool wear in diamond turning of steel and other ferrous materials. Song et al. (2009) proposed that the contact time between the diamond tool
and the steel in the cutting process is crucial for diamond tool wear. Through reducing the contact time by intermittent cutting such as milling or fly-cutting, single point diamond tool can be successfully used to cut steel. Moriwaki et al. (1991) utilized ultrasonic vibration at a frequency of 40 kHz to the single point diamond tool along the cutting direction to realize the ultra-precision diamond turning of stainless steel; a surface roughness with Rmax less than 0.03 μm was obtained in their experiment. Shamoto et al. (2007) took elliptical vibration cutting in comparison with the conventional vibration cutting. The experimental results showed that elliptical vibration cutting has excellent performance, i.e. high quality surface finish, small cutting force and long tool life. There are also some other methods for reducing diamond tool wear when cutting steel, such as Casstevens et al.’s (1983) suggested that diamond turning of steel can effectively reduce diamond tool wear in carbon-saturated atmospheres; and Dhar et al. (2001) who significantly reduced tool wear rate, surface roughness and dimensional inaccuracy by cryogenic cooling using a liquid nitrogen jet in the plain turning of AISI 1040 and E4340C steel.

2.4 Tool Wear Monitoring Methods

2.4.1 Direct Tool Wear Detection Methods

Many methods have been used to monitor diamond tool wear in the cutting process so as to identify the occurrence of tool wear in a timely manner. The methods can be divided into two categories: direct tool wear monitoring methods, and indirect tool wear monitoring methods.
Direct tool wear monitoring methods are mostly optical: Optical microscope (Sortino, 2003), Computer vision (Kerr et al., 2006), CCD camera (Jurkovic et al., 2005), and SEM (Zhang et al., 2011). In optical methods, streaming images will be captured by CCD camera or microscope with a magnifying lens set against the diamond tool. The digital image will be processed to reconstruct the 3D topographic surface so that tool wear can be monitored in real time. By using this method, through digital image processing and digital signal processing, the relationship between tool wear and surface quality can be established, which can then be used to predict the surface integrity of the component without the need to measure the surface directly.

For example: Jeon et al. (1988) developed an optoelectronic method to monitor tool flank wear based on vision technology in real time, whereby the tool is illuminated by a laser beam, the wear zone is visualized using a Vidicon camera, and the captured image is converted into digital pixel data so that it can be processed and used to present the wear land width; Choudhury et al. (1999) utilized an optoelectronic sensor in conjunction with a multilayered Neural Network to evaluate the tool flank wear; Sortino et al. (2003) adopted a method of statistical filtering to optically detect the occurrence of tool wear; Wang et al. (2005, 2006) utilized optical methods to directly measure the flank wear of diamond tools; and Castejón et al. (2007) proposed a new method to evaluate the tool wear level to identify the tool life based on a computer vision and statistical learning system.

2.4.2 Indirect Tool Wear Monitoring Methods

In some cases it is difficult to monitor diamond tools by direct methods because
diamond tools are usually covered by chips during the cutting process. Therefore, researchers have tested many indirect tool wear monitoring methods. Indirect monitoring methods involve monitoring tool wear during the cutting process through indirect signals that can reflect the gradually wear of cutting tools. Many signals have been utilized to monitor the occurrence of diamond tool wear, such as tool force signals (Thamizhmanii et al., 2010; Tansel et al., 2000), acoustic emission signals (Patra and IAENG, 2011; Teti, 1989), feed current (Li, 2001), and power consuming (Shao et al., 2004). Based on these cutting signals, many tool wear monitoring systems have been established: Salgado et al. (2007) presented an online tool condition monitoring system (TCMS) by monitoring the feed motor current and the sound signal; Alonso et al. (2008) developed a reliable TCMS based on the processing and analysis of the composition of the captured tool vibration signals; Lin et al. (1995) utilized force signals to achieve on-line drill wear monitoring; and Lee et al. (2002) utilized acoustic emission (AE) to monitor the cutting process. Many kinds of sensors were used to detect the desired signals in the aforementioned monitors, such as dynamometer (Ertunc et al., 2004), computer vision (Lanzetta et al., 2001), motor spindle speed and power consumption (Tauno et al., 2000), and simultaneous vibration and strain measurements (Scheffer et al., 2001). Researchers also utilized different methods to process signals, as is shown in Figure 2.5. Although Fast Fourier Transform (Noh and Hong, 2011) is the most common method used for processing detected signals, there are also many other methods such as power spectrum analysis (Szwajka and Gorski, 2006), singular spectrum analysis (SSA) (Kilundu, 2011;
Salgado et al., 2006), wavelet analysis (Choi et al., 2004; Gong et al., 1997), and statistical methods (Jaharah et al., 2010).

Figure 2.5 Different methods used for processing signals (Salgado et al., 2006)

In addition to detecting diamond tool wear, an integrated monitoring system should also be able to predict the machined surface quality. Although much meaningful research has been conducted in this area (Azmi et al., 2013; Rizal et al., 2013; Palani and Natarajan, 2011; Palanisamy et al., 2008), relatively little research has been focused on the monitoring of tool wear in UPRM. This may be because the diamond tool is continuously rotating during the UPRM process and the characteristics of discontinuous cutting make the cutting tool more difficult to be monitored when compared with conventional cutting and single point diamond turning.

2.5 Tool Wear Monitoring Using Cutting Force

2.5.1 Cutting Force Model

Cutting force is a very important signal, which can be used to help in exploring
the fundamental cutting mechanisms and to detect tool wear in the cutting process. The analysis of cutting force cannot be executed without a cutting force model. In cutting force modeling, a considerable amount of research has focused on the creation of a feasible cutting force model for single point diamond turning and conventional machining processes. Merchant (1945) proposed an orthogonal cutting force model, as illustrated in Figure 2.6. This model is used to predict cutting force based on cutting parameters and cutting conditions like shear angle, rake angle, and friction coefficient etc. However, Merchant did not consider material spring back in his model. Researchers later developed a large number of cutting force models for continuous cutting in which the material spring back and its rebound force on the flank face of diamond tools are considered. For example, Foe et al. (1988) developed a cutting force model, in their model the rebound force on the flank face of diamond tools was considered. Drescher (1992) revealed in his PhD dissertation that the normal force component in the orthogonal cutting process is mainly originated from the material spring back. Wang et al. (2004) proposed a cutting force model considering the force system characteristics and tool geometry in which the forces imposing on the cutting edge, the rake face, and the clearance face of diamond tools were explored. Sumet et al. (2010) developed a cutting force model for orbital single-point micro machining based on property of high frequency micro-orbital cutting.
Due to the efforts of researchers, cutting force models for single point diamond turning and conventional machining are becoming increasingly sophisticated and cutting force models for particular materials are now available. For example, Pramanik et al. (2006) proposed a model to predict the cutting force as diamond turning of aluminum-based SiC/Al2O3 particle reinforced MMCs. Based on their model, the generation of cutting force was attributed to three factors: the ploughing force, the particle fracture force, and the chip formation force. He et al. (2006) proposed an analytical model to predict the cutting force in the hard turning of 51CrV4. In addition, some researchers have explored the relations between cutting force and cutting parameters, e.g. Kamely et al. (2011) investigated the effect of cutting tool materials on cutting force in hard turning of AISI D2 cold work tool steel and found that cutting force is directly affected by the cutting tool material. Saglam et al. (2007) thought cutting speed have some effects on cutting force components and the generated temperature on the tool tip.
Moreover, a large body of research has been developed to model the cutting force for conventional or micro end milling process (Zaman et al., 2006; Bouzakis et al., 2003). Martellotti et al. (1941) were among the first to analyze the cutting force in the milling process, but it was not until over three decades later that Tlusty et al. (1975) derived their model to express cutting force as a function of cutting area, chip thickness, and specific cutting force. A decade later, Yellowley (1985) developed a cutting force model where the cutting force acted on the cutting edge was decomposed into flank and rake face components. In recent years, researchers have conducted research on cutting force modeling in micro milling process. For example, Dow et al. (2004) developed a cutting force model to predict the cutting force in both the feed and thrust directions in the micro milling process by using an open-loop technique. Kang et al. (2007) developed a mathematical model to simulate the cutting force in micro milling process in which the contact of cutting tool and workpiece and the effect of the cutting edge radius are considered. Moreover, researchers like Fontaine et al. (2007a, 2007b, 2006) and Wei et al. (2011) have carried out some research on cutting force modeling for the ball end milling. However, there apparently has been no research on the modeling of cutting forces in UPRM.

2.5.2 Tool Wear Monitoring

The monitoring of tool wear using cutting forces have been drawn many researchers’ attention. For example, Belmontea et al. (2004) investigated the evolution of the cutting forces in dry turning of sintered hard metal (WC-25 wt.%Co) with the tool wear of chemical vapor deposition (CVD) diamond brazed tools. In their
investigation, the effect of the feed rate, cutting speed, and cutting depth on the cutting forces is detected and an explicit relationship between the cutting forces, tool wear, and the quality of machined surface was found. Huang et al. (2007) developed a tool wear monitoring system based on a well-designed observer model. By using the observed variables and cutting force, the tool wear monitoring system can help to suppress the tool wear and keep the cutting tools in well working condition. Kuljanic and Sortino (2005) developed a tool wear indicator by analyzing the characteristics of the cutting force signals captured by using a rotating dynamometer. Through the indicator, any tiny disturbance of cutting force signals can be found and analyzed to detect the wear of diamond tool in face-milling. However, the existence of background noise or other unexpected vibration in the captured cutting force signals makes the extraction of the useful information well correlated with tool wear difficult. Therefore, current research interests are focused on the investigation of the analysis methods of cutting force including wavelets (Zhu et al., 2009; Li, 1998), singular spectrum analysis (Kilundu et al., 2011; Salgado and Alonso, 2006), and power spectrum analysis (Liu et al., 2011; Sze, 2006). These analysis methods can be used to extract useful information from cutting force signals and evaluate tool wear characteristics. However, little research has been conducted on monitoring tool wear in UPRM. This is because the diamond tool rotates with high speed during the UPRM process, the intermittent cutting property makes the cutting tool more difficult to be monitored (Zhao et al., 2009).
2.6 Tool Wear and Chip Morphology

2.6.1 Chip Formation in the Cutting Process

Cutting chip morphologies in cutting are affected by the combined effects of tool geometry, cutting parameters and even material properties. It is essential to investigate the mechanism of chip formation since it is related to the surface integrity and machining process optimization. Therefore, a lot of research has been focused on the chip formation in different kinds of cutting process by using both experiment and simulation methods. Simulation methods can simulate cutting process and predict the chip formation process with low-expense. The most used simulation method in chip formation has been the Finite Element Method (FEM). For example, Ceretti et al. (1999) conducted a FEM simulation on the formation of serrated chip in orthogonal cutting. Their research indicated that the customized FEM model is effective for: (i) the prediction of chip morphologies and the effects of cutting conditions on chip shapes, and (ii) the prediction of cutting forces and process parameters. Bouzakis et al. (2008) presented an integrated procedure for simulating the complicated chip generation and material flow in gear hobbing process. Guo and Yen (2004) presented a new method to predict the discontinuous chip morphologies in high-speed machining of AISI 4340 (32 HRc). They successfully conducted the simulation of discontinuous chips formation using the general commercial FEA code, the progress of discontinuous chip generation and its corresponding von Mises stress contours is shown in Figure 2.7. Kountanya et al. (2009) performed a group of experiments with
varying tool geometry parameters and cutting conditions together with finite element simulations to investigate the effects of two mechanisms proposed in the literature: \textit{SCH} (surface shear-cracking) and \textit{CTI} (catastrophic thermoplastic instability) on the chip morphology. Mahnama and Movahhedy (2012) investigated the finite element simulation of the chip formation process combined with simulation of chatter dynamics and the inter-relationship between the chip formation process and the chatter phenomenon.
Figure 2.7 Initial and progression of discontinuous chips and von Mises stress contour.

(Guo and Yan, 2004)

For experiment investigation, chip morphology was usually investigated in orthogonal and straight cutting processes. Wang et al. (2010a, 2010b) investigated chip morphology with regularly spaced shear bands (RSSBs) generated in the orthogonal micro cutting of cold rolled brass, and critically discussed the reasons why Merchant’s model and its improved versions fail to simulate the RSSBs evolution. Denkena et al. (2014) analyzed the influences of the crystal lattice orientation of monocry stalline FeAl on the chip formation to understand thermo mechanical mechanisms in the material separation process in relation to the cutting direction. Research results revealed that lattice planes engaged in the cut can significantly influence segmentation as well as chip thickness.
2.6.2 Relationship between Tool Wear and Chip Formation

Cutting chip is directly generated from the material removal processes in metal cutting. Therefore, the occurrence of tool wear can directly affect the chip morphology, and vice versa. The relationship between tool wear and cutting chips includes two aspects: first, chip generation has a remarkable effect on tool status and tool life in metal cutting process (Jawahir et al., 1995); second, the tribology at the tool–chip interface controls tool wear and chip generation (Gekonde and Subramanian, 2002). A significant body of research has been performed on the relationship between chip morphology and tool wear in conventional cutting and single-point diamond turning. For example, Yao and Fang (1993) presented a novel method by using neural networks techniques to quantify the relationship between the change of chip breakability and that of corresponding wear status. Ee et al. (2003) presented a methodology to model the phenomenon of chip-curl in machining with progressively worn grooved tools. His method was based on the measurement of cutting forces by using the equivalent tool face (ET) model. Kishawy (2003) studied the relationship between chip morphology and modes of tool wear in the cutting of hardened steel. Ning et al. (2008) conducted a comprehensive exploration on the correlation between chip formation tool wear progress and in ultra-fine-grained cemented carbide ball-end-milling. Ginta et al. (2008) investigated the tool wear patterns and chip formations in end milling of Ti–6Al–4V using uncoated WC-Co inserts. It was found that both primary and secondary serrated teeth are formed in the end milling process and the peak to valley ratio of chip segmentation can be introduced to investigate the
stability of a chip. Ebrahimi and Moshksar (2009) investigated the chips morphologies and chip/tool contact length in turning of micro-alloy and quenched-tempered steels. Bhuiyan (2012) conducted a new method to explore the effect of chip generation on the tool condition using an acoustic emission method. SenthilKumar (2013) performed a study on the relation between chip formation and tool wear during the drilling of carbon fiber reinforced polymer (CFRP)/titanium alloy (Ti6Al4V) stacks. However, there has been no research on the relationship between chip morphology and tool flank wear in UPRM.

2.7 Surface Generation in UPRM

2.7.1 Machined Surface Topography Prediction

The study of on-line surface quality evaluation is important since it can detect the deteriorated machined surfaces by undesirable factors such as tool wear, tool vibration, and slide error, and timely remedy them by optimizing cutting parameters and cutting strategies. According to a study by Azouzi and Guillot (1997), factors leading to the formation of poor surface quality include: (i) feed marks generated by the tool geometry and the kinematics relative to the machined component, (ii) self-excited vibrations and machine tool vibrations, and (iii) surface plastic deformation caused by tool wear, built-up edge or material softening due to the high temperature during the cutting. To evaluate and even improve the machined surface quality, these factors should be considered during the cutting process. To date, research about surface generation and surface quality evaluation has focused on conventional machining,
single point diamond turning, micro milling and conventional drilling processes. For example, Quinsat et al. (2008) proposed a 3D surface roughness parameter formalizing the relative influence of both cutting parameters and surface requirements in the ball end milling process. Ahn et al. (2009) devised an elaborate methodology to predict the surface roughness of layered manufactured processed parts. Cheung and Lee (2001) studied the characterization and affecting factors of Nano-surface generation in single-point diamond turning, and followed up a year later with a study that focused on the effect of tool interference on surface generation and surface roughness in single-point diamond turning (Cheung and Lee, 2002). To realize surface quality prediction, many methods were employed. Grzesik and Brol (2009) characterized the surface topographies formed in longitudinal turning by using normalized fractal dimension $D_n$ and continuous wavelet transform (CWT). Karayel (2009) presented an approach to predict and control surface roughness in a CNC lathe based on neural network technology. Singh et al. (2004) revealed a new method to predict surface roughness of engineering surfaces based on acoustic characterization. Moreover, the relationship between tool wear and surface roughness was conducted by Kılıçkap et al. (2005) on the machining of homogenized SiC-p reinforced aluminum metal matrix composite.

### 2.7.2 Surface Generation

UPRM is an enabling machining method to fabricate optical components with surface roughness down to nanometric levels, which is more suitable for producing non-rotational symmetric surface and complex micro structures. UPRM is a typical
intermittent cutting process, the relatively complex cutting process of UPRM makes the study of on-line surface generation difficult. Research related to surface generation in UPRM has been reported under geometric modeling, kinematics error, and spindle vibration. Cheung et al. (2004) developed a model-based simulation system to predict the cutting performance and optimize the cutting strategies in UPRM of freeform surfaces. Cheung et al. (2006) refined this model by considering the cutting mechanics, cutting strategy, and the kinematics of machine tools in the cutting process. Later, Cheng et al. (2008, 2007) conducted a theoretical and experimental investigation on nano-surface generation in UPRM from a geometric perspective. Based on their study, the surface quality in UPRM can be improved by optimizing the cutting conditions and cutting strategy. Similar research was conducted by To and Wang (2011). Kong et al. (2009) presented a study on the possible factors that affect surface roughness in UPRM. The research results show that tool geometry, machining parameters, tool wear, and cutting strategy are the key factors affecting the super mirror surfaces formation, while tool path, cutting strategies, and slide errors are the essential factors to the freeform surfaces’ form accuracy. Wang et al. (2013) proposed a theoretical and experimental investigation into the effect of workpiece material property on the surface generation in UPRM. In their research, the effects of tool-tip vibration and material swelling on surface roughness in UPRM were studied. Zhang and To (2013a, 2013b) conducted a series of studies on the effects of spindle vibration on the surface generation in UPRM and found that (i) surface generation in UPRM is predominantly influenced by a coupled-tilting spindle vibration; and (ii)
impulse spindle vibration can lead to irregular spindle-vibration waves, which can cause an irregular, lattice-like, or striped pattern (or their hybrids) on the machined surface. Zhang et al. (2014a) conducted a study about spindle inclination error identification and compensation methods to reduce the effects of existing errors on the machined surface roughness. Kong and Cheung (2012b) presented an Integrated Kinematics Error Model (IKEM) to analyze the form error in the UPRM of optical freeform surfaces. However, surface generation under the consideration of fracture wear of diamond tools has not been reported in UPRM, especially for on-line evaluation using cutting chips.

2.8 Summary

Although extensive research has been conducted on tool wear characteristics, tool wear mechanism, tool wear monitoring, and tool wear suppressing methods in conventional machining and single-point diamond turning, the following gaps in the research have been identified:

1. For conventional cutting and signal point diamond turning, the tool wear characteristics have been reported as different tool wear patterns based on different materials. For UPRM however, the tool wear characteristics are still unclear since they may be different from conventional cutting and signal point diamond turning due to the impact effect in UPRM. It is therefore important to study diamond tool wear characteristics in UPRM.

2. In UPRM the cutting duration is quite short, which means that the captured cutting force signals shown as a force pulse. Because the force pulse contains
little information about tool wear, the conventional cutting force analysis and signal-processing methods may not be feasible for processing cutting force signals and extracting useful information to represent tool wear. Therefore, new cutting force analysis and processing methods are needed to monitor tool wear.

3. The intermittent cutting property of UPRM fully generates cutting chips in UPRM rotary cutting, which makes it feasible to use cutting chips to measure tool wear on–machine; however, the lack of knowledge concerning the relationship between cutting chips and tool wear has delayed its realization. It is therefore necessary to study cutting chip morphology and tool wear in UPRM.
Chapter 3 Tool Wear Characteristics in UPRM

3.1 Introduction

The study of tool wear characteristics is essential in the ultra-precision machining field. Cutting tools, the direct executor to form a desired surface topography, can be directly imprinted on the machined surface in the surface generation process. Therefore, the occurrence of tool wear can affect the machined surface quality.

This chapter focuses on tool wear characteristics and their effects on machined surface quality in ultra-precision raster milling (UPRM). Through a group of cutting experiments, it is found that the tool wear characteristics in UPRM include cutting edge fractures, workpiece material welding, wear plane formation, and sub-wear-plane formation. The effects of tool wear characteristics on the machined surface quality, cutting chip morphology, and cutting forces are explored. This research is meaningful since it helps in monitoring diamond tool wear and reducing the effects of tool wear on the machined surface quality.

3.2 Experiments

3.2.1 Experimental Setup

Cutting experiments were conducted on the Precitech 705G CNC ultra-precision machine (Precitech Inc. USA). Figure 3.1 shows the schematic diagram of the kinematics axis of the Freeform 705G ultra-precision raster milling machine and the experimental setup. The ultra-precision machine possesses 5-axes including three
translational axes (X, Y and Z axes) and two optional rotary axes (B and C axes). In the UPRM process, the workpiece is installed on the B axis rotatable table, while the diamond tool is installed on an aerostatic gas bearing spindle holder and rotating around with spindle circularly. During the cutting process, the pose of the spindle can be adjusted by operating the rotatable C axis so that multiple surface structures can be machined using this machine.

Figure 3.1 (a) Schematic of the Freeform 705G machine (b) experimental setup for tool wear characteristics study

3.2.2 Experimental Procedures

In this experiment, brass (CuZn30 alloy) is chosen as the workpiece material, the cutting parameters used in the cutting experiment are listed in Table 3.1. To explore the tool wear progress, flat cutting experiments were conducted. The total straight cutting distance is about 5000 meters. During the cutting, cutting chips were collected at an interval and then examined by a Hitachi TM3000 scanning electron microscope (SEM). After every 1000 meters of cutting, the diamond tool was inspected by the Hitachi TM3000 SEM. Meanwhile, the workpiece was dismounted and inspected by a
Wyko NT 8000 microscope and an Olympus BX60 optical microscope.

Table 3.1 Cutting parameters used in the flat cutting

<table>
<thead>
<tr>
<th>Cutting parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool type</td>
<td>APEX insert diamond tool</td>
</tr>
<tr>
<td>Rake angle</td>
<td>-2.5°</td>
</tr>
<tr>
<td>Clearance angle</td>
<td>15°</td>
</tr>
<tr>
<td>Tool radius</td>
<td>0.631mm</td>
</tr>
<tr>
<td>Swing distance</td>
<td>28.35mm</td>
</tr>
<tr>
<td>Feed rate</td>
<td>200mm/min</td>
</tr>
<tr>
<td>Step distance</td>
<td>0.025mm</td>
</tr>
<tr>
<td>Spindle speed</td>
<td>4500 rpm</td>
</tr>
<tr>
<td>Depth of cut</td>
<td>0.03mm</td>
</tr>
<tr>
<td>Cutting strategy</td>
<td>Horizontal cutting</td>
</tr>
<tr>
<td>Cutting environment</td>
<td>Lubricant on</td>
</tr>
</tbody>
</table>

The cutting force was captured by a dynamometer Kistler 9256C1 at a sampling rate of 300000Hz during the cutting process. The captured cutting force signals were then converted to figures by DynoWare software and analyzed by using MATLAB software. In addition, the captured cutting forces at different cutting distances were compared and then analyzed by power spectrum analysis.

3.2.3 Cutting Distance Calculation

In UPRM, the calculation of cutting distance has two methods: one is to calculate the straight cutting distance; the other is to calculate the rotary cutting distance. Usually, the straight cutting distance is shorter than the rotary cutting distance.
Straight cutting distance is the nominal cutting distance, as is illustrated in Figure 3.2. It merely considers the total length of spindle motion while the overlap during the cutting process is neglected. In horizontal cutting, if the workpiece has a rectangular plane with a length of $l$ and width of $w$, the straight cutting distance for a complete plane cutting can be calculated as:

$$\frac{lw}{s_t}$$  \hspace{1cm} (3-1)

Where $s_t$ is the step distance. Therefore, for the rectangular workpiece surface used in this experiment with a length of 50mm and a width of 25mm, where the step distance is 0.025mm, the cutting distance over a complete plane cutting can be calculated as 50m based on Eq. 3-1. In this experiment, each workpiece has 20 complete plane cuttings, thus 5 workpieces produces the 5000m desired straight cutting distance.

The rotary cutting distance is the actual cutting distance in UPRM taking into
account the overlap effect in the cutting. Figure 3.3 shows the schematic illustration of the cutting distance in a rotary cutting in UPRM. It is found from the figure that the tool tip trajectory in rotary cutting is an arc $ad$, named as $\hat{r}$, whose length can be solved through a geometric relationship, given by:

$$|\hat{r}| = (\alpha + \beta)s_w \quad (3-2)$$

Where $\alpha$ is the tool entry angle, $\beta$ is the tool exit angle, $s_w$ is the swing distance.

![Figure 3.3 Schematic illustration of cutting distance in rotary cutting](image)

In triangle $oab$, angle $\alpha$ can be calculated by:

$$\alpha = \arccos \left( \frac{s_w - a_p}{s_w} \right) \quad (3-3)$$

In triangular $ocd$, angle $\beta$ can be solved by:

$$\beta = \arcsin \left( \frac{f_e/2}{s_w} \right) \quad (3-4)$$

Where $f_e$ is the feed rate with the unit in mm/rev., it can be solved by:
\[ f_e = \frac{f_e'}{s_p} \quad (3-5) \]

Where \( f_e' \) is the feed rate with the unit in mm/min, \( s_p \) is the spindle speed with the unit in r/min.

For a workpiece where its machined surface profile is a rectangle, to finish a complete plane cutting, the number of rotary cuttings can be calculated from:

\[ n = \frac{h_w}{f_e s_i} \quad (3-6) \]

Form Eq. 3-2 to Eq. 3-6, the cutting distance to finish a complete plane cutting can be obtained as:

\[ e = \frac{h_w s_e}{f_e s_i} \left( \arccos \left( \frac{s_w - a_p}{s_w} \right) + \arcsin \left( \frac{f_e / 2}{s_w} \right) \right) \quad (3-7) \]

Based on the Eq. (3-7) and the cutting parameters listed in Table 3.1, the cutting distance to finish a complete plane cutting is calculated as 1492.4m. For a workpiece with 20 times complete plane cutting, the total rotary cutting distance of 5 workpiece is calculated as 149240m.

Table 3.2 shows that the rotary cutting distance is much longer than the straight cutting distance. At the given cutting parameters, the rotary cutting distance is about 29 times larger than the straight cutting distance. It should be noted that the deviation between straight cutting distance and rotary cutting distance depends on the cutting parameters.

\[
\begin{array}{|c|c|c|c|c|c|}
\hline
\text{Workpiece No.} & \text{No.1} & \text{No.2} & \text{No.3} & \text{No.4} & \text{No.5} \\
\hline
\text{Straight cutting distance} & 1000 & 2000 & 3000 & 4000 & 5000 \\
\hline
\text{Rotary cutting distance} & 29848 & 59696 & 89544 & 119392 & 149240 \\
\hline
\end{array}
\]
3.3 Tool Wear Characteristics and Their Effects

Diamond’s extreme hardness and high thermal conductivity make it suitable to be a cutting tool, since the existence of these properties suppresses the occurrence of tool wear. However, during the UPRM process, the cyclic contact between diamond tools and workpiece will impose cyclic thermal and cutting impact stresses on the cutting edge of diamond tools. Although the intermittent cutting property of UPRM can reduce the contact time between diamond tool and workpiece, the stress state of the diamond tool and cutting condition make the diamond tool wear gradually with the increasing of the cutting distance. Figure 3.4 shows a SEM photograph of a fresh diamond tool, it is found that the cutting edge is sharp. In the following experiment, this tool is used to cut desired surface structures.

![SEM photograph of a fresh diamond tool](image1.png)

Figure 3.4 Fresh cutting tool with sharp cutting edge

3.3.1 Fracture Wear

Figure 3.5 (a) and (b) indicates the tool wear characteristics at early tool wear
stage. It shows that after cutting about 1000m, some fractures are found on the cutting edge. The occurrence and distribution of these fractures on cutting edges have no order and they were found following the statistical laws.

Figure 3.5 SEM figures of diamond tool fracture at cutting distance of 1000m

The occurrence of tool fracture wear can be imprinted on the cutting chip surface as a group of ‘ridges’, as is shown in Figure 3.6. The ridges are along the cutting direction and have the same profile and distances in between as the tool fractures shown in Figure 3.5 (a). The cross-sectional profile and their distance in between the ridges can be used to identify the tool wear characteristics.

Figure 3.6 Cutting chip morphology and the ridges imprinted on the chip surface

During the UPRM process, the surface topography is generated by the imprints
of cutting edges. Therefore, the tool fracture wear can directly affect the machined surface quality. The occurrence of fractures on the cutting edge of a diamond tool also can lead to the formation of ‘ridges’ on the machined surface, as is shown in Figure 3.7. The formation of these ridges can deteriorate the machined surface quality and affect the function of machined products. However, whether these ridges affect the surface roughness is subject to their location in a tool mark and their height.

Figure 3.7 Ridges formed on the machined surface inspected by: (a) Olympus BX60 optical microscope and (b) Wyko NT8000 microscope

3.3.2 Material Welding

After 2000m of flat cutting, some workpiece material was found to be welded on the rake face of the diamond tool, as shown in Figure 3.8. The material was welded on the place of rake face closed to the cutting edge. The material welding can be used to identify the cutting edge section used to cut. In addition, it is found that small fractures existing at the cutting distance of 1000m had disappeared; only some relative larger fractures and a rounded cutting edge could be observed. These small fractures were thought to be flattened or rounded with the tool wear process.
The occurrence of material welding can lead to the breakage of cutting chips, as is shown in Figure 3.9. It is observed that cutting chips were broken and curled at their tool entry side, while at the tool exit side, the curl is not explicit. This may be because cutting chips are quite thin at their tool entry side and easily curled due to the effect of surface stresses.

The breakage of cutting chips is caused by the increase of friction force on the interface between cutting chips and the rake face of the diamond tool. This is because materials welding on the rake face of a cutting tool can significantly increase the
friction coefficient on the interface between cutting chips and the rake face of the cutting tool. The increased friction force causes the cutting chips to break and curl at their tool entry side. However, with the increase of cutting distance, the welded material is gradually flattened; therefore, the effect of material welding on the increase of friction force is also decreased.

The captured cutting force in the thrust direction can prove the increase of friction force. It is found that the cutting force in the thrust direction increases from 0.121N to 0.205N as the cutting distance grows from 1000m to 2000m, as is shown in Figure 3.10 (a) and (b).

![Figure 3.10](image)

Figure 3.10 Cutting force and its power spectrum characteristics under the occurrence of material welding on the rake face of the cutting tool

It also can be found from Figure 3.10 (d) that the PSD of cutting force is more decentralized at the cutting distance of 2000m compared to that in Figure 3.10 (a) at the cutting distance of 1000m. This phenomenon is caused by material welding on the
rake face of diamond tools. The friction between diamond tool and cutting chips has an unsteady damping effect, which will disturb the free vibration of dynamometer and was reflected by the power spectrum plot as the dispersion of spectrum peak at the natural frequency of the used dynamometer.

The broken cutting chips can scratch machined surface and lead to a poor quality surface. Figure 3.11 shows the machined surface topography inspected by Olympus BX60 optical microscope and Wyko NT8000 microscope. In Figure 3.11 (a), it is found that the machined surface is fuzzy; the broken chip burrs and deteriorates the machined surface. The poor machined surface topography can also be inspected from Figure 3.11 (b), which shows black points due to missing data in some inspection areas because the existing burrs exceed the field depth of the Wyko NT8000 microscope.

![Figure 3.11 Machined surface inspected by (a) Olympus BX 60 optical microscope and (b) Wyko NT 8000 White Light Interferometer (WLI) microscope](image)

3.3.3 Flank Wear Land Formation

Diamond material has excellent material properties e.g. low friction coefficient
and extreme hardness. However, with a prolonged cutting distance the mechanical wear of a diamond tool is evitable. With the continuous occurrence of the fracture wear, fractures are connected gradually. After a certain cutting distance, a wear land is generated on the cutting edge of the diamond tool, as is shown in Figure 3.12. The wear land has a crescent-like profile, which is narrow at two sides (see Figure 3.12 (b) and (c)), however broad at the center (see Figure 3.12 (d)). The width of wear land increases with the growing cutting distance. It is found that after 5000m flat cutting, the width of wear land is about 1um. The formation of wear land can tort the tool nose profile and change the tool nose radius and its center position. In addition, the formation of wear land can lead to a ploughing effect on machined surface, which is harmful for the surface finish.

Figure 3.12 SEM figures of tool wear characteristics after 5000m flat cutting
From Figure 3.12, it is found that the welded material still exists on the rake face of the diamond tool, although it has become smoother. This may be caused by the continuous wear effect between the rake face of the diamond tool and cutting chips. In addition, it is found that the formation of wear plane incorporates small fractures and flattens relative large fractures. As is shown in Figure 3.12 (d), it is found that the craters existing in Figure 3.5 (a) are flattened and hard to be distinguished.

The formation of wear land also has some effects on the cutting chips. As is shown in Figure 3.13, it is found some shutter-like structures are formed at the tool entry side of cutting chips under the occurrence of tool flank wear. Tool flank wear can also make the cutting chips truncated at the position where the chip thickness is comparable to the width of flank wear land.

Figure 3.13 Shutter-like structure occurs at the tool entry side of cutting chips cut down by flank wear tool

As the direct executor forming the machined surface, the occurrence of flank wear on a cutting tool also has some effects on the quality of the machined surface. With the progress of tool flank wear, a ploughing effect instead of cutting occurs. The
ploughing is harmful since it can lead to the formation of burrs at the bottom of tool imprints. Figure 3.14 shows the machined surface topography at different cutting distances. It is found that at the cutting distance of 1000m the machined surface patterns are clear and well-shaped, as shown in Figure 3.14 (a). Figure 3.14 (b) illustrates that the surface topography at the cutting distance of 3000m is a little confused and fuzzy due to the changing of the cutting process from cutting to ploughing that caused a pile up of material. Figure 3.14 (c) indicates that after 5000m cutting, the surface topography is extremely unclear. This is because by that time, ploughing instead of cutting had become the dominant machining process resulting in a substantial build-up of material.

Figure 3.14 Surface topography after cutting distance (a) 1000m (b) 3000m (c)
In addition, it is found that with the increase of cutting distance, the surface roughness $R_z$ at the inspection area increases slightly. During the cutting process, the surface roughness suffers from the effects of multi-factors such as tool tip vibration, slide error, spindle vibration, and even material spring back. These factors may make the surface roughness value different at different measurement areas. However, these affecting factors can be suppressed by calculating the average peak-to-valley roughness at a large number of tool marks.

To explore the effects of tool flank wear on machined surface roughness, the mean peak-to-valley values of machined surface at different cutting distances were measured. As shown in Figure 3.15, the mark profile of tool imprints is undulating due to the existence of surface affecting factors. However, these factors exist at all tool wear stages, which can be subtracted and suppressed.

![Figure 3.15 Tool imprints mark profile used to identify peak-to-valley roughness](image)

It should be mentioned that although the ploughing effect may cause burrs on the machined surface, they can be distinguished and neglected during the recording of peak-to-valley value in a tool imprint mark. In Figure 3.15, $p_i$ denotes the peak value...
of tool mark boundary, while \( v_i \) is the valley value of the tool mark boundary. The peak-to-valley roughness can be calculated by solving the mean value of the deviation between peaks and valleys of the tool marks.

Statistical methodology is used to process the measured peak-to-valley roughness. Suppose the measured peak-to-valley value in each tool imprint are defined as \( x_1, x_2, \ldots, x_n \). Their mean value can be calculated through:

\[
\bar{x} = (x_1 + x_2 + \cdots + x_n) = \frac{\sum x_i}{n} \tag{3-8}
\]

Where \( x_i \) is the measured value of each sample, \( \bar{x} \) is the mean value of the measured peak-to-valley values, \( n \) is the total amount of samples.

The residuals between measured value of \( x_i \) and mean value of \( \bar{x} \) can be calculated by:

\[
v_i = x_i - \bar{x} \tag{3-9}
\]

According to the Bessel formula, the estimation of the standard deviation can be solved by:

\[
\sigma = \sqrt{\frac{v_1^2 + v_2^2 + \cdots + v_n^2}{n-1}} \tag{3-10}
\]

Based on Eq. (3-10), the measured peak-to-valley values at different cutting distances are processed and listed in Table 3.3, in this investigation 100 samples are measured to calculate the peak-to-valley roughness.

<table>
<thead>
<tr>
<th>Cutting distance (m)</th>
<th>1000</th>
<th>2000</th>
<th>3000</th>
<th>4000</th>
<th>5000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wear land width(um)</td>
<td>0.24</td>
<td>0.61</td>
<td>0.61</td>
<td>1.34</td>
<td>0.86</td>
</tr>
<tr>
<td>Mean p-v values(um)</td>
<td>0.123656</td>
<td>0.123448</td>
<td>0.124048</td>
<td>0.124442</td>
<td>0.125512</td>
</tr>
<tr>
<td>Standard deviation(um)</td>
<td>0.010035</td>
<td>0.009865</td>
<td>0.009865</td>
<td>0.011627</td>
<td>0.011231</td>
</tr>
</tbody>
</table>
From Table 3.3, it is found that the mean peak-to-valley surface roughness $R_z$ at different cutting distance increases slightly with the growing cutting distance. For example, the mean value of peak-to-valley roughness increases from 0.1236um to 0.1255um as the cutting distance grows up from 1000m to 5000m. Since the increase of surface roughness is a relative value compared to the shorter cutting distance, and the longer cutting distance usually leads to a relative wider wear land, the increasing of surface roughness is probably caused by the occurrence of tool flank wear. However, the standard deviations of the measured data are quite larger than the increased surface roughness. Therefore, further studies are needed to verify the surface roughness changes with tool flank wear.

### 3.3.4 Sub-Wear-Land Formation

After 5000m flat cutting, it is found a sub-wear-land is formed at the up boundary of wear land, as is shown in Figure 3.16.

![Figure 3.16 SEM figure of sub-wear-land](image)
Chapter 3: Tool Wear Characteristics in UPRM

The sub-wear-land is along the cutting edge and has a relatively small width e.g. the sub-wear-land has a width about one third of the width of wear land. In addition, it is found that the sub-wear-land has a smaller wear land angle. Obviously, the formation of sub-wear-land can re-sharp the cutting edge. However, its effects on the cutting chips and machined surface quality are still unclear.

3.4 Concluding Remarks

In this chapter, through an extensive cutting experiment, the tool wear characteristics at different tool wear stages in UPRM and their effects on cutting chips morphology, cutting force signals and machined surface quality, are investigated. The cutting distance calculation methods are provided, and the method to eliminate the surface quality affecting factors was introduced. Specific conclusions drawn from this experiment are:

(i) At the tool wear early stage, the tool wear characteristics tend to be fractures of the cutting edge. These fractures occur on the cutting edge and follow the statistics law. The occurrence of tool fracture wear is imprinted both on the cutting chips and machined surface as a group of ‘ridges’.

(ii) Material welding on the rake face is another wear pattern of a diamond tool. Material welding can enlarge the cutting force in the thrust direction and decentralize the power spectrum density of the cutting force. In addition, material welding can lead to the breakage of cutting chips, which deteriorates the machined surface quality by scratching it and making it fuzzy and burred.
(iii) A wear plane is formed at the steady tool wear stage. The width of the wear plane increases with the growing of cutting distance. The formation of wear plane can make the cutting chips form a shutter-like structure at the tool entry side and probably increase the peak-to-valley roughness of the machined surface.

(iv) The formation of sub-wear-land is another tool wear pattern in UPRM. The sub-wear-land can reduce the wear land angle and re-sharp the cutting edge. However, its effects on the cutting chips and machined surface quality are not explicit.
Chapter 4 Tool Wear Monitoring Method Using Cutting Force

4.1 Introduction

In the ultra-precision raster milling (UPRM) process, analysis of the cutting force is an important topic that includes two aspects. The first aspect is to explore the cutting force characteristics in the time domain, which mainly is related to cutting force modeling. The other aspect is to find useful power spectrum peaks in the frequency domain, which is usually related to the power spectrum analysis. Analysis of cutting force has been widely used to predict tool wear and design machine tools. However, there has been relatively little research into cutting force analysis on tool wear measurement and prediction.

In this chapter, cutting force and its power spectrum analysis is conducted on detecting tool wear in UPRM. A cutting force model is established, which can be used to simulate the cutting force amplitude in both the feed direction and thrust direction. A dynamic model is established to simulate the free vibration components of captured cutting force signals. A group of cutting experiments is conducted to explore the cutting force composition and the power spectrum characteristics of which at different tool wear levels. Research results reveal that in the time domain, the cutting force in UPRM is figured as a force pulse followed by damped free vibration signals; the vibration can be seen as a second order impulse response of the measuring system. The amplitude of the cutting force in the thrust direction increases with the tool wear
progress, whereas that in the feed direction is not explicit. In the frequency domain, it is found that both the power spectrum density at the natural frequency of dynamometer and the first order modal frequency of the workpiece increases with the tool wear progress. The relationship between the width of wear plane and values of PSD peaks is an approximately linear relation. These frequencies could be utilized to evaluate tool wear in UPRM.

4.2 Experiments

4.2.1 Experimental Setup

The UPRM cutting experiments were performed on a CNC ultra-precision raster milling machine (Precitech Freeform 705G, Precitech Inc. USA). The experimental setup is shown in Figure 4.1.

Figure 4.1 Schematic configuration of experiment setup

The experiments are divided into two stages. In the first stage, the experiment mainly focused on verifying the cutting force model, exploring the cutting force
compositions and the relations between cutting parameters and cutting force amplitude. This work is performed through cutting a V-groove on a brass (CuZn30 alloy) bulk material. To make the measured results convincing, the cutting force values are determined by solving the mean values of 100 captured cutting force peaks. To reduce the distortion of cutting force signals due to the existence of background noise and vibration, a filter is performed with a band stop at a frequency around 380Hz before comparison and analysis of the cutting force signals. The cutting parameters used in this investigation are listed in Table 4.1.

Table 4.1 Cutting parameters used in this investigation

<table>
<thead>
<tr>
<th>Items</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamond tool</td>
<td>Contour S68661</td>
</tr>
<tr>
<td>Rake angle</td>
<td>0°</td>
</tr>
<tr>
<td>Clearance angle</td>
<td>10°</td>
</tr>
<tr>
<td>Feed rate</td>
<td>40mm/min</td>
</tr>
<tr>
<td>Step distance</td>
<td>0.03mm</td>
</tr>
<tr>
<td>Spindle speed</td>
<td>4000 rpm</td>
</tr>
<tr>
<td>Depth of cut</td>
<td>0.02mm</td>
</tr>
<tr>
<td>Swing distance</td>
<td>27.04mm</td>
</tr>
<tr>
<td>Cutting environment</td>
<td>Lubricant on</td>
</tr>
</tbody>
</table>

The second stage focuses on the investigation of cutting force evolution and its power spectrum characteristics with tool wear progress. In this part, brass (CuZn30 alloy) was chosen as workpiece material and a long lasting flat-surface cutting experiments were conducted. The cutting parameters are listed in Table 3.1 in Chapter 3. The long lasting cutting was performed on five brass bulks, each bulk was cut at a distance of 1000m. Therefore the total cutting distance is 5000m. In the cutting process, cutting force signals were captured in a certain interval time, which was then
processed by power spectrum analysis. After finishing cutting each workpiece, the diamond tool wear was dismounted and then inspected by a Scanning Electron Microscope (SEM) Hitachi TM3000.

### 4.2.2 Cutting Force Acquisition

In the UPRM, the measurement of cutting force was performed on a three-channel dynamometer Kistler 9256C1 dynamometer connected to a Kistler 5080A charge amplifier and Kistler 5697A2 DAQ-System. The workpiece was installed on the dynamometer, while the dynamometer is fixed on the B-axis rotary table of the Freeform 705G. The analog signals of the cutting force were captured first by the sensor of the Kistler 9256C1 dynamometer and then amplified by the Kistler 5080A charge amplifier and at last converted to digital signals by the Kistler 5697A2 DAQ-System at a sampling frequency of 300000Hz, the captured signals was then read by the DynoWare software attached to the measurement system. The signal can also be output from the DynoWare and processed by the MATLAB software. The flowchart of the cutting force signal capturing process is shown in Figure 4.2.

![Flowchart of cutting force signal capturing process](image)

**Figure 4.2 Flowchart of cutting force signal capturing process**
4.2.3 Cutting Force Components

In UPRM, the study of cutting force is significant since it has a closed relation with the diamond tool wear. The captured original cutting force signals are shown in Figure 4.3. Since the Kistler 9256C1 dynamometer owns three channels, it captures cutting force signals in three directions named $x$, $y$ and $z$. However, because the cutting force in the thrust direction is more sensitive to diamond tool wear, the cutting force component in the thrust direction was analyzed to describe tool wear characteristics. As UPRM is an intermittent cutting process, the cutting duration occupies only a small proportion of the rotary cutting. Here, the cutting duration is defined as a period of time when the diamond tool cuts into the workpiece and out again in a rotary circle. In a rotary cutting duration, the cutting force value increases first to the peak value, then decreases to the valley value. Since no cutting exists between two rotary cuttings, the cutting force value is zero theoretically if ignoring the noise and the cutting force induced free vibration.

![Figure 4.3 Original cutting force signals](image)

The force components imposed on the tool tip of a diamond tool in UPRM are
plotted in Figure 4.4. To describe cutting force in different reference objects, two coordinate systems are established: fixed coordinate system $o$-xyz and movable coordinate system $o'$-trs.

![Cutting force components imposed on the diamond tool tip](image)

The fixed coordinate system is attached to the spindle of machine tools and moves with the translation of the spindle. In the coordinate system, $F_x$ is the force component in the feed direction, $F_y$ is the force component perpendicular to the workpiece surface, while $F_z$ is the force component in the step direction. The movable coordinate system is attached to the tip of diamond tool and moves with the diamond tool rotation. In the coordinate system, $F_r$ is the instantaneous force component in the radial direction, $F_t$ is the instantaneous force component along the cutting direction, and $F_s$ is the instantaneous force component along the step direction. The force
components $F_x$, $F_y$, $F_z$ can be measured directly by the dynamometer, while the force components $F_r$, $F_t$ and $F_s$ can just be obtained indirectly. The force components $F_x$, $F_y$ and $F_z$ in coordinate system $o$-$xyz$ and the force components $F_r$, $F_t$ and $F_s$ in coordinate system $o'$-$trs$ can be converted to each other by the following equation, given by:

$$
F_r = F_x \sin \theta + F_y \cos \theta \\
F_t = F_x \cos \theta - F_y \sin \theta \\
F_s = F_z
$$

Where $\theta$ is the rotation angle of the diamond tool. Through Eq.4-1, the force components $F_r$, $F_t$ and $F_s$ in the coordinate frame $o'$-$trs$ can be calculated based on the value of the force components $F_x$, $F_y$ and $F_z$ in the coordinate frame $o$-$xyz$.

### 4.3 Modeling and Analysis of Cutting Force in UPRM

#### 4.3.1 Modeling of Cutting Force Pulse

The study of cutting force modeling in UPRM is quite important since it is usually related to tool wear detection. The cutting force modelling in this section mainly comes from our published work (To and Zhang, 2014).

In UPRM, the diamond tool rotates circularly around the spindle axis of the machine tool while the workpiece is fixed. In a spindle rotation circle, the spindle idling section occupies quite a large proportion, while the cutting section occupies a relatively small proportion. Therefore, UPRM is a typical intermittent cutting process. However, when only considering the cutting section in a rotation circle, the UPRM process can be seen as a continuous cutting process. In a continuous cutting process,
the cutting tool presses the workpiece with its rake face, and the workpiece material
will slide continuously along its shear plane generating chips along the rake face of
the cutting tool. The continuous cutting process is schematically illustrated in Figure
4.5, where $\gamma$ is the rake angle of the diamond tool, and $\phi$ is the shear angle.

![Figure 4.5 Schematic illustration of continuous cutting process](image)

To derive the cutting force model, some simplifying assumptions are made:

(i) After chip formation, the chip will no longer impose shear force on the workpiece;

(ii) The friction coefficient on the interface between the diamond tool and workpiece
is a constant during the cutting process;

(iii) The normal stress $\sigma_s$ imposed on the shear plane is regarded as uniaxial flow
stress.

(iv) Based on Von Mises criterion for material failure, the shear stress on the shear
plane is expressed as $\tau_s = H/3\sqrt{3}$.

(v) The cutting process is an isothermal and adiabatic process.
In a continuous cutting process, if taking the diamond tool as the research object, it is found that it is subjected to several force components as shown in Figure 4.6. Where $F_c$ and $F_t$ are the cutting force in feed direction and thrust direction respectively, which are imposed by the machine tools; $F_u$ is the material rebound force, which is normal to the machined surface; $F_{cf}$ is the friction force on the interface of tool tip and workpiece; and $F_m$ and $F_{mf}$ are the normal force and the friction force on the interface between the diamond tool and the chip respectively, whose relationship is $F_{mf} = \mu F_m$, where $\mu$ is the friction coefficient on the interface of the diamond tool and the chip.

Due to the cutting process being a continuous and force equilibrium process, the summation of these force components should equal to zero, yields:

$$
F_c = F_m (\cos \gamma + \mu \sin \gamma) + F_{cf}
$$
$$
F_t = F_m (\mu \cos \gamma - \sin \gamma) + F_{tr}
$$

Figure 4.6 Schematic of force components imposed on the diamond tool
If taking the chip as the research object, it is found from Figure 4.7 that the chip is suffering from the following force components: the normal force on the shear plane $F_n$; the shear force on the shear plane $F_s$; the normal force $F'_m$; and friction force $F'_{mf}$ from the diamond tool. The summation of these force components equals to zero, yields:

$$F'_m = F_n \sin(\phi - \gamma) + F_s \cos(\phi - \gamma)$$

$$F'_{mf} = F_n \cos(\phi - \gamma) - F_s \sin(\phi - \gamma)$$

(4-3)

![Figure 4.7 Schematic illustration of force components imposed on chips](image)

According to Drescher (1992), on the shear plane, the normal stress is expressed as $\sigma_s = H/3$, therefore the normal force on the shear plane can be derived as:

$$F_n = \sigma_s A_s = \frac{H}{3} \frac{A_o}{\sin \phi}$$

(4-4)

Where $H$ is the Viker’s hardness of the workpiece materials, $A_s$ is the area of shear plane, $A_o$ is the uncut area.

From the above discussion, the shear stress on the shear plane is expressed as
\[ \tau = \frac{\sigma}{\sqrt{3}} = H / 3\sqrt{3}, \] 

therefore, the shear force on the shear plane can be expressed as:

\[
F_s = \tau_s A_v = \tau_s \frac{A_v}{\sin \phi} = \frac{H}{3\sqrt{3}} \frac{A_v}{\sin \phi} \quad (4-5)
\]

Substituting Eqs. 4-4, 4-5 for \( F_s \), \( F_n \) in the first equation of Eqs. 4-3 and considering \( F_m = F_m' \), yields:

\[
F_m = \frac{H}{3} \frac{A_v}{\sin \phi} \sin(\phi - \gamma) + \frac{H}{3\sqrt{3}} \frac{A_v}{\sin \phi} \cos(\phi - \gamma) = \frac{H}{3} \frac{A_v}{\sin \phi} (\sin(\phi - \gamma) + \frac{\cos(\phi - \gamma)}{\sqrt{3}}) \quad (4-6)
\]

Based on Eq. 4-6, Eqs. 4-2 can be rewritten as:

\[
F_c = \frac{H}{3} \frac{A_v}{\sin \phi} (\sin(\phi - \gamma) + \frac{\cos(\phi - \gamma)}{\sqrt{3}})(\cos \gamma + \mu \sin \gamma) + F_{cf}
\]

\[
F_t = \frac{H}{3} \frac{A_v}{\sin \phi} (\sin(\phi - \gamma) + \frac{\cos(\phi - \gamma)}{\sqrt{3}})(\mu \cos \gamma - \sin \gamma) + F_{ct}
\]

In Eqs. (4-7), \( F_{cf} \) and \( F_{ct} \) are the force components generated by workpiece materials’ spring back. According to Kang (2007), the value of materials spring back is a function of the elastic modulus, the hardness of the workpiece material and the cutting edge radius, given by:

\[
s = k_1 r H / E \quad (4-8)
\]

Where \( k_1 = 43 \) is a constant (Arcona and Dow, 1998), \( r \) is the cutting edge radius, \( E \) and \( H \) are the Elastic modulus and the Viker’s hardness of workpiece materials respectively.

Thus, the contact length between cutting tool and workpiece \( W \) on the clearance face of the cutting tool can be derived as:

\[
W = \frac{s}{\sin \delta} = \frac{k_1 r H}{E \sin \delta} \quad (4-9)
\]

Where \( \delta \) is the clearance angle of the diamond tool.
From Drescher (1992), it is known that the rebound stress imposed on the flank face of the diamond tool can be expressed as:

\[ \sigma_r = k_2 H \sqrt{s/r} = KH \sqrt{H/E} \]  

(4-10)

Where \( K = k_2 \sqrt{k_1} = 4.1 \) is a constant (Arcona and Dow, 1998).

Therefore, \( F_t \) and \( F_c \) can be derived as:

\[
F_t = \sigma_r Wb = \frac{Kk_trH^{5/2}}{E^{3/2}} b \sin \delta \\
F_c = \frac{\mu \sigma_r Wb}{\sin(\xi/2)} = \frac{\mu Kk_trH^{5/2}}{E^{3/2} \sin \delta \sin(\xi/2)} b
\]

(4-11)

Where \( \xi \) is the angle between two edges of a V-shaped diamond tool, \( b \) is the equivalent contact width on the interface of the workpiece and diamond tool.

Therefore, the cutting force in the feed direction and thrust direction can be written as the following equations:

\[
F_c = \frac{H}{3} A_o \sin \phi \left( \sin(\phi - \gamma) + \frac{\cos(\phi - \gamma)}{\sqrt{3}} (\cos \gamma + \mu \sin \gamma) + \frac{\mu Kk_trH^{5/2}}{E^{3/2} \sin \delta \sin(\xi/2)} b \right)
\]

\[
F_t = \frac{H}{3} A_o \sin \phi \left( \sin(\phi - \gamma) + \frac{\cos(\phi - \gamma)}{\sqrt{3}} (\mu \cos \gamma - \sin \gamma) + \frac{Kk_trH^{5/2}}{E^{3/2} \sin \delta} b \right)
\]

(4-12)

From Eqs. 4-12, it is found that the cutting force in feed direction and thrust direction depend on the uncut area \( A_o \) and the equivalent contact width \( b \).

In single point diamond turning, the uncut area and the equivalent contact width are theoretically constant. However, it is different in the UPRM process due to the continuous rotation of the diamond tool. As shown in Figure 4.8, the uncut chip area is enveloped by the trajectory of the previous rotary cutting, the current rotary cutting, and the workpiece surface. With a different rotation angle \( \alpha \), the chip thickness is different and there is a crucial angle \( \theta \), which divides the chip area into two sections.
This crucial angle can be derived through geometric method, given by:

$$\theta = \arctan \frac{2s_w a_p - a_p^2 - f_e}{s_w - a_p}$$  \hspace{1cm} (4-13)

In Figure 4.8, as $0 \leq \alpha \leq \theta$, the diamond tool is located at the first chip section. The cross-sectional shape of cutting chips in the first chip section is shown in Figure 4.9, which indicates that the chip is formed by the tool imprint in the previous rotary cutting, the current rotary cutting, and the workpiece surface. The cross-section area of the chips and the equivalent contact width in the first chip section can be derived as:

$$A_b = ((h + l)^2 - l^2) \tan(\xi / 2) = h(h + 2l) \tan(\xi / 2)$$

$$b = 2(h + l) \tan(\xi / 2)$$  \hspace{1cm} (4-14)

Where $h = f_e \sin \alpha$ is the chip thickness, $l = s_w - a_p \cos \alpha$ is the previous cutting depth.
Figure 4.9 Cross-sectional shape of the cutting chips as $0 \leq \alpha \leq \theta$

In Figure 4.8, the diamond tool is located at the second chip section as $\theta < \alpha \leq \beta$. In this section, the chip is generated by the tool imprint of the current rotary cutting and the workpiece surface, as is shown in Figure 4.10. The cross-section area of the cutting chips and the equivalent contact width can be derived as:

$$A_0 = l'^2 \tan(\xi / 2)$$
$$b = 2l' \tan(\xi / 2)$$

(4-15)

Figure 4.10 Cross section of the chip when $\theta \leq \alpha \leq \beta$

Where $l'$ is the current cutting depth, which can be calculated approximately by

$$l' = s_w - \frac{s_w - a_p}{\cos \alpha}.$$
From what have been discussed above, it is found that the cutting force formula in Eqs.4-12 just depends on the rotation angle $\alpha$ as other parameters are determined. In other words, the cuttings force values in UPRM changes with the changing of rotation angle. However, the dynamometer can only measure the horizontal and vertical force components. Therefore, for easy comparison, the force components in the horizontal and vertical directions were calculated in this cutting force model in terms of different rotation angle $\alpha$. The schematic illustration of force components in horizontal and vertical directions in UPRM is shown in Figure 4.11 (a), while the calculation formula is given by:

$$
F_x = F_h = c_1(F_v \sin \alpha + F_c \cos \alpha)
$$
$$
F_z = -F_v = c_2(F_v \sin \alpha - F_c \cos \alpha)
$$

(4-16)

Where $c_1$, $c_2$ are the correction coefficients, which are used to compensate the effect of impact in UPRM, their values are subject to the spindle speed.

![Figure 4.11](image)

Figure 4.11 (a) Schematic illustration of cutting force components in horizontal and vertical direction (b) simulated cutting force pulse for UPRM

In this paper, brass (CuZn30 alloy) was chosen as the workpiece material, whose hardness and elastic modulus are 2.4 GPa and 117 GPa respectively, the value of two
correction factors were determined as $c_1=1.4$, $c_2=1.1$ at the spindle speed of 4000 rpm. Through the MATLAB simulation program, the simulated cutting force pulse is drawn in Figure 4.11 (b).

From the simulated cutting force, it is found that the duration of cutting force is quite short as the diamond tool cut into and out of the workpiece, the amplitude of the cutting force increases at first and then decreases rapidly. Therefore, the cutting force for UPRM can be simplified as a force pulse. The cutting force modeling presented in this section is suitable for V-groove cutting, however, through a little change of the chip cross-sectional shape, the cutting force model can also be suitable for other cutting processes.

### 4.3.2 Investigation of Cutting Force Composition

During the cutting force capturing process, the original cutting force signal was captured first by the three-channel dynamometer Kistler 9256C1 and then displayed by the DynoWare software. The captured original cutting force signals for UPRM are shown in Figure 4.3. Through the processing of the DynoWare, the original cutting force signals can be decomposed into cutting force components in ‘x’, ‘y’ and ‘z’ directions respectively. In UPRM, the existence of background noise and vibration can definitely distort the cutting force signals. The noise and vibration signals affect the cutting force signals mainly at low frequency band. Taking the force component in the ‘z’ direction as an example (see Figure 4.12 (a)), it is found that the low frequency vibration signal can distort the cutting force signals, this phenomena also appears in the other cutting force components.
Figure 4.12 (a) Cutting force signals distortion under the effect of low frequency (b) power spectrum plot of cutting force signals at air cutting process.

From Figure 4.12 (a), it is found that the period of low frequency vibration mainly occurs at the frequency around 380Hz. It is thought to be the background vibration of machine tools, since the low frequency vibration signal also exists in the air cutting process, as shown in Figure 4.12 (b). Therefore, to sufficiently explore the characteristics of cutting force in UPRM, the cutting force signal was filtered first with band stop at the frequency bend of 350Hz to 400Hz before analysis.

In the UPRM process, the diamond tool rotates continuously at high speed cutting into and out of the workpiece surface intermittently, the contact between the diamond tool and workpiece is therefore discontinuous. In every rotary cutting, the cutting duration is closely related to the cutting parameters of swing distance and depth of cut. From the analysis, it is clear that the first cutting force signals captured is the cutting force pulse (see Figure 4.13), while the following vibration signals are the cutting force induced free vibration signals since at that time the diamond tool has been out of the workpiece surface.
In UPRM, the diamond tool rotates periodically cutting into and out of the workpiece surface. In a rotary cutting, the duration of a cutting process is a function of the swing distance and the cutting depth, given by:

\[
t = 60 \arccos \left( \frac{s_w - a_p}{s_w} \right) / 2\pi s_p
\]  
(4-17)

Where \( s_w \) is the swing distance (mm), \( t \) is the duration of a rotary cutting (s), \( s_p \) is the spindle speed (rpm), and \( a_p \) is the cutting depth (mm).

As Table 4.1 shows that \( s_w = 27.04 \text{mm} \), \( a_p = 0.02 \text{mm} \), and \( s_p = 4000 \), the duration of a rotary cutting can be calculated as \( 0.000091826 \text{s} \), which is confirmed with the measured duration of \( 0.00009 \text{s} \) by using the cursor tool in the DynoWare software.

After a force pulse, a free vibration signal is captured, as is shown in Figure 4.13, which is thought to be the free vibration excited by the pulsed cutting force since the diamond tool has left the workpiece surface at this point of time.

### 4.3.3 Cutting Force Induced Free Vibration

In the cutting force measurement system, the piezoelectric force sensors possess a certain elastic property, which can stretch or shrink with the force imposed on them.
Thus, the workpiece and the dynamometer can be simplified and modeled as a second order mass-spring-damper system (see Figure 4.14)

![Figure 4.14 Schematic illustration of cutting force measurement system](image)

The captured vibration signals can be seen as a second order impulse response of the measurement system, a diagram of which is shown in Figure 4.15.

![Figure 4.15 Block diagram of the transfer function](image)

Based on the analysis, the cutting force in thrust direction acting on the measurement system can be formulated as:

$$x(t) = \begin{cases} F & t = 0 \\ 0 & t \neq 0 \end{cases}$$  \hspace{1cm} (4-18)

For a typical mass-spring-damper system, a second order partial differential equation is usually used to depict the system property:

$$\frac{d^2y}{dt^2} + 2\zeta\omega_n \frac{dy}{dt} + \omega_n^2 y = \omega_n^2 x$$  \hspace{1cm} (4-19)
Through Laplace transform, the transfer function of Eq. 4-19 can be derived as:

\[ G(s) = \frac{Y(s)}{X(s)} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \]  \hspace{1cm} (4-20)

The Laplace transform of cutting pulse is \( X(s) = L(x(t)) = F \), therefore, the output response is:

\[ Y(s) = G(s)X(s) = \frac{F\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \]  \hspace{1cm} (4-21)

In this measurement system, a Kistler 9256C1 dynamometer was used to capture the cutting force signal for UPRM. According to the manual, it stiffness is \( 2.5 \times 10^6 \) N/m and the damping ratio is about 0.03. Based on the dynamic parameters of the Kistler 9256C1 dynamometer, the simulated free vibration signal is shown in Figure 4.16 (a) while the captured free vibration signals are given in Figure 4.16 (b). Through the comparison of the measured and simulated signals, it is found that the measured cutting force signals are in agreement with the simulated ones. Based on the analysis of cutting force composition in UPRM, it is found that the first pulses in both Figure 4.16 (a) and Figure 4.16 (b) show the cutting force pulses.

Figure 4.16 (a) Simulated cutting force (b) measured cutting force
4.3.4 Effects of Cutting Parameters on the Amplitude of Cutting Force

The same as other cutting processes, UPRM cutting parameters can directly affect the value of cutting force. Figure 4.17 shows the curves of the cutting force amplitudes in both the feed and thrust directions with respect to the depth of cut. It is found that the cutting forces both in feed and thrust directions increase with the growing cutting depth. Also, the measured cutting forces are found to agree well with the simulated ones in both the feed and thrust directions.

Figure 4.17 Effect of depth of cut on cutting force in (a) feed direction and (b) thrust direction
Figure 4.18 Effect of feed rate on cutting force in (a) feed direction and (b) thrust direction

Figure 4.18 indicates the changing trends of cutting force with respect to the feed rate. It is revealed that with the increase of feed rate, the cutting force in both feed direction and thrust direction increases. Also the simulated cutting forces are accordant with the simulated ones in both directions, although there is a little deviation between them that may be caused by the hidden items in the model and the ignored noises.

In the cutting force model for UPRM, the cutting depth and feed rate are two important cutting parameters. As one parameter changes, the relationship curves between cutting force and the other parameter change as well. Therefore, a
relationship surface, which describes the relationship between the cutting force amplitude and cutting parameters such as feed rate, cutting depth, is established. From Figure 4.19 and Figure 4.20, it is found that the depth of cut has more contribution to the cutting force amplitude both in the feed direction and thrust direction than the feed rate has.

![Figure 4.19 Relationship surface between cutting force in feed direction and cutting parameters: feed rate and cutting depth](image)

Figure 4.20 reveals that the cutting force in the thrust direction is more sensitive to larger depth of cut and feed rate than smaller ones; e.g. when the depth of cut is bigger, the cutting force in thrust direction increases more drastically with the growing feed rate. The opposite is also true. However, this relationship is not explicit for the cutting force in the feed direction.
4.4 Cutting Force Evolution with Tool Wear Progress

4.4.1 Experimental Observations

In UPRM, the investigation of cutting force and its power spectrum analysis is meaningful because it can be used to evaluate the wear of diamond tool. As shown in Figure 4.21, with the growing of the cutting distance, the cutting force amplitude in the thrust direction increases from 0.0754 N at the cutting distance of 3.6 m to 0.321 N at the cutting distance of about 5000 m. Therefore the cutting force amplitude goes up gradually with the increasing of the cutting distance. From Figure 4.21, it is found that the increase of cutting force amplitude from the cutting distance of 1000m to 2000m is relatively larger than that at other cutting distances. This is because in this cutting period, the occurrence of material welding on the rake face of a diamond tool leads to growing friction force and increases the measured cutting force in the thrust direction.
Figure 4.21 Comparison of cutting force amplitudes at the cutting distance of a) 3.6m, b) 1000m, c) 2000m, d) 3000m, e) 4000m and f) 5000m

The cutting force evolution with the progress of tool wear is curved as shown in Figure 4.22 (Zhang et al., 2015). Although the cutting force in the thrust direction increases with the growing of the cutting distance, the value in the feed direction has no significant changes, as shown in Figure 4.22 (b).

Figure 4.22 Curves of cutting force amplitude in (a) thrust direction and (b) feed direction with respect to cutting distance
The different response of the cutting force to tool wear in the thrust direction and feed direction can be interpreted as: with the increasing of cutting distance, a wear land is formed on the cutting edge, as shown in Figure 4.23. The formation of wear land will lead to the increase of the contact area between the diamond tool and workpiece and as a result enlarging the cutting force in the thrust direction. Since the wear land is formed on the flank face, it has little effect on the cutting force in the feed direction.

![SEM images of tool flank wear at the cutting distance of 5000m](image)

**Figure 4.23 SEM images of tool flank wear at the cutting distance of 5000m**

### 4.4.2 Theoretical interpretation

In UPRM, the amplitude of cutting force in the thrust direction increases with the diamond tool wear. This is because the cutting force in the thrust direction is partially generated by the material rebound to the flank face of the diamond tool. The cutting processes by a fresh tool and worn tool is schematically illustrated in Figure
Chapter 4: Tool Wear Monitoring Method Using Cutting Force

4.24, which shows that the diamond tool with a flank wear land usually has a relative larger contact area with the workpiece material, this will increase the cutting force in the thrust direction.

From Eq. 4-8 it is known that the value of material spring back is a function of the hardness, the elastic modulus of the workpiece material and the tool edge radius. And from Eq. 4-9, the contact length of tool-workpiece \( W \) on the flank face of cutting tools can be solved.

Figure 4.24 Schematic of the cutting process by (a) fresh tool (b) worn tool

For a worn tool, the total contact width on the tool flank face is \( W_i \cos \alpha + W \), as shown in Figure 4.24. \( W_i \) is the wear land width of the diamond tool, \( \alpha \) is the wear land angle.

Based on Eqs. 4-8, 4-9, 4-10, the force generated by material rebound can be derived as:

\[
F_t = \sigma_i (W_i \cos \alpha + W)b = KHB\sqrt{H/E} \left( \frac{\gamma H}{E \sin \delta} + W_i \cos \alpha \right)
\]  

(4-22)

Where \( b \) is the average length of contact area along the step direction.

Eq. 4-22 is the formula to calculate the force component generated from material spring back under tool flank wear. It is found that \( F_t \) is a function of the width of wear land that directly increases \( F_t \).
4.5 Power Spectrum Density Characteristics of Cutting Force under Tool Wear

4.5.1 PSD Characteristics of Cutting Force

Power spectrum analysis is a commonly used method to investigate the signal characteristics in frequency domain, in the power spectrum analysis of a certain signals, the energy distribution of the signals at a certain frequency is usually described by power spectral density (PSD). Usually, the PSD of the signals is obtained by a periodogram algorithm in which the cutting force signal $F(t)$ is sampled by $N$ points at an equal interval and denoted by $F(k)$, where $k=0, 1, 2, \ldots, N-1$, $N$ is the amount of samples in a sampling period, then the PSD of the cutting force signals in UPRM can be calculated through computing its discrete Fourier transformation (DFT) by a fast Fourier transformation (FFT) algorithm, given by:

$$P(f_n) = \sum_{k=0}^{N-1} F(k) e^{-2\pi inf_n}$$  \hspace{1cm} (4-23)

where $f_s$ is the sampling rate, $f_n$ presents the $nth$ frequency component of the cutting force signals.

It should be noted that the sampling rate $f_s$ should be two times at least as large as the maximum non-zero frequency $f_{max}$ of the cutting force signals based on the sampling theorem, i.e:

$$f_s \geq 2f_{max}$$  \hspace{1cm} (4-24)

The sampling rate is chosen as 300000Hz in this experiment.

In this research, the Hanning lag window is utilized to obtain the PSD so as to
reduce the distortion of the true spectrum caused by Gibb’s phenomenon, which is given by (Cheung and Lee, 2003):

\[
PSD(f_0) = 0.25(P(f_1))^2 + 0.5(P(f_0))^2 + 0.25(P(f_2))^2
\]  

(4-25)

where PSD\( (f_0) \) is the PSD of a certain frequency \( f_0 \), \( f_1 \) and \( f_2 \) are the preceding and the succeeding frequencies for \( f_0 \) respectively.

In this research, the cutting force signals are converted into frequency domain first and then analyzed by using power spectrum analysis so that the characteristic spectrum peaks related to diamond tool wear in UPRM can be presented. Figure 4.25 (a) shows the power spectral plot of the cutting forces in the air cutting process. It can be seen that the background spectrums consist of random frequency peaks with relatively low PSD values. In Figure 4.25 (a), the spectrum peaks were appeared at the frequency components of \( X=100Hz \), 566.7Hz, 1198Hz and 2546Hz respectively, which is attributed to the background vibration, electrical noise, and a spray of coolant. However, the spectrum peaks at the frequencies of \( X=200Hz \) and \( 300Hz \) are thought to be the harmonic spectrums of the spectrum peak with \( X=100Hz \). From the manual of Kistler 9256C1 dynamometer, it is found that the characteristic spectrum peak at the frequency of 4880Hz is the natural frequency of the dynamometer. In addition, it is found from Figure 4.25 (a) that there are no any notable spectrums in the frequency band higher than 5000Hz.
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Figure 4.25 Power spectral plots of the cutting force signals in (a) the air cutting process (b) the flat cutting process

In the flat cutting process, the power spectral plot of the cutting forces is shown in Figure 4.25 (b). The figure indicates that the power spectrum peaks at the frequencies of $X=100\text{Hz}$, $566.7\text{Hz}$, $1198\text{Hz}$ and $4888\text{Hz}$ are still existed, whereas the power spectrum peak at the frequency of $X=2546\text{Hz}$ has disappeared. Since the peak merely exists in the air cutting process, it is not thought to be generated from the cutting process. Through comparison between Figure 4.25 (a) and (b), it is found that the power spectrums at the frequency band of $0$-$1300\text{Hz}$ have no significant different between the air cutting and flat cutting processes. However, the power spectrum at the frequency band of $4500$-$5100\text{Hz}$ changes a lot, e.g. the PSD peak increases from $0.08255$ in the air cutting process to $4.151$ in the flat cutting process. This frequency band is the dynamometer’s natural frequency, which can be verified from the manual
of the dynamometer.

### 4.5.2 PSD of the Free Vibration of Dynamometer

Some content in this section comes from our published work (Zhang et al., 2015). The increase of wear land width on the flank face can increase the cutting force in the thrust direction, this will lead to a more serious vibration of the dynamometer with its natural frequency and a relatively large power spectrum peak at the natural frequency of the dynamometer. Therefore the free vibration of the dynamometer can be used to monitor tool wear. Based on the simulated cutting force signal shown in Figure 4.16 (a), the simulated power spectrum plots of cutting force at different cutting distances is shown in Figure 4.26.

![Figure 4.26 PSD plots of simulated cutting force signals at different cutting distances](image)

It is found that with the growing cutting distance, the PSD peak at the frequency of about 5000Hz increases simultaneously. This result can be proved by the power spectral plots of captured cutting forces at the same cutting distance, as shown in Figure 4.27. Figure 4.26 and Figure 4.27 were plotted using the same sampling rate.
and data number, thus the simulated PSD is well proved by the measured PSD. This predominant spectrum peak can be used to detect tool wear in UPRM.

Figure 4.27 The PSD plots of captured cutting force signals at different cutting distances

Figure 4.28 indicates the relationship curves between the predominant spectrum peaks of cutting force signals and cutting distance. It is found that the predominant peaks in both simulated PSD and measured PSD are growing with the increase of cutting distance. In the power spectrum analysis, PSD is more suitable for monitoring tool wear than cutting force itself since it can overlap the signals at the same frequency.

Figure 4.28 Relationship curves between the predominant PSD peak of cutting force and the cutting distance
4.5.3 PSD of the Modal Vibration of Workpiece

The tool wear progress can also be presented by the modal frequencies of workpiece. With the increase of cutting force in the thrust direction under tool flank wear, a more serious free vibration of workpiece is caused. As shown in Figure 4.29, the power spectrum plots of cutting force at the frequency band between 0Hz-18000Hz at different cutting distances are presented.

Figure 4.29 Power spectrum plots of cutting forces in the (a) air cutting process and at the cutting distance of (b) 1000m, (c) 2000m, (d) 3000m, (e) 4000m and (f) 5000m respectively
Figure 4.29 (a) shows the power spectrum plot in the air cutting process. It is found that no significant PSD peaks exist at the frequency band larger than 6000Hz. However, from comparing Figure 4.29 (b-f), it is found that three PSD peaks at the frequency of 7800Hz, 10000Hz and 15800Hz are notably increasing with the growing cutting distance. It is interesting to note that the PSD values at the frequencies of 7800Hz, 10000Hz and 15800Hz increase from 0.02987, 0.001861 and 0.005156 at the cutting distance of 1000m to 0.05597, 0.010532 and 0.0124 at the cutting distance of 5000m respectively. These characteristic frequencies are likely generated from the modal vibration of the workpiece. According to the modal analysis based on Finite Element Method (FEM), it is found the first 5 order vibration frequencies are quite close to the measured frequencies, as listed in Table 4.2.

Table 4.2 Modal frequencies of workpiece calculated by FEM

<table>
<thead>
<tr>
<th>Mode No.</th>
<th>Frequency(Rad/sec)</th>
<th>Frequency(Hertz)</th>
<th>Period(Seconds)</th>
<th>Mode shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50291</td>
<td>8004</td>
<td>0.00012494</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>61080</td>
<td>9721.2</td>
<td>0.00010287</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>97778</td>
<td>15562</td>
<td>6.43E-05</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.00E+05</td>
<td>15918</td>
<td>6.28E-05</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.03E+05</td>
<td>16356</td>
<td>6.11E-05</td>
<td></td>
</tr>
</tbody>
</table>

From Table 4.2, it is found that all five modal frequencies are within the
frequency band from 7500Hz to 17000Hz, while the measured three peaks are the first three modal frequencies of workpiece as compared in Table 4.3.

Table 4.3 Comparison between measured and calculated values of the first three order PSD peaks

<table>
<thead>
<tr>
<th>Main peaks in PSD of cutting force</th>
<th>Three predominant order modal frequencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>7800Hz</td>
<td>8004Hz</td>
</tr>
<tr>
<td>10000Hz</td>
<td>9721 Hz</td>
</tr>
<tr>
<td>15800Hz</td>
<td>15562 Hz</td>
</tr>
</tbody>
</table>

From Table 4.3, it is found that the measured predominant three PSD peaks agree well with the simulated first three order modal frequencies. Since the three predominant peaks did not exist in the air cutting process, they are proved to be the first three order modal frequencies of the workpiece.

![Figure 4.30 Schematic of the first order workpiece modal vibration during UPRM](image)

The increase of the PSD peak values with the growing of cutting distance can be interpreted as: the workpiece has its modal frequencies, while the short cutting force of UPRM can be seen as a stimulus, as shown in Figure 4.30 above. With the increase of cutting distance, the increase of cutting force in thrust direction due to the flank
wear of cutting tools can cause a more serious workpiece vibration in their modal frequencies, thus the increased power spectrum density was captured.

Figure 4.31 shows the PSD peaks of cutting force with respect to the cutting distance. It is found that with the increase of cutting distance, all three predominant modal frequencies of the workpiece increase correspondingly, although the first order of PSD peaks (F1) increased the most. Therefore, the first order modal frequency of the workpiece is a good candidate for monitoring tool wear.

![Figure 4.31 Relationship curves of PSD peaks with respect to the cutting distance](image)

**4.6 Concluding Remarks**

This research investigated cutting forces in UPRM and their relationships with diamond tool wear. A novel cutting force model for UPRM was established that can be used to calculate or predict cutting forces both in the feed direction and thrust direction. Based on the cutting force model, the cutting force composition and the effect of cutting parameters on the cutting force amplitude were explored. Cutting force evolution and its power spectrum characteristics with tool wear progress were explored. In the frequency band, the method of power spectrum analysis was adopted
to analyze the cutting forces, two power spectral density peaks were found to be feasible for monitoring tool wear. Specific conclusions drawn from the research areas follow:

(i) The cutting force is figured as a force pulse due to the short cutting duration in UPRM. The cutting force pulse is closely related to the geometric shape of chips and a crucial rotation angle exists that divides the chip area into two sections. Therefore, in UPRM, the cutting force pulse curve is composed of two segments.

(ii) The workpiece and dynamometer can be modeled as a second order mass-spring-damper dynamic system, while the cutting force pulse can be thought of as an external excitation. As the diamond tool cuts into and out of the workpiece, the dynamic system is stimulated and a vibration signal can be captured by the dynamometer as a free vibration signal induced by the cutting force.

(iii) Cutting parameters can affect the amplitude of the cutting force in UPRM. Both the experimental and simulation results show that the cutting force in the feed direction and thrust direction increases with the increasing depth of cut and feed rate. The depth of cut has more influence on cutting force than the feed rate has. In addition, it is found that the cutting force in thrust direction is more sensitive to larger depths of cut and feed rate than smaller ones, although it is implied for the cutting force in feed direction.

(iv) In UPRM, the amplitude of the cutting force in the thrust direction increases gradually with tool wear progress. According to the mathematical model, this is caused by the increase of wear land width. However, the increase is not explicit for
the cutting force in the feed direction.

(v) Two power spectrum peaks are found to be closely related to tool wear in UPRM. The amplitude of the predominant spectrum peak increases with the tool wear progress. The characteristic frequencies are the free vibration of the dynamometer and the first three orders of workpiece modal vibration induced by the cutting force.
Chapter 5 Tool Fracture Wear Evaluation Method using Cutting Chips

5.1 Introduction

Although cutting chips directly generated in the cutting process can reflect the cutting condition and tool status, there has been no research on the evaluation of tool wear by using cutting chips because in a traditional continuous cutting process the cutting edge section used to generate surface topography cannot be imprinted on the surface of cutting chips. However, tool wear evaluation using cutting chips can be realized in ultra-precision raster milling (UPRM) due to its intermittent cutting property. During the UPRM process, tool wear characteristics can be imprinted directly both on the machined surface and cutting chips. Through examining the cutting chips, both the tool wear characteristics and machined surface topography can be predicted.

This chapter focuses on the evaluation of tool fracture wear and their effects on machined surface quality by using cutting chips. Based on the fact that tool fractures can be imprinted both on the machined surface and cutting chips as a group of ‘ridges’, a novel on-machine tool wear and machined surface topography evaluation method in UPRM are proposed. Through the method, both tool wear characteristics and machined surface quality can be predicted without the need for stopping the cutting process. In the tool fracture wear and surface topography prediction model, the ridges’ parameters like distance between two neighboring ridges, the height and width of
ridges are measured and then used to simulate the machined surface topography. A mathematical model was established to calculate the machined surface roughness considering the tool fracture wear. Based on the on-line evaluation, the machined surface quality can be potentially improved by optimizing the cutting parameters.

5.2 Experiment

In the experiment, a Precitech Freeform 705G (Precitech Inc., USA) multi-axes CNC ultra-precision raster milling machine was employed to generate the designed surface topography and cutting chips. The cutting tool was an Apex insert diamond tool (Apex Inc., UK), whose parameters are: tool radius of 0.631mm, rake angle of -2.5°, clearance angle of 15°. The cutting parameters employed in this experiment are: feed rate 200mm/min, depth of cut 0.03mm, spindle speed 4500rpm, swing distance 28.35mm, step distance 0.025mm, the cutting strategy is horizontal cutting, and the cutting environment is lubricant on. The workpiece material is brass (CuZn30 alloy) and the cutting distance is about 1000 meters.

In this experiment, two brass bulks are prepared: one (no.1 workpiece) was cut by a fresh tool; the other (no.2 workpiece) was finished by the same tool after 1000 meters cutting. The experiment procedures were: after one layer of surface cutting, the no.1 workpiece was dismounted and examined by a Wyko NT8000 White Light Interferometer (WLI) microscope. Meanwhile, no.2 workpiece was installed on the fixture and cut continuously by the same tool. At the end of flat cutting, cutting chips were collected and inspected by a Hitachi TM3000 scanning electron microscope (SEM). The inspection results are then used to simulate the machined surface
topography. After the cutting process, no.2 workpiece was examined by an Olympus BX60 optical microscope and the Wyko NT8000 WLI microscope respectively. The diamond tool was also disassembled and inspected by Hitachi TM3000 SEM, the inspected results were then compared with the results predicted by the cutting chips.

5.3 Results and Discussion

Figure 5.1 shows the inspected cutting chip after the flat cutting process. It is found that several ridges were imprinted on the cutting chip surface.

![Image of cutting chip with ridges](image_url)

Figure 5.1 Ridges imprinted on the chip surface

All the ridges are along the cutting direction and were generated by the imprint of cutting edge fractures (fracture 1 and fracture 2 in Figure 5.2) since they have the same profile and distance.
Figure 5.2 Fracture wear exists on the cutting edge

From Figure 5.1 and Figure 5.2, it is found that cutting chips reflect the fracture wear characteristics clearly. Therefore, it is feasible to evaluate tool wear by using cutting chips. UPRM is an intermittent cutting process whereby the cutting chips are fully generated by a rotary cutting of the diamond tool. Hence, the cutting chips can be collected without the need to stop the cutting process, which allows on-machine tool wear measurement to be realized.

During the UPRM process, all the ridges formed on the cutting chips truly reflect the tool edge fractures. However, only a small part of the ridges can be imprinted both on the cutting chips and machined surface and it is this part of the ridges that are used to predict machined surface topography. Figure 5.3 indicates the figure of ridges imprinted on the machined surface.
The imprints of tool fracture on the cutting chips are shown in Figure 5.4. It is found that the marked ridges (a, b, c, d, e) in the two figures have similar profile and distances in between on both the cutting chip and machined surface, which is because they are generated from the same group of ridges.

In Figure 5.5, it is found that cutting chips split at the tool entry side of these ridges. These splits are along the cutting direction, which are thought to be formed by the stress accumulation effect. The thickness of cutting chips is thinner at the tool entry side, which is easy to split under the effect of stress accumulation. However,
with the increase of chip thickness along the cutting direction, the split is stopped. The generation of spits can help to find the location of ridges.

Figure 5.5 Splits generated on the tool entry side of a cutting chip

In the UPRM process, the cutting mechanism makes the tool entry side of cutting chips quite thin, but makes the tool exit side of cutting chips relatively thick. From Figure 5.4 it is found that the ridges have a relatively clear signature at the tool entry side of the cutting chips. Some of them even cause the formation of splits. However, the ridges are not quite clear at the tool exit side. This is because at the tool entry side the chip is thinner than that at the tool exit side, and the ratio between the chip thickness and height of the ridges is relative small as well.

5.4 Modeling of Cutting Chip and Virtual Cutting Edge

5.4.1 Cutting Chip Model

The study of cutting chip morphology is important since it can help in understanding the cutting mechanism and cutting chips generation. Unlike continuous
cutting, in UPRM the cutting chip can be fully generated in a rotary cutting process, thus the cutting chip can be collated on-line. In the UPRM process, the diamond tool rotates fast, cutting into and out of the machined surface intermittently. In every rotary cutting, the cutting chip can be generated by three cutting steps: previous step cutting, previous rotary cutting and current rotary cutting, as is shown in Figure 5.6. The cutting chip is actually enveloped by the initial surface, the surface formed by previous rotary cutting, the current rotary cutting, and the previous step cutting.

Figure 5.6 Schematic of chip formation on a workpiece

Figure 5.7 shows side view of the cutting mechanism and chip formation in UPRM, while its back view is shown in Figure 5.8. For convenience, a coordinate system \( o-xyz \) is established at the intersection point of tool holder axis and spindle axis with its \( x \)-axis pointing to the feed direction and \( y \)-axis along the step direction. Coordinate system \( p-uvw \) is built up with a distance of \( f \) behind the coordinate system \( o-xyz \) and with same orientation as the coordinate system \( o-xyz \).
Figure 5.7 and Figure 5.8, the shadow area is the chip formation area. It is found that in the side view, the chip area is formed by previous rotary cutting and current rotary cutting; while in the back view, the shadow area is generated by the previous step cutting and current step cutting.

Based on the geometry relationship in the chip formation as shown in Figure 5.7 and 5.8, a cutting chip was simulated by using Solidworks commercial software under the given cutting parameters. The simulated cutting chip morphology is shown in Figure 5.9 from which it can be seen that the cutting chip is enveloped by four
surfaces which are named as surface A, B, C, and D. The four surfaces intersect each other and form six curves named as curve a, b, c, d, e, and f. The six curves are connected by four points named as point i, j, m, and k.

Figure 5.9 Simulated cutting chip morphology in Solidworks

Based on Figure 5.7, 5.8 and 5.9, a mathematical model was established to simulate the 3D cutting chip morphology. Since the cutting chip is enveloped by four surfaces, four separate equations are derived to model the cutting chip.

(1) Surface formed by previous rotary cutting (surface A)

\[
\left( \sqrt{u^2 + w^2 - s_w} + R \right)^2 + v^2 = R^2
\]  

(5-1)

Where \( s_w \) is the swing distance, \( R \) denotes the tool nose radius.

From Figure 5.7, coordinate components of any point in coordinate system
\( o-uvw \) can be expressed in coordinate system of \( o-xyz \) through coordinate transformation, given by:

\[
\begin{bmatrix}
  u \\
  v \\
  w \\
  1
\end{bmatrix} = T
\begin{bmatrix}
  x \\
  y \\
  z \\
  1
\end{bmatrix}
\]

(5-2)

Where \( T = \begin{bmatrix} 1 & 0 & 0 & f_r \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \) is the transformation matrix.

Based on Eq. 5-1, Eq. 5-2 can be expressed in coordinate system \( o-xyz \) as:

\[
\left( \sqrt{(x + f_e)^2 + z^2} - s_w + R \right)^2 + y^2 = R^2
\]

(5-3)

Where \( f_e \) is the feed rate in mm/r.

(2) Surface formed by current rotary cutting (surface \( B \))

\[
\left( \sqrt{x^2 + z^2} - s_w + R \right)^2 + y^2 = R^2
\]

(5-4)

(3) Surface formed by previous step cutting (surface \( C \))

\[
(z - s_w + R)^2 + (y + s_i)^2 = R^2
\]

(5-5)

Where \( s_i \) is the step distance.

(4) Initial surface (surface \( D \))

\[
z = s_w - a_p
\]

(5-6)

Where \( a_p \) is the cutting depth.

From Figure 5.9, it is found the four surfaces intersect at six boundaries, which can be formulated by six equations. The equation for each curve can be derived by solving the same solution of the equations of two neighboring surfaces. Actually, solving the mapping equation of each curve on the \( x-y \) plane is more useful for
building up the 3D model of cutting chips. The mapping equations for the six curves are derived below:

(1) For curve a, it is the boundary curve of surface A and B, combining Eq. 5-3 and Eq. 5-4 and eliminating z, yields:

\[ x = -\frac{f_e}{2} \]  

(5-7)

(2) For curve b, it is the boundary curve of surface A and C, combining Eq. 5-3 and Eq. 5-5 and eliminating z, yields:

\[ x = \sqrt{s_i (2y + s_i) + 2(s_w - R)(\sqrt{R^2 - y^2} - \sqrt{R^2 - (y + s_i)^2}) - f_e} \]  

(5-8)

(3) For curve c, it is the boundary curve of surface B and C, combining Eq. 5-4 and Eq. 5-5 and eliminating z, given by:

\[ x = \sqrt{s_i (2y + s_i) + 2(s_w - R)(\sqrt{R^2 - y^2} - \sqrt{R^2 - (y + s_i)^2})} \]  

(5-9)

(4) For curve d, it is the boundary curve of surface C and D, combining Eq. 5-5 and Eq. 5-6 and eliminating variable z, given by:

\[ y = \sqrt{a_p (2R - a_p)} - s_i \]  

(5-10)

(5) For curve e, it is the boundary curve of surface A and D, combining Eq. 5-3 and Eq. 5-6 and eliminating z, we obtain:

\[ x = \sqrt{(\sqrt{R^2 - y^2} + s_w - R)^2 - (s_w - a_p)^2} - f_e \]  

(5-11)

(6) For curve f, it is the boundary curve of surface B and D, combining Eq. 5-4 and Eq. 5-6 and eliminating z, yields:

\[ x = \sqrt{(\sqrt{R^2 - y^2} + s_w - R)^2 - (s_w - a_p)^2} \]  

(5-12)

Moreover, it is found from Figure 5.9 that the six curves are joined by four points, which are the boundary points of the six curves. Their coordinate components in x and
y axes can be derived as follows:

(1) For point $i$, it is the boundary point of curves $a$, $b$, and $c$, whose coordinate components in $x$ axis and $y$ axis are:

$$
\begin{align*}
  x_i &= -f_e / 2 \\
  y_i &= \text{root of } (\sqrt{s_i(2y+s_i)} + 2(s_w-R)(\sqrt{R^2-y^2} - \sqrt{R^2-(y+s_i)^2}) - f_e / 2 = 0)
\end{align*}
$$

(5-13)

The explicit expression of $y$ in Eq. 5-13 is quite complex, its value can be solved by mathematically using MATLAB.

(2) For point $j$, it is the boundary point of curve $a$, $c$ and $f$, whose coordinate components in $x$ axis and $y$ axis can be solved as:

$$
\begin{align*}
  x_j &= -f_e / 2 \\
  y_j &= \sqrt{R^2 - \left(\frac{1}{4} f_e^2 - s_w - a_p + R\right)^2}
\end{align*}
$$

(5-14)

(3) For point $m$, it is the boundary point of curve $b$, $d$ and $e$, whose coordinate components in $x$ axis and $y$ axis can be derived as:

$$
\begin{align*}
  x_m &= \sqrt{R^2 - a_p(2R-a_p) + 2s_i(2R-a_p) - s_i^2 + s_w - R} - (s_w - a_p)^2 - f_e \\
  y_m &= a_p(2R-a_p) - s_i
\end{align*}
$$

(5-15)

(4) For point $k$, it is the boundary point of curve $c$, $d$ and $f$, whose coordinate components in $x$ axis and $y$ axis can be expressed as:

$$
\begin{align*}
  x_k &= \sqrt{R^2 - a_p(2R-a_p) + 2s_i(2R-a_p) - s_i^2 + s_w - R} - (s_w - a_p)^2 \\
  y_k &= a_p(2R-a_p) - s_i
\end{align*}
$$

(5-16)

Eqs. 5-1~5-16 are the mathematical model of cutting chips. In this paper, MATLAB® commercial software is used to plot the 3D profile of cutting chip based on the given tool geometry parameters and cutting parameters. Figure 5.10 shows the cutting chip figures from different views.
Figure 5.10 Cutting chip gradient figure (a) and out-line figures of the cutting chip in top view (b), side view (c) and back view (d).

From Figure 5.10, it is found the cutting chip under the given cutting parameters has an approximate length of 0.65 mm, and a width of 0.2 mm. However, the pressure from the rake face of diamond tools can make the cutting chip shrink slightly in the cutting direction, thus the simulated length of cutting chips is a little longer in the feed direction than the captured ones.

Figure 5.11 shows the plotted cutting chip figure and its comparison with the inspected one. It is found that the two figures concur with each other in morphology. Only a part of the cutting chip can reflect the machined surface topography. Referring to Figure 5.8 and Figure 5.11(a), the chip section between line a and line b can be used to reflect the machined surface topography, since in this section the tool fracture characteristics can be imprinted both on machined surface and cutting chip surface.
According to the geometric relationship, the distance between line $a$ and line $b$ is equal to the arc length in a tool imprint. Therefore, it is easy to find this section on the chip surface.

![Diagram](image.png)

Figure 5.11 Comparison of simulated cutting chip figure (a) and the inspected cutting chip figure by SEM (b)

Derivation of the cutting chips model is important since it can help with an understanding of the cutting mechanism and chip generation in UPRM, e.g. the section related to the surface generation.

### 5.4.2 Virtual Cutting Edge Buildup under Tool Fracture Wear

Some content in this section comes from our published work (Zhang et al., 2014b). In the cutting process, the machined surface topography can be seen to be formed by a virtual diamond tool cutting edge that forms the same surface topography as the real diamond tool does. In the ultra-precision machining process, cutting tools are divided into two categories: cutting tools with cylinder clearance and with conical...
clearance, as is shown in Figure 5.12. Cutting tools with cylinder clearance usually have an ellipse cutting edge in the virtual cutting plane, while cutting tools with conical clearance usually have a circular cutting edge in the virtual cutting plane. Since the circular cutting edge is the most used cutting edge in the cutting process, this study employed a circular cutting edge. For a circular virtual cutting edge, the description equation is:

\[
\frac{-2}{y} + \frac{-2}{z} = R^2
\]  

(5-17)

Figure 5.12 Schematic of cutting tools with (a) cylindrical clearance and (b) conical clearance

During the UPRM process, the fracture wear of diamond tools is directly imprinted on the chip surface as a group of ‘ridges’, therefore the fracture characteristics of cutting tools can be predicted by examining the cross-sectional shape of these ridges. In this research, a 3D module in the Hitachi TM3000 SEM was used to measure the cross-sectional shape of these ridges and build up the virtual cutting edge considering tool fracture wear. Based on the Figure 5.8 and Figure 5.11 (a), the chip section within line \(a\) and \(b\) was inspected. The measured length is equal
to the arc length along the cutting edge outline within a tool imprint, which can be calculated by the expression:

\[ \hat{e} = 2R \arcsin\left(\frac{s_j}{2R}\right) \]  

(5-18)

Due to the chip surface usually being uneven, the measured profile of the cutting chip surface cannot be directly used to build up the virtual cutting edge. In this research, SEM was only used to measure the distance between two neighboring ridges (Figure 5.13) and the cross-sectional shape of ridges (Figure 5.14).

Figure 5.13 Schematic of the distance between ridges

Figure 5.14 Schematic of the cross-sectional shape of ridges
For simplification, the measured cross-sectional shape of these ridges was approximated into two geometric elements: isosceles triangle and semi-circle, so that they can be formulated, as shown in Figure 5.15.

![Diagram of geometric elements](image)

Figure 5.15 Geometric elements depicting the cross-sectional shape of ridges

Inspections found that all the cross-sectional shape of ridges can be approximated into one of them. To depict the geometric elements, parameters such as width and height of the isosceles triangle, radius of the semi-circle, and distance between two neighboring ridges were measured, as listed in Table 5.1.

<table>
<thead>
<tr>
<th>( d_i )</th>
<th>Ridges distance(um)</th>
<th>Ridge No.</th>
<th>Ridge profile</th>
<th>Width((t_i))(um)</th>
<th>Height((h_i))(um)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d_1 )</td>
<td>2.25</td>
<td>ridge ①</td>
<td>( \wedge )</td>
<td>0.63</td>
<td>0.185</td>
</tr>
<tr>
<td>( d_2 )</td>
<td>7.45</td>
<td>ridge ②</td>
<td>( \wedge )</td>
<td>0.35</td>
<td>0.1</td>
</tr>
<tr>
<td>( d_3 )</td>
<td>3.1</td>
<td>ridge ③</td>
<td>( \bigcirc )</td>
<td>0.43</td>
<td>---</td>
</tr>
<tr>
<td>( d_4 )</td>
<td>5.85</td>
<td>ridge ④</td>
<td>( \wedge )</td>
<td>0.4</td>
<td>0.06</td>
</tr>
<tr>
<td>( d_5 )</td>
<td>4.15</td>
<td>ridge ⑤</td>
<td>( \wedge )</td>
<td>0.55</td>
<td>0.16</td>
</tr>
<tr>
<td>( d_6 )</td>
<td>2.43</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

After measurement, the approximated geometric elements were ‘assembled’ on a
line with its length equal to the arc length calculated in Eq. 5-18, which is depicted in Figure 5.16.

![Figure 5.16 Geometric elements assembled on a line](image)

After assembling, the line with the geometric elements was ‘bent’ accordant with the curvature of diamond tool as shown in Figure 5.17 thereby forming the virtual cutting edge under tool wear.

![Figure 5.17 Line geometric elements bent into the virtual cutting edge](image)

The geometric elements assembling and line bending process are completed by the mathematical calculation. For clarity, three coordinate systems $o - \bar{y}\bar{z}$, $o' - y'z'$, and $o_i - y_i z_i$ were established, as shown in Figures 5.16 and 5.17. Among them, $o_i - y_i z_i$ is established according to the location of geometric elements. The equations of geometric elements in coordinate system $o_i - y_i z_i$ are expressed as:
Chapter 5: Tool Fracture Wear Evaluation Method using Cutting Chips

For isosceles triangle:

\[
\begin{align*}
\frac{2y_i + z_i}{t_i} &= -1 \quad (y_i, z_i < 0) \\
\frac{2y_i - z_i}{t_i} &= 1 \quad (y_i > 0, z_i < 0)
\end{align*}
\]  (5-19)

For semi-circle:

\[
y_i^2 + z_i^2 = \frac{t_i^2}{4} \quad (z_i < 0)
\]  (5-20)

The origin of coordinate system \(o_i\text{-}y_i\text{z}_i\) can be expressed in the \(y'\)-axis of coordinate system \(o'\text{-}y'z'\) as:

\[
p_i = \frac{\vec{e}}{2} - \sum_i d_i
\]  (5-21)

Based on the coordinate transformation, Eqs.5-19 and 5-20 can be expressed in coordinate system \(o'\text{-}y'z'\) as:

\[
\begin{bmatrix}
y_i \\
z_i \\
1
\end{bmatrix} =
\begin{bmatrix}
1 & 0 & p_i \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
y' \\
z' \\
1
\end{bmatrix}
\]  (5-22)

To ‘bend’ the line with geometric elements into an arc accordant with the diamond tool profile, all points in the line should be transferred to the points in the arc. The transformation formula is derived as:

\[
\begin{align*}
y &= (R + z')\sin \delta \\
z &= (R + z')\cos \delta
\end{align*}
\]  (5-23)

Where \(\delta = y'/R\) is the transformation angle.

After derivation, all the equations should be transformed to and expressed in the global coordinate system \(o\text{-}xyz\). The transformation operation is realized by:
It should be noted that to acquire the parameters depicting the profile of ridges and distance between two neighboring ridges accurately, the measurement is not limited to one cutting chip. Actually, to make all the acquired parameters for the ridges’ profile more reliable, many chips were collected for inspection.

Based on the measured parameters of ridges as listed in Table 5.1, a predicted virtual cutting edge is plotted by MATLAB® software as shown in Figure 5.18 (a), while the inspected one is shown in Figure 5.18 (b). It is found the measured cutting edge concurs with the simulated one.

![Figure 5.18 Comparison of virtual cutting edge built up by (a) cutting chips, and (b) the examined cutting edge](image)

The buildup of the virtual cutting edge is important since it can be directly used to simulate the machined surface generation and predict the machined surface quality on-machine. Although some errors exist when approximating the cross-sectional shape of ridges into geometric elements, and the stacking effect of chip material...
during the ridge formation make the ridges’ cross-section size larger than the real one, when comparing the virtual cutting edge built up from the cutting chips and the examined cutting edge, it is found that the tool wear monitoring method based on cutting chips can predict tool wear characteristics effectively without the need to stop the cutting process.

5.5 Modelling and Analysis of Surface Roughness under Tool Fracture Wear

5.5.1 Surface Topography Simulation under Tool Fracture Wear

As mentioned above, to acquire the cross-sectional shape of the ridges imprinted on the chip surface and the distances between them, a 3D module of the Hitachi TM3000 SEM was used to capture the cross-sectional shape of the ridges. The measured length on the cutting chips should be equal to the arc length in a tool imprint. Since the ridges are imprinted both on the chip surface and the machined surface in this section, the machined surface topography could be predicted through inspection of the cutting chips.

To simulate the machined surface topography, a different mathematical method was used to present the surface topography. The same as the virtual cutting edge formation, the cross-sectional shape of ridges and the distance between two neighboring ridges were measured separately to reduce the effect of the cutting chip’s uneven surface on the accuracy of the rebuilt surface. To formulate the measured cross-sectional shape of ridges, they were approximated into two geometric elements:
isosceles triangle and semi-circle. According to a large number of previous experimental observations, all the cross-sectional shape of ridges imprinted on the cutting chips can be approximated into one of them. To parameterize the geometric elements, parameters such as the width and height of the isosceles triangle, the radius of the semi-circle, and the distance between two neighboring ridges were measured.

Table 5.2 Ridges’ parameters used to rebuild machined surface topography

<table>
<thead>
<tr>
<th>$d_i$</th>
<th>Ridges distance (um)</th>
<th>Ridge No.</th>
<th>Ridge profile</th>
<th>Ridges’ Width (um)</th>
<th>Ridges’ height (um)</th>
<th>Width correction factor</th>
<th>Height correction factor</th>
<th>Width after correction(um)</th>
<th>Height after correction(um)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_1$</td>
<td>2.25</td>
<td>ridge ①</td>
<td>0.63</td>
<td>0.185</td>
<td>0.85</td>
<td>0.3</td>
<td>0.5355</td>
<td>0.0555</td>
<td></td>
</tr>
<tr>
<td>$d_2$</td>
<td>7.45</td>
<td>ridge ②</td>
<td>0.35</td>
<td>0.1</td>
<td>0.85</td>
<td>0.3</td>
<td>0.2975</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>$d_3$</td>
<td>3.1</td>
<td>ridge ③</td>
<td>0.43</td>
<td>0.215</td>
<td>0.8</td>
<td>0.35</td>
<td>0.344</td>
<td>0.07525</td>
<td></td>
</tr>
<tr>
<td>$d_4$</td>
<td>5.85</td>
<td>ridge ④</td>
<td>0.4</td>
<td>0.08</td>
<td>0.85</td>
<td>0.3</td>
<td>0.34</td>
<td>0.024</td>
<td></td>
</tr>
<tr>
<td>$d_5$</td>
<td>4.15</td>
<td>ridge ⑤</td>
<td>0.55</td>
<td>0.2</td>
<td>0.85</td>
<td>0.3</td>
<td>0.4675</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>$d_6$</td>
<td>2.43</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

However, the stacking effects of chip material during the ridge formation process make the cross-sectional shape of ridges larger than the real ones, the effect is more serious in the height direction than that in the width direction. In addition, during the cutting process the material spring back can also distort the true profile of the ridges. To reflect the cross-sectional shape of ridges in reality, a correction factor was used to correct the measured width and height of ridges, as listed in Table 5.2 above. The factors were obtained by a large number of comparisons between the measured...
cross-sectional shape of ridges on the cutting chips and the machined surface. For brass material, in the height direction, the value is 0.3-0.4; while in width direction, the value is 0.8-0.9. Since the stacking is occurs in the cutting direction, the distance between two neighboring ridges do not need to be corrected.

The measured distance between two neighboring ridges is the straight-line distance on the chip surface. To bend the measured distances accordant with the arc $\widehat{ab}$, the arc angle of each distance should be calculated by:

$$\delta_i = \frac{d_i}{R} \quad i=1,2,\cdots,n$$  \hspace{1cm} (5-25)

For the geometric elements, they can be described by mathematical equations. These equations are expressed in a local coordinate system $o_{ri}uw_i$, as is shown in Figure 5.19 (a-b). After measurement and correction, the geometric elements were assembled on the arc $\widehat{ab}$ (see Figure 5.19 (c)). Thus, the cross-sectional profile of the machined surface in a tool imprint is formed. The geometric elements assembling process is completed mathematically.

![Figure 5.19 Geometric elements and their assembling on the arc within a tool imprint](image)

Coordinate transformation is used to assemble the geometric elements on the arc.
From Figure 5.19 (c) it can be seen that any point in the coordinate system of $o_i-u_iw_i$ can be expressed in the coordinate system of $p$-$uw$ by coordinate transformation:

$$
\begin{bmatrix}
  u_i \\
  w_i \\
  1
\end{bmatrix} =
\begin{bmatrix}
  \cos \theta_i & \sin \theta_i & -R \sin \theta_i \\
  -\sin \theta_i & \cos \theta_i & R \cos \theta_i \\
  0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  u \\
  w \\
  1
\end{bmatrix}
$$

(5-26)

Where $\theta_i = \sum_i \delta_i - \beta$ is the rotation angle.

Based on coordinate transformation, the boundary points $(-h_i, 0)$ and $(h_i, 0)$ of the semi-circle element in the coordinate system $o_i-u_iw_i$ can be expressed in the coordinate system $p$-$uw$, whose coordinates in the $u$-axis are:

$$
\begin{align*}
  u_1 &= R \sin 2\theta_i - h_i \cos \theta_i \\
  u_2 &= R \sin 2\theta_i + h_i \cos \theta_i
\end{align*}
$$

(5-27)

Through coordinate transformation, the semi-circle equation in coordinate system $p$-$uw$ can be derived as:

$$
u^2 + w^2 + R^2 - 2R u \sin 2\theta_i + 2Rw \cos 2\theta_i = h_i^2
$$

(5-28)

From Eq. 5-28, variable $w$ can be solved and expressed by variable $u$ as:

$$
w = -R \cos 2\theta_i \pm \sqrt{h_i^2 - (u - R \sin 2\theta_i)^2}
$$

(5-29)

For the isosceles triangle element, the boundary points $(-e_i/2, 0)$, $(0, h_i)$ and $(e_i/2, 0)$ in coordinate system $o_i-u_iw_i$ can be expressed in coordinate system $p$-$uw$, whose coordinates in the $u$-axis are:

$$
\begin{align*}
  u_1 &= R \sin 2\theta_i - \frac{e_i}{2} \cos \theta_i \\
  u_2 &= R \sin 2\theta_i - h_i \sin \theta_i \\
  u_3 &= R \sin 2\theta_i + \frac{e_i}{2} \cos \theta_i
\end{align*}
$$

(5-30)

Through coordinate transformation, the equation of isosceles triangle in the coordinate system $p$-$uw$ can be derived as:
The arc in a tool imprint can be expressed by the following equation:

\[ w = \sqrt{R^2 - u^2} \quad (-s/2 < u < s/2, w < 0) \]  

Based on the Eqs. 5-27~5-32, the simulated cross-sectional profile of the machined surface in a tool imprint is plotted by Matlab\textsuperscript{®} commercial software, as is shown in Figure 5.20. It is found from Figure 5.20 that no.1 and no.5 ridges are higher than the height of the step boundary, which means no.1 and no.5 ridges can increase the surface roughness, especially for the peak-to-valley roughness.

After obtaining the cross-sectional profile of the machined surface in a tool imprint, the flat-machined surface topography under the effects of tool fracture wear can be simulated. To simulate the surface generation in a rotary cutting, equations expressed in coordinate system \( p-uw \) should be expressed in global coordinate \( o-xyz \) by coordinate transformation, given by:

\[
\begin{align*}
\mathbf{w} &= (e_i \sin \theta_i + 2h_i \cos \theta_i)u + (e_i h_i - 2h_i R \sin \theta_i - e_i R \cos \theta_i) & u_i < u < u_2 \\
\mathbf{w} &= (e_i \cos \theta_i - 2h_i \sin \theta_i) & u_2 < u < u_3
\end{align*}
\]
Chapter 5: Tool Fracture Wear Evaluation Method using Cutting Chips

\[
\begin{bmatrix}
u \\
w \\
1
\end{bmatrix} = 
\begin{bmatrix}
1 & 0 & 0 \\
0 & -1 & s_w - R \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
y \\
z \\
1
\end{bmatrix}
\]  
(5-33)

After transformation, the rotary cutting simulation can be realized by changing variable \( z \) by \( \sqrt{x^2 + z^2} \) in Eqs. (5-33), yields:

\[
\begin{cases}
u = y \\
w = -\sqrt{x^2 + z^2} + s_w - R
\end{cases}
\]  
(5-34)

Substituting variables of \( u \) and \( w \) in Eqs. 5-27~5-32 by the expression in Eq. 5-33, the surface topography equations can be obtained.

Figure 5.21 (a) indicates the surface topography simulated based on the cutting chips, while Figure 5.21 (b) presents the measured surface topography generated by the real cutting tool. It is found that the surface predicted by cutting chips agreed well with the measured one. In addition, through the comparison of the surfaces formed by the virtual cutting edge and real one, it is found the fracture wear identified by cutting chips can directly imprinted on the surface as several ridges (see the five numbers in Figure 5.21 (a)), these ridges can also be found on the measured surface (see the five numbers in Figure 5.21 (b)). The location and height of these ridges can be potentially used to predict the machined surface quality on-machine. From Figure 5.21 (b), it is found that the width of the step boundary is a little different for different steps. This may be caused by the slide error in the depth direction. In addition, it is found that the real step boundary is a little ahead of the predicted one in the step cutting direction. This may be caused by the material flow in the step direction during the cutting process.
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Figure 5.21 Surface topography comparisons between (a) simulated surface and (b) measured machined surface by Olympus BX60 optical microscope (50×)

The prediction of machined surface quality on-machine is significant since it can help in finding surface quality deterioration in a timely manner and potentially remedying the surface deterioration by changing the cutting conditions. This research has found that the on-machine surface topography prediction based on cutting chips can realize the simulation of machined surface topography precisely without the need to stop the cutting process.

5.5.2 Surface Roughness Evaluation under Tool Fracture Wear

In the description of machined surface quality, the maximum peak-to-valley height ($R_t$) is an important parameter because it describes the deviation from the lowest valley to the highest peak in a sampling area. For UPRM, the theoretical maximum peak-to-valley height can be calculated mathematically.

In the UPRM process, there are two cutting strategies: horizontal cutting and vertical cutting. In the horizontal cutting process, the cutting direction is accordant
with the feed direction while the step direction is perpendicular to the feed direction, as shown in Figure 5.22.

![Figure 5.22 Schematic of cutting strategies and maximum peak-to-valley roughness in horizontal cutting](image)

However, in the vertical cutting process, the cutting direction is perpendicular to the feed direction, as shown in Figure 5.23. For each cutting strategy, the surface roughness calculation is different.

![Figure 5.23 Schematic of cutting strategies and maximum peak-to-valley roughness in vertical cutting](image)

The theoretical surface roughness ($R_t$) of the machined surface in both horizontal
cutting and vertical cutting can be geometrically calculated. From Figure 5.22 and Figure 5.23, it is found the surface roughness \( R_t \) in a tool imprint and swing imprint can be calculated by:

\[
\begin{align*}
R_{t\_tool} &= R - \sqrt{R^2 - \left(\frac{s_t}{2}\right)^2} \\
R_{t\_swing} &= s_w - \sqrt{s_w^2 - \left(\frac{f_s}{2}\right)^2}
\end{align*}
\] (5-35)

However, the surface generation is the combined effects of feed cutting and step cutting. Thus, the surface roughness \( R_t \) is composed of two elements in the feed direction and step direction respectively.

In UPRM, there is a phase shift in the feed direction at different cutting steps. The existence of phase shift lowers the height of peak point, as shown in Figure 5.24, and directly affects the surface roughness.

Figure 5.24 Schematic of surface roughness composition in UPRM

According to Figure 5.24, the theoretical surface roughness \( R_t \) of the machined surface was modeled with consideration of phase shift effects on the surface quality evaluation, given by:
\[
\begin{align*}
R_{t,\text{min}} &= R_{t,\text{tool}} = R - \sqrt{R^2 - \left(\frac{s_s}{2}\right)^2} \\
R_{t,\text{max}} &= R_{t,\text{swing}} + R_{t,\text{tool}} / \cos \alpha = s_w - \frac{s_w^2 - \left(\frac{s_f}{2}\right)^2}{s_w} + \frac{s_w \left( R - \sqrt{R^2 - \left(\frac{s_s}{2}\right)^2} \right)}{\sqrt{s_w^2 - \left(\frac{s_f}{2}\right)^2}}
\end{align*}
\] (5-36)

Where \( \alpha \) is the swing cutting angle, which can be calculated from Figure 5.25, given by:

\[
\cos \alpha = \frac{\sqrt{s_w^2 - \left(\frac{s_f}{2}\right)^2}}{s_w}
\] (5-37)

Figure 5.25 Schematic of surface roughness calculation in a swing distance

However, the existence of tool fracture wear can make the calculation of the surface roughness \( (R_t) \) different. To evaluate the effects of the ridges generated from tool fracture wear on the machined surface quality (see Figure 5.19), the surface roughness \( (R_t) \) under the existence of tool fracture wear in a tool imprint was calculated, given by:

\[
R_{t,\text{ridge}} = \max( R - (R - h_i) \cos \theta_i ) \quad i = 1, \cdots, n
\] (5-38)

Eq. 5-38 only presents the effect of ridges on the roughness in a tool imprint. Since ridges have no effect on the roughness in a swing imprint, the surface roughness
(\(R_t\)) in a swing imprint is still depicted by the second equation in Eq. 5-35.

If \(R_{t\text{-ridge}}\) is less than \(R_{t\text{-tool}}\), this means the ridges have no effect on the machined surface roughness. However, if \(R_{t\text{-ridge}}\) is larger than \(R_{t\text{-tool}}\), the ridges increase the surface roughness. At this time, the formula for calculating the surface roughness (\(R_t\)) range changes to:

\[
\begin{align*}
R_{t\text{-min}} &= R_{t\text{-ridge}} = \max(R - (R - h_i)\cos\theta) \\
R_{t\text{-max}} &= R_{t\text{-swing}} + R_{t\text{-ridge}} / \cos\alpha = s_w - \sqrt{s_w^2 - \left(\frac{f_e}{2}\right)^2} + \frac{s_w(\max(R - (R - h_i)\cos\theta))}{\sqrt{s_w^2 - \left(\frac{f_e}{2}\right)^2}}
\end{align*}
\] (5-39)

From Eq. 5-39, it is found that the surface roughness (\(R_t\)) under the occurrence of tool fracture wear is closely related to the height of ridges and their location.

This research measured the machined surface cut by a fresh tool and a worn tool. The predicted surface roughness based on cutting chip was calculated and a comparison between measured and calculated surface roughness is listed in Table 5.3. It is found the measured values are a little bigger than the calculated ones for both the fresh tool and the worn tool. This may be affected by factors exiting in the cutting process e.g. spindle vibration, slide error, material spring back, and the measurement error in the measurement process.

**Table 5.3 Comparison of calculated and measured surface roughness values**

<table>
<thead>
<tr>
<th></th>
<th>Surface cut by fresh tool</th>
<th>Surface cut by fracture wear tool</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Theoretic value</td>
<td>Mean value in five times measurement</td>
<td>Predicted value based on cutting chips</td>
</tr>
<tr>
<td>(R_{t\text{-tool}})</td>
<td>123.82nm</td>
<td>---</td>
<td>146.69nm</td>
</tr>
<tr>
<td>(R_{t\text{-swing}})</td>
<td>8.71nm</td>
<td>---</td>
<td>8.71nm</td>
</tr>
<tr>
<td>(R_{t\text{-tool}}+R_{t\text{-swing}})</td>
<td>132.53nm</td>
<td>135.82nm</td>
<td>155.4nm</td>
</tr>
</tbody>
</table>

Figure 5.26 shows that the machined surface topographies cut by the fresh tool
are smoother and the tool imprint boundaries are clearer. The surface roughness is also relatively lower.

![Figure 5.26 Surface topographies cut by the fresh tool](image)

Figure 5.26 Surface topographies cut by the fresh tool

However, for the surface cut by the worn tool after 1000m of cutting, several ridges are formed in a tool imprint on the surface (see Figure 5.27). In addition, it is found that the height of ridges on the step boundary is relatively higher than the height of the step boundary, which increases the roughness of the machined surface.

![Figure 5.27 Surface topographies cut by a fracture wear tool](image)

Figure 5.27 Surface topographies cut by a fracture wear tool

In UPRM, if the machined surface is determined to be affected by tool fracture wear, action should be taken to improve the machined surface quality on-line. The
actions include changing the cutting parameters, and overlapping cutting. By these actions, the deteriorated surface quality can be remedied.

5.6 Concluding Remarks

In this chapter, a novel tool fracture wear measurement and surface topography prediction method using cutting chips was explored in ultra-precision raster milling (UPRM). This method can realize the prediction of the fracture wear characteristics occurring on the cutting edge of a diamond tool, the machined surface topography, and even the roughness on-machine without need to stop the cutting process. According to the comparison between predicted results and measured ones, it is found that both the tool fracture wear measurement method and the surface quality prediction method are reliable methods. Some specific conclusions drawn from the research include:

1. Cutting chips are fully generated in the rotary cutting of UPRM. It is found that the tool fracture wear characteristics can be directly imprinted on both the cutting chip surface and machined surface as a group of ridges. By examining the ridges’ cross-sectional shape and their locations, both tool wear and machined surface topography can be predicted without the need to stop the cutting process.

2. Cutting chips split at the starting position of the ridges. These splits are thought to be generated by the tool fracture wear under the effect of stress accumulation. The formation of spits can help to find the ridges’ location.

3. A mathematical model was established to predict the cutting chip morphology. The simulated cutting chip morphology was verified by the examined one. Only
a small section of cutting chip can reflect both tool wear characteristics and surface topography.

4. Two geometric elements were employed to model the ridges’ cross-sectional shape: isosceles triangle and semi-circle. Based on the two geometric elements and the distance between two neighboring ridges, the virtual cutting edge was modeled and verified by inspection of the actual cutting edge.

5. A mathematical model was established to predict the machined surface topography under tool fracture wear based on the approximated geometric elements and the distance between two neighboring ridges. In the prediction of machined surface cross-sectional profile, a correction factor was used to correct the parameters of geometric elements. The surface topography was verified by the examined one. The model can also be used to calculate the range of the maximum peak-to-valley surface roughness on both the machined surface cut by fresh tool and tool fracture wear. The calculated results show that the model can predict the surface roughness.

6. The proposed method is a progressive tool wear and surface topography evaluation method compared to conventional ones, since it not only can find the occurrence of tool wear and obtain tool fracture wear characteristics on-line, but it can also predict machined surface topography and evaluate the machined surface roughness.
Chapter 6 Tool Flank Wear Evaluation Method using Cutting Chips

6.1 Introduction

As cutting chips are directly generated from the material removal processes in metal cutting, chip morphology is directly affected by tool wear and vice versa. In the field of ultra-precision machining, the study of the relationship between chip morphology and tool wear is significant because tool wear characteristics can be reflected by the morphology of cutting chips. The relationship between cutting chips and tool wear is such that on one hand the occurrence of tool wear has some effect on cutting chip morphology, while on the other hand cutting chips have some effect on tool wear. Ultra-precision raster milling (UPRM) is an intermittent cutting process, the special cutting mechanism of which makes the cutting chips thicker at the central location while thinner at the two sides. Therefore, the occurrence of flank wear of a diamond tool makes cutting chip morphology different from the chip morphology created by the cut of a fresh diamond tool. This difference can be modeled and used to evaluate tool wear level.

In this chapter, cutting chip morphology is used to measure the tool flank wear and predict the machined surface quality. A cutting experiment is performed to explore chip morphology under different widths of flank wear land and to investigate the effect of tool wear on surface roughness; the machined surface quality is examined at different cutting distances. A geometric model is developed to identify the width of
flank wear land based on chip morphology. Another mathematical model is established to calculate the theoretical peak-to-valley roughness under the occurrence of tool flank wear. The influences of flank wear land width and angle on surface roughness is discussed and surface improvement methods are suggested based on the mathematical model. The research provides a good understanding of the effect of tool wear on cutting chip morphology and surface roughness, in addition, the results of this research will help in detection of tool flank wear and the evaluation of machined surface quality in intermittent cutting processes.

6.2 Experiments

In the experiment, flat cutting was conducted on a Precitech Freeform 705G (Precitech Inc., USA) multi-axes CNC ultra-precision raster milling machine. The cutting parameters are listed in the first column of Table 6.1.

<table>
<thead>
<tr>
<th>Cutting parameters</th>
<th>Flat cutting</th>
<th>Depth cutting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool type</td>
<td>APEX insert diamond tool</td>
<td></td>
</tr>
<tr>
<td>Rake angle</td>
<td>-2.5°</td>
<td></td>
</tr>
<tr>
<td>Clearance angle</td>
<td>15°</td>
<td></td>
</tr>
<tr>
<td>Tool radius</td>
<td>0.631mm</td>
<td></td>
</tr>
<tr>
<td>Swing distance</td>
<td>28.35mm</td>
<td>28.35mm</td>
</tr>
<tr>
<td>Feed rate</td>
<td>200mm/min</td>
<td>225 mm/min</td>
</tr>
<tr>
<td>Step distance</td>
<td>0.025mm</td>
<td>0.025mm</td>
</tr>
<tr>
<td>Spindle speed</td>
<td>4500 rpm</td>
<td>4500 rpm</td>
</tr>
<tr>
<td>Depth of cut</td>
<td>0.03mm</td>
<td>0.002, 0.005, 0.010, 0.015mm</td>
</tr>
<tr>
<td>Cutting strategy</td>
<td>Horizontal cutting</td>
<td>Horizontal cutting</td>
</tr>
<tr>
<td>Cutting environment</td>
<td>Lubricant on</td>
<td>Lubricant on</td>
</tr>
</tbody>
</table>
The workpiece material is brass (CuZn30 alloy) and the total cutting distance is 5000m. Before and after every 1000m of flat cutting, a group of depth cutting at the cutting depth of 2um, 5um, 10um and 15um were conducted using the cutting parameters listed in the second column of Table 6.1. The schematic of the flat cutting and depth cutting on the workpiece are shown in Figure 6.1. The depth cutting can be used to investigate the effect of tool wear on the cutting chips morphology.

![Figure 6.1 Schematic of cutting strategies](image)

Figure 6.1 Schematic of cutting strategies in (a) flat cutting, and (b) depth cutting on the workpiece

To compare the chip morphology cut by a fresh tool and the worn tool at different cutting distances, cutting chips were collected before and after every 1000m of flat cutting, and after each depth cutting. The collected chips were then examined by a Hitachi TM3000 scanning electron microscope (SEM) and the inspected results were reordered and used to calculate the width of flank wear. In addition, after every 1000m of flat cutting, the diamond tool was dismounted and examined by the SEM to measure the width of flank wear land.

### 6.3 Results and Discussion

After the cutting process, the tool wear progress was inspected and then fully
figured as shown in Figure 6.2.

Figure 6.2 SEM photographs of the cutting edge of (a) fresh tool (b) worn tool at the cutting distance of 1000m (c) 2000m (d) 3000m (e) 4000m (f) 5000m

It is found from Figure 6.2 (a) that a fresh diamond tool usually has a sharp cutting edge. After 1000m flat cutting, some fractures are found on the cutting edge, the bigger ones of which are marked by F1 and F2 in Figure 6.2 (b). After 2000m of flat cutting, it is found from Figure 6.2 (c) that some workpiece material was welded on the rake face of the diamond tool. The welded material can increase the friction force on the rake face and make the chip crushed at its tool entry side, also it is found
that these bigger fractures were flattened a little. Figure 6.2 (d) shows the tool figure after 3000m flat cutting, it is found that the material was still welded on the rake face of the cutting tool. Moreover, the cutting edge was not sharp but rounded, and the two bigger fractures were flattened a lot. Figure 6.2 (e) indicates the diamond tool figure at the cutting distance of 4000m where it is found that a wear land is formed with a width of about 1um. In addition, at this cutting distance, the two bigger fractures are flattened and hard to distinguish. Figure 6.2 (f) shows the SEM tool wear figure at the cutting distance of 5000m where it is found that the figure has no significant difference from the cutting tool figure as shown in Figure 6.2 (e), only the width of wear land has increased a little.

The occurrence of tool wear certainly affects the cutting chip morphology. Figure 6.3 shows chip figures at different cutting distances. Figure 6.3 (a) shows the cutting chip figure cut down by a fresh tool, it is found that the tool entry side of cutting chips is quite thin. After cutting about 1000m, it can be seen that there are some tool wear traces on the chip surface (see Figure 6.3(b)). These traces are thought to be imprinted by fracture of the cutting edge because they have the same distance and cross-sectional profile. Figure 6.3 (c) shows the chip figures at the cutting distance of 2000m. It can be seen that the chip is crushed at the tool entry side, which may be because the welding of the material increased the friction force on the rake face of the cutting tool so that a crush occurred at the tool entry side of the cutting chips. Moreover, it is found that the chip is coiled due to the accumulation of workpiece material on the rake face of the cutting tool, which makes the chip surface hard to
examine.

Figure 6.3 SEM photograph of cutting chip morphology cut by (a) fresh tool (b) worn tool at the cutting distance of 1000m (c) 2000m (d) 3000m (e) 4000m (f) 5000m

Figure 6.3 (d) shows the cutting chip figure at the cutting distance of 3000 meters. Similar to that at the cutting distance of 2000m, the chip is crushed at the tool entry side of cutting chips due to the materials welding. Figure 6.3 (e) shows the chip figure at the cutting distance of 4000m. It is found that at the tool entry side, some shutter-like structure was formed. This is because at this cutting distance, the cutting edge radius of a cutting tool is comparable with the thickness of cutting chips at the
tool entry side, so that a macro cutting instead of micro cutting process is dominant. Figure 6.3 (f) shows a chip figure at the cutting distance of 5000m where it is found the cutting chip was truncated at the place near to its tool entry side. This is caused by the increase of wear land width.

The increase of wear land width has a significant effect on the cutting chips. Figure 6.4 shows a comparison of cutting chip morphology of the fresh tool and the tool after 5000m flat cutting at the tool entry side. It is found the cutting chips cut by a fresh tool at its tool entry side have a feather-like structure. However the chip truncated and some shutter-like structures formed at the tool entry side under cutting by a worn tool.

![Feather-like structure](image1.png)

**Figure 6.4 Comparison of cutting chip cut by (a) fresh tool (b) worn tool**

Before cutting and after every 1000m of flat cutting, a group of depth cutting experiments was performed at the cutting depth of 2um, 5um, 10um, and 15um. During the cutting process, cutting chips were collected at different cutting depths. Figure 6.5 shows the cutting chip figures at different cutting depths of cut by a fresh tool; it is found that all the cutting chips can be fully generated during the cutting process.
Figure 6.5 Cutting chip morphologies caused by a fresh tool at the cutting depth of (a) 2um (b) 5um (c) 10um (d) 15um

Figure 6.6 shows the cutting chip figures cut by a worn tool after cutting 5000m. From these figures, it is found that the cutting chips are figured as different morphologies at the different cutting depths. At the cutting depth of 2um, the cutting chips have not formed but some needle-like chips were found as shown in Figure 6.6 (a). At the cutting depth of 5um, some chips were found they are all truncated and some parts are consumed (see Figure 6.6 (b)). At the cutting depth of 10um and 15um, although truncation still exists, the chip consumed area is reduced considerably as compared to the cutting depth of 5um.
Figure 6.6 Cutting chip morphologies caused by a worn tool at the cutting depth of: (a) 2um, (b) 5um, (c) 10um and (d) 15um

The different cutting chip morphologies shown in Figure 6.6 were caused by the occurrence of tool wear, which can be clearly concluded as comparing the cutting chip morphology cut by fresh tool and worn tool. As shown in Figure 6.7, cutting chip morphologies generated from the fresh tool and worn tool after 5000m flat cutting at the cutting depth of 0.005um are compared; it is found that cutting chips were fully generated with the fresh tool. However, cutting chips cannot be fully cut down by the tool after 5000m of flat cutting, instead truncated cutting chips were formed as shown in Figure 6.7 (b). Through a comparison between Figure 6.7 (a) and (b), it is found that the truncation of cutting chips occurs on both their tool entry and tool exit sides, and that it occurs in the step direction.
6.4 Modelling and Identification of Flank Wear Land

6.4.1 Chip Thickness along the Feed Direction

Some content in this section comes from our published work (Zhang et al., 2014c). To explore the relation between tool wear and cutting chip morphology, a mathematical model is established to simulate the cutting chip figure, as discussed in Chapter 5. Since the cutting chip is enveloped by four surfaces, four equations are derived to present the cutting chip with each one representing one surface, given by:

\[
\begin{align*}
\left(\sqrt{(x + f_c)^2 + z^2} - s_w + R\right)^2 + y^2 &= R^2 \\
\left(\sqrt{x^2 + z^2} - s_w + R\right)^2 + y^2 &= R^2 \\
(z - s_w + R)^2 + (y + s)_p^2 &= R^2 \\
z &= s_w - a_p
\end{align*}
\]

The four equations in Eq. (6-1) owns six boundary curves, given by:
Chapter 6: Tool Flank Wear Evaluation Method using Cutting Chips

Eq (6-1) and Eq. (6-2) present the mathematical model of cutting chips and the cutting chip morphology based on the tool geometric parameters and cutting parameters plotted in Figure 6.8.

\[
\begin{align*}
    x &= -\frac{f_e}{2} \\
    x &= -\sqrt{s_i(2y + s_i) + 2(s_w - R)(\sqrt{R^2 - y^2} - \sqrt{R^2 - (y + s_i)^2})} - f_e \\
    x &= -\sqrt{s_i(2y + s_i) + 2(s_w - R)(\sqrt{R^2 - y^2} - \sqrt{R^2 - (y + s_i)^2})} \\
    y &= \sqrt{a_p(2R - a_p) - s_i} \\
    x &= \sqrt{(\sqrt{R^2 - y^2 + s_w - R})^2 - (s_w - a_p)^2} - f_e \\
    x &= \sqrt{(\sqrt{R^2 - y^2 + s_w - R})^2 - (s_w - a_p)^2}
\end{align*}
\]  

(6-2)

In Figure 6.8, the curves \(d\) and \(e\) are described by the forth to the fifth equation in Eq. (6-2), while the surface \(B\) is presented by the second equation in Eq. (6-1). According to the derived mathematical model and geometric knowledge, it is found in the feed direction that chip morphology is thicker at the center and thinner at the two sides.

For a cutting tool, there is a critical chip thickness (CCT) in the feed direction of
the cutting chips. If the cutting depth is smaller than the CCT, the cutting tool cannot cut any materials, and therefore cutting chips cannot be generated. If the related CCT is smaller than the maximum thickness of the chip being cut, the chip will be truncated at the thickness around the CCT. In this case, according to the principle of critical cutting depth, the CCT is thought to be the height of flank wear land of the cutting tool.

For the cutting chips generated from UPRM, the thinnest thickness in the step direction (TTSD) is usually associated with the first occurrence of truncation, which can lead to the full truncation of cutting chips along the step direction. Therefore, the relation curve of TTSD values with respect to the position of cutting chips in the feed direction is important for flank wear identification. From geometric knowledge and the cutting mechanism of UPRM, it is found that all the TTSDs of cutting chips are on the curve \(d\) or \(e\), as shown in Figure 6.8. Therefore, the TTSD values can be calculated by solving the straight distance from curve \(d\) or \(e\) to surface \(B\). In UPRM, the spindle moves quite a small distance along the feed direction during chip cutting, which can be ignored. Assuming the spindle axis has no translation during the chip cutting process, the TTSDs over the cutting chips in the feed direction can be derived as follows:

For line \(d\), any point on it denotes as:

\[
\begin{align*}
    x_0 & \leq x_0 \leq x_i \\
    y_0 & = \sqrt{a_p (2R-a_p)} - s_i \\
    z_0 & = s_e - a_p
\end{align*}
\]  

(6-3)

While for curve \(e\), any point on it can be expressed as:
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\[
x_0 = \sqrt{(R^2 - y_0^2 + s_u - R)^2 - (s_u - a_p)^2 - f_e}
\]

\[
\sqrt{a_p(2R - a_p) - s_i} \leq y_0 \leq \sqrt{R^2 - \left(\frac{f_e}{4} + (s_u - a_p)^2 - s_u + R\right)^2}
\]

\[
z_0 = s_u - a_p
\]

The origin of coordinate system \(o-xyz\) is \((0, 0, 0)\), thus the line equation passing through the origin point and the point \(S (x_0, y_0, z_0)\) is derived as:

\[
\frac{x}{x_0} = \frac{y}{y_0} = \frac{z}{z_0}
\]

While intersection point \(T\) between the line expressed in Eq. (6-5) and the back surface \(B\) are the roots of the following equations:

\[
\begin{align*}
x_1^2 + y_1^2 + z_1^2 & = x_0^2 + y_0^2 + z_0^2 \quad x_1^2 - 2(s_u - R)x_1 + s_u^2 - 2s_uR = 0 \\
y_1^2 + y_0^2 + z_1^2 & = y_0^2 \quad y_1^2 - 2(s_u - R)y_1 + s_u^2 - 2s_uR = 0 \\
z_1^2 + y_0^2 + z_1^2 & = z_0^2 \quad z_1^2 - 2(s_u - R)z_1 + s_u^2 - 2s_uR = 0
\end{align*}
\]

The roots of Eq. (6-6) are solved as:

\[
\begin{align*}
x_1 = x_0(s_u - R)\sqrt{x_0^2 + z_0^2} + x_0\sqrt{R^2(x_0^2 + z_0^2) - y_0^2s_u(s_u - 2R)} \\
y_1 = y_0(s_u - R)\sqrt{y_0^2 + z_0^2} + y_0\sqrt{R^2(y_0^2 + z_0^2) - y_0^2s_u(s_u - 2R)} \\
z_1 = z_0(s_u - R)\sqrt{x_0^2 + z_0^2} + z_0\sqrt{R^2(x_0^2 + z_0^2) - y_0^2s_u(s_u - 2R)}
\end{align*}
\]

\(x_1, y_1, z_1\) are the coordinate components of the intersection point \(T\). The location of point \(T\) depends on the location of point \(S\) and fulfills the following limitations:

\[
\begin{align*}
-\frac{f_e}{2} \leq x & \leq \sqrt{(\sqrt{a_p(2R - a_p) - s_i}^2 + s_u - R)^2 - (s_u - a_p)^2 - f_e} \\
\sqrt{a_p(2R - a_p) - s_i} \leq y & \leq \sqrt{a_p(2R - a_p)} \\
s_u - a_p \leq z & \leq s_u
\end{align*}
\]
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The distance between point $S$ and $T$ is the TTSD, which can be calculated by:

$$l = \sqrt{(x_1-x_0)^2 + (y_1-y_0)^2 + (z_1-z_0)^2}$$  \hspace{1cm} (6-9)

Eq. (6-9) presents the TTSD function over the cutting chips in the feed direction. For ease of understanding, the TTSD is henceforth referred to as chip thickness.

Based on the derived mathematical model, the TTSD profile and its three side views are shown in Figure 6.9. The three views in Figure 6.9 (b), (c) and (d) can be used to verify the calculation results. It is found from Figure 6.9 (c) that a maximum chip thickness exists since the chip thickness increases first and then decreases, which is accordant with the previous simulation results.

![Figure 6.9 Profile figures of the TTSD in (a) isometric view (b) top view (c) side view (d) back view](image)

The relationship curve of chip thickness with respect to the position in the feed
direction of the cutting chip is shown in Figure 6.10. Figure 6.11 is the curve of chip thickness with respect to the chip width. It is found from Figure 6.10 and Figure 6.11 that the chip thickness increases first and then drops subsequently with the growth of the chip width and the distance in the feed direction; the maximum chip thickness occurs on the point $m$ in Figure 6.8. The relationship curve between chip thickness and chip width can be used to predict the width of flank wear land based on chip morphology.

Figure 6.10 Relationship curve of chip thickness with respect to the position in the feed direction of cutting chips

Figure 6.11 Relationship curve of chip thickness with respect to the chip width
The chip thickness change can also be examined by the cross-sectional profile of the cutting chip. The simulated chip morphology and its cross-sectional curve at different positions in the feed direction are drawn as shown in Figure 6.12 (a) and (b). From Figure 6.12 (b) it is found that the thickness of the cutting chip increases first and then decreases in the feed direction; a maximum chip thickness exists.

Figure 6.12 Simulated chip morphology based on (a) the given cutting parameters (b) its cross-section curve at different positions in the feed direction of the cutting chips

From Figure 6.7 (b), the widths \((l_1\) and \(l_2\)) of the cutting chip at both truncation positions are measured as 32um and 22um respectively. According to Figure 6.11, the thicknesses of the cutting chip at both the widths of 32um and 22um are about 0.6um. From Figure 6.10, it is found that the \(x\) coordinate components at the chip thickness larger than 0.6um are from 0.3151mm to 0.3414mm. The truncated chip length was calculated as 26.3um, which agrees well with the chip length in Figure 6.7 (b). However, from Figure 6.10 and Figure 6.12 (a), it is found that the \(x\) coordinate components of the full cutting chips are from -0.025mm to 0.3879mm; the full chip length was calculated as 412.9um. Through comparison of the truncated chip length
(26.3\text{um}) and the full chip length (412.9\text{um}), it can be concluded that tool flank wear makes most parts of the cutting chip truncated under the given cutting parameters.

To identify the chip thickness at the chip truncation position, two methods can be used. In the first method, the width of cutting chips at their truncation position was used to identify the thickness of cutting chips based on the Figure 6.1 (a). Another method is based on the length of truncated cutting chips, as shown in Figure 6.1 (b). However, it should be noted that due to the compression effect in the chip formation process, the chip length should be corrected before the tool flank wear identification.

![Figure 6.1](image)

**Figure 6.13** Two methods used to identify the chip thickness: (a) chip width method at the truncation position (b) chip length method

Cutting parameters can directly affect the chip thickness identification and cutting chip morphology. According to the geometric relationship as shown in Figure 6.14, we obtain:

\[ \cos \phi = \frac{R - a_p}{R} \]  

(6-10)

From Eq. 6-10 the angle \( \phi \) in Figure 6.14 can be calculated as:

\[ \phi = \arccos\left(\frac{R - a_p}{R}\right) \]  

(6-11)
Similarly, the angle $\beta$ in Figure 6.14 can be calculated as:

$$\beta = \arcsin\left(\frac{s_t}{2R}\right)$$  \hspace{1cm} (6-12)

As shown in Figure 6.14, to move the maximum chip thickness point (MCTP) to the central place of cutting chips in the step direction, the tool arc length should be equal to the step distance, which yields:

$$s_t = R\left(\arccos\left(\frac{R-a_p}{R}\right) - \arcsin\left(\frac{s_t}{2R}\right)\right)$$  \hspace{1cm} (6-13)

From Eq. (6-13), the optimized cutting depth can be solved as:

$$a_p = R\left(1 - \cos\left(\frac{s_t}{R} + \arcsin\left(\frac{s_t}{2R}\right)\right)\right)$$  \hspace{1cm} (6-14)

According to Table 6.1 and Eq. (6-14), $s$ is 0.025mm, $R$ is 0.631mm, the optimized value of $a_p$ is calculated as 1.1um.

According to the geometric relationship shown in Figure 6.15, we obtain:

$$\cos \varphi = \frac{s_w - a_p}{s_w}$$  \hspace{1cm} (6-15)
From Eq. 6-15 angle $\varphi$ can be solved as:

$$\varphi = \arccos \left( \frac{s_w - a_p}{s_w} \right)$$ (6-16)

While angle $\alpha$ can be solved as:

$$\alpha = \arcsin \left( \frac{f_e}{2s_w} \right)$$ (6-17)

As is shown in Figure 6.15, to move the MCTP to the central place of cutting chips in the feed direction, the swing arc length should be equal to the feed rate, which yields:

$$f_e = s_w \left( \arccos \left( \frac{s_w - a_p}{s_w} \right) - \arcsin \left( \frac{f_e}{2s_w} \right) \right)$$ (6-18)

According to Table 6.1 and Eq.(6-18), $s_w$ is 28.35mm, $R$ is 0.631mm, $a_p$ is 1.1um.

By using the calculation program in MATLAB, $f_e$ is calculated as 166.5um.

Based on the optimized cutting parameters, the cutting chip morphology is plotted in Figure 6.16, while its thickness curve with respect to the distance in feed direction is shown in Figure 6.17. It is found that after optimization, the thickest position of the cutting chip moves to its central place.
From the discussion above, it is found that the cutting depth and step distance can seriously affect the cutting chip profile. The cutting depth mainly affects the cutting chip morphology in the feed direction, while the step distance can affect cutting chip morphology in the step direction. This cutting chip morphology optimization is beneficial for tool wear measurement by using cutting chips.
6.4.2 Wear Land Angle Identification

Usually, the wear land has an angle with respect to the rake face of the diamond tool, called wear land angle. The existence of wear land angle leads to inconformity between the height and width of the flank wear land. The wear land angle is different for different materials being cut. The difference of wear land angle makes the cutting chip morphology different although the cutting tool used has the same wear land width.

To identify the wear land angle, this research conducted straight cutting with the worn tool on a thin brass sheet to imprint the wear land angle of the cutting tool. The brass sheet was then examination by the SEM from the side view to obtain the wear land angle. The wear land angle is an important parameter in this investigation. The SEM figure of the side view of the brass sheet with wear land angle imprint is shown in Figure 6.18.

Figure 6.18 SEM image of the wear land angle imprinted on a thin brass sheet
Since the relationship between tool flank wear and chip morphology was investigated based on the geometric method, the research results are also feasible for UPRM of other diamond turnable ductile materials, such as copper and its alloys, aluminium and its alloys, and electroless nickel. However, it should be noted that the wear land angle of cutting tools is different in UPRM since different materials are cut. Therefore, the same chip morphology may refer to the different width of flank wear land for UPRM of different materials.

6.4.3 Wear Land Width Calculation

Some content in this section comes from our published work (Zhang et al., 2014c).

Usually, the flank wear land has an angle with respect to the rake face of cutting tools, as shown in Figure 6.18.

![Figure 6.19 Schematic of the calculation of the wear land width](image-url)
According to their geometric relation as shown in Figure 6.19 above, the width of flank wear land can be calculated by:

\[ w = h / \cos \theta = h / \cos(\alpha + \gamma) \]  

(6-19)

where \( w \) is the width of flank wear land; \( h \) is the height of flank wear land, which is obtained from the mean value calculation of identified CCTs; \( \alpha \) is the wear land angle, which in this investigation was measured as 40.5°; \( \gamma \) is the rake angle of diamond tool, \( \gamma = -2.5° \).

Based on the relationship between chip morphology and tool flank wear in UPRM, the width of flank wear land can be identified. The identification procedures are as follows:

**Step 1.** Measuring the chip width \( l_1 \) and \( l_2 \) at the truncation positions of cutting chips, as shown in Figure 6.7 (b).

**Step 2.** Calculate the CCTs and their mean value based on the measured chip width \( l_1 \) and \( l_2 \). The mean value of the CCTs is the height of flank wear land.

**Step 3.** Based on the height of flank wear land and the wear land angle, calculate the width of flank wear land through Eq. 6-19.

Based on the flank wear identification procedures listed above, the width of flank wear land of the cutting tool at different cutting distances was identified as listed in Table 6.2. The identified widths of flank wear lands are listed in the sixth column of the table, while the last column of the table is the measured widths of these flank wear lands.
Table 6.2 Identification of the widths of flank wear lands and their comparison with the measured ones at different cutting distance

<table>
<thead>
<tr>
<th>Cutting distance(m)</th>
<th>Width of cutting chip(um)</th>
<th>Calculated CCT(um)</th>
<th>Mean value of the CTT(um)</th>
<th>Calculated width of the wear land(um)</th>
<th>Measured width of the wear land(um)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>$l_1$ 90</td>
<td>0.1486</td>
<td>0.1495</td>
<td>0.2044</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>$l_2$ 5.5</td>
<td>0.1504</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>$l_1$ 82</td>
<td>0.2753</td>
<td>0.2750</td>
<td>0.3760</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>$l_2$ 10</td>
<td>0.2746</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3000</td>
<td>$l_1$ 67</td>
<td>0.4074</td>
<td>0.4035</td>
<td>0.5517</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td>$l_2$ 14.5</td>
<td>0.3995</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4000</td>
<td>$l_1$ 51</td>
<td>0.5078</td>
<td>0.5026</td>
<td>0.6872</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>$l_2$ 18</td>
<td>0.4974</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5000</td>
<td>$l_1$ 32</td>
<td>0.6025</td>
<td>0.60595</td>
<td>0.8285</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>$l_2$ 22</td>
<td>0.6094</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Based on Table 6.2, the identified widths of flank wear land based on cutting chip morphologies and the measured ones at cutting distances from 1000 meters to 5000 meters are compared in Figure 6.20. It is found that both the identified width and measured width of the flank wear land increase with the increasing cutting distance. However, the measured widths are a little bigger than the identified ones, this may be caused by: (i) the deviation between the critical cutting depth and the height of flank wear land; and (ii) the existence of cutting and measurement errors.
Figure 6.20 Relationship curves of the identified widths of flank wear land and measured ones with respect to the cutting distance

Since the relationship between tool flank wear and chip morphology was investigated based on geometric methods, the research results are also feasible for UPRM of other diamond turnable ductile materials, such as copper and its alloys, aluminium and its alloys, and electroless nickel. However, it should be noted that the wear land angle of cutting tools is different in UPRM as different material are cut. Therefore, according to Eq. 6-19, the same chip morphology may refer to the different width of flank wear land for UPRM of different materials.

6.5 Modelling and Analysis of Surface Roughness under Tool Flank Wear

The occurrence of tool flank wear directly affects surface form error and surface roughness, and since the tool flank wear of diamond tool has a regular profile, the effects of tool flank wear on the machined surface quality can be modeled.
6.5.1 Surface Roughness Modeling under Tool Flank Wear

The occurrence of flank wear of a diamond tool makes the cutting edge retract on the thrust plane and forms a new cutting edge. Figure 6.21 shows a schematic of the cutting edge retraction and their effects on theoretical surface roughness. Suppose the newly formed cutting edge profile is an arc, and the largest distance between the original cutting edge arc and the new cutting edge arc is at the central position of the arc. From Figure 6.21, it is found that the new cutting edge arc has a larger tool nose radius and a different center.

Figure 6.21 Schematic of (a) side view and (b) top view (K--K' plane) of tool flank wear, and (c) effect of tool flank wear on surface roughness
For clarity, four coordinate systems \( o-yz \), \( o'-y'z' \), \( o_1-y_1z_1 \) and \( o_1'-y_1'z_1' \) were established to present different arcs, as shown in Figure 6.21 (b) and (c). In this figure, \(|bc|\) is the wear land width, whose value can be identified from the cutting chips, and \( \phi \) is the wear land angle whose value is 40.5° as the brass material is cut.

Based on the geometric relationship, the cutting edge retraction \(|bd|\) can be calculated from the sine law. As shown in Figure 6.21 (a), in triangle \( \Delta abc \), \( \angle acb = \phi \), \( \angle bac = 90° - \delta - \gamma \), so according to the sine law:

\[
\frac{|bc|}{\sin(90°-\delta-\gamma)} = \frac{|ab|}{\sin \phi} \quad (6-20)
\]

From Eq. 6-20, the length \(|ab|\) can be calculated as:

\[
|ab| = \frac{\sin \phi}{\sin(90°-\delta-\gamma)} |bc| = \frac{\sin \phi}{\sin(90°-\delta-\gamma)} w \quad (6-21)
\]

Where \( w \) is the wear land width.

In triangle \( \Delta abd \), the length \(|bd|\) can be calculated as:

\[
|bd| = |ab| \sin \delta = \frac{\sin \phi \sin \delta}{\sin(90°-\delta-\gamma)} w \quad (6-22)
\]

In the thrust plane \( K-K' \), suppose \( h = |b'd'| \), we obtain:

\[
h = |b'd'| = |bd| = \frac{\sin \phi \sin \delta}{\sin(90°-\delta-\gamma)} w \quad (6-23)
\]

The tool flank wear in the UPRM process makes the tool material loss zone a crescent-like profile that is thicker at the center position while thinner at the two sides.

Suppose the new formed cutting edge and the original cutting edge intersected at the point \( m \) and \( n \), while the central point of new cutting edge arc \( mn \) is \( b' \), the coordinates of point \( m \), \( n \) and \( b' \) in coordinate system \( o-yz \) and \( o'-y'z' \) can be derived.

In coordinate system \( o-yz \), based on the cutting parameters and geometric relationship, the coordinate of point \( m \) is derived as \( y = -\frac{s_t}{2}, z = \sqrt{R^2 - \frac{s_t^2}{4}} \); the
coordinate of point n is expressed as \( y = \sqrt{a_p(2R - a_p)}, z = R - a_p \).

In Figure 6.21 (b), according to the geometric relationship, we obtain:

\[
\begin{align*}
\cos \alpha &= \frac{R - a_p}{R} \quad (6-24) \\
\sin \beta &= \frac{s_t}{2R} \quad (6-25)
\end{align*}
\]

From Eq. 6-24 and Eq. 6-25, two angles \( \alpha \) and \( \beta \) can be calculated as:

\[
\begin{align*}
\alpha &= \arccos \left( \frac{R - a_p}{R} \right) \quad (6-26) \\
\beta &= \arcsin \left( \frac{s_t}{2R} \right) \quad (6-27)
\end{align*}
\]

Therefore, \( \theta \) in Figure 6.21(b) can be calculated as:

\[
\theta = \frac{\alpha + \beta}{2} \quad (6-28)
\]

While \( \theta - \beta \) is obtained as:

\[
\theta - \beta = \frac{\alpha - \beta}{2} \quad (6-29)
\]

Therefore, in coordinate system \( o-yz \), the coordinate of point \( b' \) is \( y = (R - h) \sin \left( \frac{\alpha - \beta}{2} \right), z = (R - h) \cos \left( \frac{\alpha - \beta}{2} \right) \).

Based on the coordinate transformation, any points in coordinate system \( o-yz \) can be expressed in coordinate system \( o'-y'z' \) as:

\[
\begin{align*}
y' &= y + l \\
z' &= z + t 
\end{align*}
\]

Therefore, the coordinates of points \( m, n \) and \( b' \) can be expressed in coordinate system \( o'-y'z' \) as: \( (l - \frac{s_t}{2}, \sqrt{R^2 - \frac{s_t^2}{4}} + t), (\sqrt{a_p(2R - a_p)} + l, R - a_p + t) \) and \( ((R - h) \sin \left( \frac{\alpha - \beta}{2} \right) + l, (R - h) \cos \left( \frac{\alpha - \beta}{2} \right) + t) \).

For the new cutting edge arc, \( |o'm| = |o'b'| = |o'n| = R' \), yields:
\[
\begin{align*}
(l - \frac{s_t}{2})^2 + \left( \sqrt{R^2 - \frac{s_t^2}{4} + t} \right)^2 &= R'^2 \\
\left( \frac{a_p(2R - a_p) + l}{2} \right)^2 + (R - a_p + t)^2 &= R'^2 \\
(R - h) \sin \left( \frac{\alpha - \beta}{2} \right) + l^2 + (R - h) \cos \left( \frac{\alpha - \beta}{2} \right) + t^2 &= R'^2
\end{align*}
\]

Expanding each equation in Eq. 6-31, yields:

\[
\begin{align*}
l^2 - s_t l + R^2 + 2t \sqrt{R^2 - \frac{s_t^2}{4} + t^2} &= R'^2 \\
2l \frac{a_p(2R - a_p) + l^2 + R^2 + 2(R - a_p)t + t^2}{} &= R'^2 \\
(R - h)^2 + 2l(R - h) \sin \left( \frac{\alpha - \beta}{2} \right) + l^2 + 2t(R - h) \cos \left( \frac{\alpha - \beta}{2} \right) + t^2 &= R'^2
\end{align*}
\]

Subtracting the second equation from the first equation in Eq. 6-32, yields:

\[
2t \left( \sqrt{R^2 - \frac{s_t^2}{4}} - (R - a_p) \right) - l \left( s_t + 2a_p(2R - a_p) \right) = 0
\]

From Eq. 6-33, variable \( l \) can be solved as:

\[ l = \frac{2 \left( \sqrt{R^2 - \frac{s_t^2}{4} - (R - a_p)} \right)}{s_t + 2a_p(2R - a_p)} \]

(6-34)

Similarly, subtracting the third equation from the first equation in Eq. 6-32 yields:

\[
(R^2 - (R - h)^2) + 2t \left( \sqrt{R^2 - \frac{s_t^2}{4} - (R - h) \cos \left( \frac{\alpha - \beta}{2} \right)} \right) - l \left( s_t + 2(R - h) \sin \left( \frac{\alpha - \beta}{2} \right) \right) = 0
\]

(6-35)

In Eq. 6-35, isolating variable \( l \), yields:

\[
l = \frac{2 \left( \sqrt{R^2 - \frac{s_t^2}{4} - (R - h) \cos \left( \frac{\alpha - \beta}{2} \right)} \right)}{(s_t + 2(R - h) \sin \left( \frac{\alpha - \beta}{2} \right))} t + \frac{(2hR - h^2)}{(s_t + 2(R - h) \sin \left( \frac{\alpha - \beta}{2} \right))}
\]

(6-36)

Solving the variables of \( l \) and \( t \) from Eq. 6-34 and Eq. 6-36 yields:

\[
t = \frac{(2hR - h^2)(s_t + 2a_p(2R - a_p))}{2s_t \left( (R - h) \cos \left( \frac{\alpha - \beta}{2} \right) - R + a_p \right) + 4(R - h) \sin \left( \frac{\alpha - \beta}{2} \right) \left( \sqrt{R^2 - \frac{s_t^2}{4} - R + a_p} + 4a_p(2R - a_p) \right) \left( R - h \cos \left( \frac{\alpha - \beta}{2} \right) - \sqrt{R^2 - \frac{s_t^2}{4}} \right)}
\]

(6-37)

\[
l = \frac{2 \left( \sqrt{R^2 - \frac{s_t^2}{4} - R + a_p} \right)(2hR - h^2)}{2s_t \left( (R - h) \cos \left( \frac{\alpha - \beta}{2} \right) - R + a_p \right) + 4(R - h) \sin \left( \frac{\alpha - \beta}{2} \right) \left( \sqrt{R^2 - \frac{s_t^2}{4} - R + a_p} + 4a_p(2R - a_p) \right) \left( R - h \cos \left( \frac{\alpha - \beta}{2} \right) - \sqrt{R^2 - \frac{s_t^2}{4}} \right)}
\]

(6-38)
While according to the geometric relationship, the radius of the new cutting edge arc can be calculated by:

\[ R' = \sqrt{l^2 + t^2 + R - h} \]  

(6-39)

Parameters \( l, t \) and \( R' \) are quite important parameters in the identification of new cutting edge since they present the new cutting edge equation and its center location.

In Figure 6.21, it can be seen that the peak-to-valley roughness \( R_t \) for a fresh tool with tool nose radius of \( R \) is the deviation of \( z \) coordinate values of point \( e \) and point \( g \). The theoretical peak-to-valley roughness is calculated as:

\[ R_t = R - \sqrt{R^2 - (s_t/2)^2} \]  

(6-40)

However, the formation of a flank wear land changes both the tool nose radius and the cutting edge arc center, which can affect the machined surface quality. The effects of tool flank wear on machined surface quality include two aspects: First, using the same cutting parameters or smaller step distance to continue the cutting, this will reduce the surface roughness due to the formation of relative larger tool nose radius. Second, using a larger step distance to continue the cutting, this will increase the surface roughness, for example, the valley point changes to point \( i \), while the peak point changes to \( u \) (Figure 6.21(c)). The surface roughness in former aspect can be calculated through Eq.6-40 by changing \( R \) into \( R' \). This section will focus on the later aspect due to the computational complexity. For clarity, three coordinate systems are established as: \( o-yz, o_1-y_1z_1, o'_1-y'_1z'_1 \).

For point \( i \), whose component value in coordinate system \( o'_1-y'_1z'_1 \) is \((0, R')\). According to the coordinate transforms, point \( i \) can be expressed in coordinate system
o₁ − y₁z₁ as (−l, R′ − t) and expressed in coordinate system o − yz as (−l − sₜ, R′ − t).

For point u, it is the intersection point of original cutting edge arc and worn cutting edge arc, the original arc equation in coordinate system o − yz can be expressed as:

\[ y^2 + z^2 = R^2 \]  \hspace{1cm} (6-41)

While the equation of worn arc in coordinate system o₁ − y₁z₁ is depicted as:

\[ y'_1^2 + z'_1^2 = R'^2 \]  \hspace{1cm} (6-42)

Through the coordinate transformation, Eq. 6-42 can be expressed in coordinate system o − yz as:

\[ (y + l + sₜ)^2 + (z + t)^2 = R'^2 \]  \hspace{1cm} (6-43)

The point u can be solved by the same solution of Eq. 6-41 and Eq. 6-43, yields:

\[
\begin{cases}
\quad y^2 + z^2 = R^2 \\
\quad (y + l + sₜ)^2 + (z + t)^2 = R'^2
\end{cases}
\]  \hspace{1cm} (6-44)

To solve the variables y and z in Eq. 6-43, expending all the brackets in Eq. 6-44 yields:

\[
\begin{cases}
\quad y^2 + z^2 = R^2 \\
\quad y^2 + 2(l + sₜ)y + (l + sₜ)^2 + z^2 + 2tz + t^2 = R'^2
\end{cases}
\]  \hspace{1cm} (6-45)

Subtracting the first equation from the second equation in Eqs.6-45, yields:

\[ 2(l + sₜ)y = R'^2 - R^2 - t^2 - (l + sₜ)^2 - 2tz \]  \hspace{1cm} (6-46)

Isolating variable y in Eq. 6-46, yields:

\[ y = \frac{R'^2 - R^2 - t^2 - (l + sₜ)^2}{2(l + sₜ)^2} - \frac{t}{(l + sₜ)^2} z \]  \hspace{1cm} (6-47)

Substituting Eq. 6-47 for ‘y’ in the first equation in Eq. 6-45 and simplifying yields:

\[ \frac{t^2 + (l + sₜ)^2}{(l + sₜ)^2} z^2 - \frac{t(R'^2 - R^2 - t^2 - (l + sₜ)^2)}{(l + sₜ)^2} z + \left( \frac{R'^2 - R^2 - t^2 - (l + sₜ)^2}{2(l + sₜ)^2} \right)^2 - R^2 = 0 \]  \hspace{1cm} (6-48)
Chapter 6: Tool Flank Wear Evaluation Method using Cutting Chips

Eq. 6-48 is a quadratic polynomial, whose root is:

\[ z = \frac{t(R'^2 - R^2 - t^2 - (l + s_L)^2) \pm \sqrt{4R^2(t^2 + (l + s_L)^2) - (R'^2 - R^2 - t^2 - (l + s_L)^2)^2}}{2(t^2 + (l + s_L)^2)} \]  (6-49)

Expression 6-49 is the root of Eq. 6-48. Based on Figure 6.21 (c), it should be noted that \( z > 0 \).

Similarly, isolating variable \( z \) in Eq. 6-47, yields:

\[ z = \frac{R'^2 - R^2 - t^2 - (l + s_L)^2}{2t} - \frac{(l + s_L)}{t}y \]  (6-50)

Substituting Eq.6-50 for ‘z’ in the first equation in Eq. 6-45 and simplifying, we obtain:

\[ \frac{t^2 + (l + s_L)^2}{t^2} y^2 - \frac{(l + s_L)(R'^2 - R^2 - t^2 - (l + s_L)^2)}{t^2} y + \left( \frac{R'^2 - R^2 - t^2 - (l + s_L)^2}{2t} \right)^2 - R^2 = 0 \]  (6-51)

Eq. 6-51 is a quadratic polynomial, whose root is solved as:

\[ y = \frac{(l + s_L)(R'^2 - R^2 - t^2 - (l + s_L)^2) \pm \sqrt{4R^2(t^2 + (l + s_L)^2) - (R'^2 - R^2 - t^2 - (l + s_L)^2)^2}}{2(t^2 + (l + s_L)^2)} \]  (6-52)

Eq. 6-51 has two minus roots, however, the smaller one is the real root.

Thus, the coordinates of point \( u \) is listed as:

\[ \begin{cases}  
  y = \frac{(l + s_L)(R'^2 - R^2 - t^2 - (l + s_L)^2) \pm \sqrt{4R^2(t^2 + (l + s_L)^2) - (R'^2 - R^2 - t^2 - (l + s_L)^2)^2}}{2(t^2 + (l + s_L)^2)} \quad (y > 0) \\
  z = \frac{t(R'^2 - R^2 - t^2 - (l + s_L)^2) \pm (l + s_L)\sqrt{4R^2(t^2 + (l + s_L)^2) - (R'^2 - R^2 - t^2 - (l + s_L)^2)^2}}{2(t^2 + (l + s_L)^2)} \quad (z > 0) 
\end{cases} \]  (6-53)

According to Figure 6.21(c), the theoretical peak-to-valley roughness under tool flank wear is derived as:

\[ R'_t = z_i - z_u = R' - t - \frac{t(R'^2 - R^2 - t^2 - (l + s_L)^2) \pm (l + s_L)\sqrt{4R^2(t^2 + (l + s_L)^2) - (R'^2 - R^2 - t^2 - (l + s_L)^2)^2}}{2(t^2 + (l + s_L)^2)} \]  (6-54)

Where \( z_i \) and \( z_u \) are the z-axis coordinate value of point \( i \) and \( u \).

6.5.2 Effects of Cutting Parameters on the Surface Roughness under Tool Flank Wear

When tool wear occurs, changing cutting parameters can reduce the effect of tool
wear on the machined surface roughness; for example, by reducing the step distance. As shown in Figure 6.21 (c) two surface roughness values exist for reducing the step distance.

As the step distance is larger than the length of line $gv$, that is $s > |gv|$, curve ① intersects with curve ② at point $u$, while the peak to valley roughness can be calculated by Eq. 6-54.

As the step distance is the same or smaller than the length of line $gv$, that is $s_t < |gv|$, in this case, curve ① intersects with curve ③, the peak to valley roughness can be calculated as:

$$R_t^* = R' - \sqrt{R'^2 - (s_t/2)^2}$$  \hspace{1cm} (6-55)

To derive the length of line $gv$, a straight line is connected to the point $g$ and point $v$, it is easy to know the $z$ coordinate component of both point $g$ and point $v$ are the same. The coordinate components of point $g$ is expressed as $(-s_t^2/2, \sqrt{R^2 - s_t^2/4})$, substituting $\sqrt{R^2 - s_t^2/4}$ for ‘$z$’ in Eq. 6-43, yields:

$$(y + l + s_t)^2 + (\sqrt{R^2 - s_t^2/4 + t})^2 = R'^2$$  \hspace{1cm} (6-56)

From Eq. 6-56, variable $y$ can be derived as:

$$y = \sqrt{R'^2 - (\sqrt{R^2 - s_t^2/4 + t})^2} - l - s_t$$  \hspace{1cm} (6-57)

Therefore, the length of line $gv$ can be expressed as:

$$|gv| = y_g - y_v = \frac{s_t}{2} + l - \sqrt{R'^2 - \left(\sqrt{R^2 - \frac{s_t^2}{4} + t}\right)^2}$$  \hspace{1cm} (6-58)

Where $y_g$ and $y_v$ are the $y$-axis coordinate value of point $g$ and $v$.

Based on Eq. 6-54, the relation between the width of wear land and the peak-to-valley roughness is shown in Figure 6.22.
Figure 6.22 Relationship between peak to valley roughness and width of wear land

It is found that the surface roughness decreases slightly and then increases drastically with the increasing width of wear land; there is a critical width of wear land at which the surface roughness is the minimum. The relationship curve between wear land angle and the peak-to-valley roughness is plotted in Figure 6.23. Similar to Figure 6.22, the surface roughness decreases at first and then increases with the increase of wear land angle; the minimum surface roughness happens at about 33° under the given cutting parameters.

Figure 6.23 Relationship between peak-to-valley roughness and wear land angle

The relationship between the surface roughness and the width of wear land at different wear land angles are shown in Figure 6.24.
Figure 6.24 Relationship curves between surface roughness and width of wear land at different wear land angles

It is found that the width of wear land associated with the minimum surface roughness increases with the decrease of wear land angle. Although Figures 6.23-6.24 reveal that the wear land angle has a significant effect on surface roughness, the wear land angle depends on the material being cut. Therefore, although the width of a wear land is the same, the surface roughness may be different due to the cutting tool cutting different material. For brass material, the wear land angle is about 40.5\degree.

The surface roughness increases with the increasing width of wear land, for conventional cutting, the width of wear land is usually more than 10um. From Figure 6.25 it is found that surface roughness at 10um is about 0.3um. However at the wear land width of 20um, the surface roughness increases to about 1.5um. For ultra-precision machining, the width of wear land is usually less 5um and therefore its effect on surface roughness is relatively small. However, with the increase of wear land width, the surface roughness increases grows exponentially.
Chapter 6: Tool Flank Wear Evaluation Method using Cutting Chips

Figure 6.25 Curves of peak-to-valley roughness of machined surface with respect to the width of wear land

From studying the relationship between cutting chip morphology and tool flank wear, it is found that tool wear characteristics and their effects can be effectively evaluated by using cutting chips. Figure 6.26 shows the framework of a tool flank wear on-machine evaluation system based on cutting chips. In this system, based on the cutting chips model and the examined cutting chip morphology, the tool wear characteristics can be evaluated and a 3D model of diamond tool wear can be established. The model can be used to predict the machined surface quality together with cutting parameters. Based on the predicted machined surface quality, some actions can be conducted to improve the machined surface quality. These actions include changing cutting parameters and changing tool geometry parameters.
The tool wear on-machine evaluation method based on cutting chips can realize measurement tool wear effectively without need to stop the cutting machine. According to the results of the experiments, the tool wear measurement method proposed in this chapter is reliable.

### 6.6 Concluding Remarks

In this research, tool flank wear and its effects on the machined surface roughness in ultra-precision raster milling (UPRM) were investigated based on chip morphologies. A mathematical model was established to explore the cutting chip morphology and surface roughness evolution with tool wear progress. It is found that cutting chips can be used to identify the tool flank wear and even the machined surface roughness. Specific conclusions from the study are as follows:

1. The occurrence of tool flank wear makes the cutting chips truncated perpendicular
to the cutting direction on both the tool entry side and tool exit side. With the progress of the tool flank wear, the truncation position in the feed direction moves from two sides to the central position of the cutting chips.

(2) The cutting chips were truncated at the position of the critical chip thickness (CCT). The CCT is calculated by the chip width at the truncation position of cutting chips, and used to identify the width of flank wear land.

(3) A mathematical model was established to simulate the chip morphology under the given cutting parameters. It is found that along the feed direction, the chip thickness increases first and then decreases. There is a position at which the chip thickness is the greatest.

(4) The measured widths of flank wear land are a little bigger than the identified ones due to the deviation between the critical cutting depth, the height of flank wear land, and the existence of measurement errors.

(5) The wear land angle is an important parameter in the tool wear identification in UPRM. Its value depends on the workpiece material that has been cut.

(6) The occurrence of tool flank wear can form a new tool nose arc with a relatively larger radius and a changed circle center.

(7) A mathematical model is established to calculate the surface roughness considering tool flank wear. The calculated result shows that with the increase of wear land width of tool flank wear, the surface roughness decreased first and then increased seriously. The surface roughness increased more seriously at the larger wear land width.
Chapter 7 Conclusions and Suggestions for Future Research

7.1 Overall Conclusions

Tool wear is an inevident phenomenon during the cutting process that can deteriorate the machined surface quality and lower cutting efficiency. The effects of tool wear on the machined surface quality can be classified into three aspects: increasing the surface roughness, generating form error, and affecting the surface finish. Also, the occurrence of tool wear can change the cutting force amplitude and chip morphology. Therefore, the tool wear information can be reflected by cutting force and chip morphology. However, information about tool wear is usually implicit and needs to be processed. It is a problem how to process the captured cutting force signal and cutting chip morphologies to exact some useful information to pinpoint tool wear levels and even machine surface quality.

Ultra-precision raster milling (UPRM) is an essential method for the fabrication of non-rotational symmetric surface structures with a micrometric and even nanometric surface finish. However, the wear of diamond tools can significantly affect the surface quality of optical products. Although the intermittent cutting mechanism of UPRM can suppress the occurrence of tool wear, and the high hardness and heat conductivity property of diamond reduces the wear speed of the diamond tool, tool wear is still an important factor when considering cutting efficiency and machined surface quality. Machining optical components using UPRM is time-consuming work
since it usually takes several days or even months to cut a small optical product. If the occurrence of tool wear makes the machined surface quality unacceptable, the long previous cutting time and cutting parameters configuration time are wasted. Therefore, on-machine tool wear measurement and machined surface quality evaluation is an important research topic in UPRM, since it can help to detect tool wear in a timely manner and remedy the machined surface quality by adjusting the cutting parameters. However, the intermittent cutting mechanism of UPRM makes the cutting duration shorter and the cutting chips discontinuous. Therefore conventional tool wear measurement methods using cutting force are not feasible for UPRM. It is a challenge to find a new method to measure tool wear by using both cutting force and cutting chips.

Figure 7.1 Overall flowchart of this study
Based on the cutting mechanism of UPRM and the observations in the cutting force and cutting chip morphology under tool wear, an on-machine tool wear measurement method is developed, the flowchart of which is shown in Figure 7.1 above. The theoretical and experimental research on which this thesis is based, originates from the fundamental physical phenomena observed in the UPRM process: with the tool wear process, the cutting force signal changes in both time domain and frequency domain; and, cutting chips morphology changes. The answers to the challenge mentioned above have been sought with the following: (1) Investigating tool wear characteristics in UPRM through a long lasting cutting experiment; (2) Capturing the cutting force signal online, analyzing its composition and processing it by FFT and power spectrum analysis, and finding out the characteristic frequencies related to the tool wear; (3) Modeling cutting forces in UPRM and discussing the effect of cutting parameters on the force amplitude; (4) Using free vibration of the dynamometer frequency and the first order workpiece modal frequency to present the tool wear level; (5) Capturing and inspecting cutting chips at an early tool wear stage to predict the tool fracture wear characteristics with the help of mathematical models; (6) Predicting the surface topography based on the cutting chips, and evaluating surface roughness based on the ridges’ location and cross-sectional shape in a tool imprint; (7) Using cutting chip morphology to predict the tool flank wear, and then using the thickness of cutting chip at the truncation position to calculate the tool flank wear width; (8) Predicting the surface topography based on the cutting chip morphology and then modeling the surface roughness by considering the identified
tool flank wear width.

Based on the above, a summary of the major findings and their significance in the theoretical and experimental study of tool wear and surface quality on-machine evaluation is as follows.

(1) Tool wear characteristics in UPRM include tool fractures, material welding, wear land formation and sub-wear-land formation. Tool fractures can be imprinted directly both on the cutting chips and machined surface as a group of ‘ridges’; material welding can lead to the breakage of cutting chips, which scratches the machined surface and makes the machined surface fuzzy and burred; wear land formation can make the cutting chips shutter-like at the tool entry side and increase the peak-to-valley roughness of the machined surface.

(2) The cutting force in UPRM is figured as a series of force pulses due to the quite small cutting duration in every rotary cutting. The cutting force pulse is closely related to the geometric shape of chips and a crucial rotation angle exists which can divide the chip area into two sections. Therefore, in UPRM, the cutting force pulse is composed of two segments.

(3) The dynamometer can be simplified as a second order dynamic system, while the cutting force pulse can be thought of as a stimulus. As the diamond tool cuts into and out of the workpiece surface, the dynamic system will be stimulated and a vibration signal can be captured by the dynamometer as a free vibration signal. In UPRM, the amplitude of the cutting force in the thrust direction increases gradually with the tool wear progress, however, it is not explicit for the cutting force in the feed direction.
(4) Cutting parameters can affect the amplitude of the cutting force in UPRM, both the experimental and simulation results show that the cutting force in the feed direction and thrust direction increases with the growing depth of cut and feed rate, however, the depth of cut has more influence on cutting force than the feed rate has. In addition, it is found that the cutting force in the thrust direction is more sensitive to larger depth of cut and feed rate than small ones. However, it is implicit for the cutting force in the feed direction.

(5) Two spectrum peaks are found to be closely related to the diamond tool wear in UPRM. The amplitudes of these predominant spectrum peaks increase with the progress of diamond tool wear. The spectrum peaks are observed from the free vibration of the dynamometer and the first order of workpiece modal frequency induced by the cutting force.

(6) Cutting chips are fully generated in the rotary cutting of UPRM. It is found that tool fracture wear can be directly imprinted on the cutting chip surface as a group of ‘ridges’. Cutting chips split at the tool entry position of these ridges and the formation of splits can help to find the location of ridges.

(7) A mathematical model is established to simulate the cutting chip morphology based on the given cutting parameters. According to the model, only a small area of the cutting chip can be used to reflect tool wear characteristics and machined surface quality. By examining the ridges’ cross-sectional shape and their locations in this area, both the tool wear and machined surface quality can be predicted without the need to stop the cutting process.
(8) Two geometric elements were employed to describe the ridges’ cross-sectional shape: isosceles triangle and semi-circle. Based on the two geometric elements and the distance between two neighboring ridges, a virtual cutting edge was modeled that was verified by the inspection of the actual cutting edge. However for the simulation of machined surface topography, a correction factor is used to correct the profile parameters of the geometric elements.

(9) The occurrence of tool fracture wear can affect machined surface roughness, which is subject to the location and height of formed ridges. A mathematical model is established to calculate the range of the maximum peak-to-valley surface roughness on the machined surface cut by both a fresh tool and a fracture wear tool. The calculated results show that the model can predict the surface roughness on-machine without need to stop the cutting process.

(10) With the progress of tool flank wear, ploughing instead of cutting occurs, which can makes the bottom of tool imprint fuzzy and unclear and make the cutting chips truncated at the critical chip thickness (CCT) on both the tool entry side and tool exit side. The CCT is calculated by the chip width at the truncation positions of cutting chips, and used to identify the width of flank wear land. With the progress of the tool flank wear, the truncation position in the feed direction moves from two sides to the central position of the cutting chips.

(11) A mathematical model was established to plot the curve of chip thickness with respect to the distance along the feed direction. It is found that along the feed direction, the chip thickness increases first and then decreases. There is a position at
which the chip thickness is the largest.

(12) The wear land angle is an important parameter in the tool flank wear identification process in UPRM, whose value depends on the workpiece material being cut. From the experiment, it is found that the measured widths of flank wear land are a little bigger than the identified ones using cutting chips due to the deviation between the critical cutting depth and the height of flank wear land, and the existence of cutting and measurement errors.

(13) A mathematical model is established to calculate the machined surface roughness considering tool flank wear. Calculation results show that with the increase of wear land width of a cutting tool, the surface roughness decreased first and then increased seriously. The occurrence of tool flank wear can form a new tool nose arc with a relative larger radius and a changed circle center. The surface roughness increases more seriously at the larger wear land width, in addition to which it is found that reducing the step distance can improve the surface roughness.

(14) The tool wear measurement and surface quality evaluation using cutting chips is a progressive method compared to conventional ones. This is because it cannot only find the occurrence of tool wear but can also obtain tool fracture wear characteristics on-machine. The proposed method can also be used to evaluate machined surface quality on-machine and remedy the deteriorated surface by changing cutting parameters.

This study’s theoretical and experimental investigation of tool wear measurement and surface roughness evaluation contributes to a deeper insight into the influence of
tool wear on the cutting force, cutting chip morphology and surface topography in UPRM. The developed mathematical models are able to predict the cutting force, chip morphology and surface topography in UPRM and help to remedy the deteriorated surface so as to improve surface quality. Moreover, the research contributes to the advancement of the state-of-the-art in UPRM, including providing a new tool wear monitoring method and surface roughness evaluation and improvement method.

7.2 Suggestions for Future Research

On one hand, UPRM is increasingly used in the fabrication of non-rotational symmetric surface structures like freeform surface, pyramid allies, and other complex optical structures with sub micrometric dimension accuracy and nanometric surface roughness. On the other hand, the occurrence of tool wear can deteriorate machined surface and reduce the cutting efficiency. Therefore conducting research on tool wear on-machine measurement and surface quality evaluation methods in UPRM is meaningful. Although this thesis provides a comprehensive tool wear measurement and surface quality evaluation method in UPRM, and the research objectives have been achieved, there is still some related research that needs to be undertaken in the near future. This includes the following.

(1) Refining tool wear monitoring methods based on cutting force

Cutting force has proved to be a valuable signal during the cutting process since it conveys a lot of information about tool condition, machine tools work status, and even machined surface quality. The study of cutting force not only benefits the configuration of cutting parameters and setting a cutting plan, but also benefits tool
status monitoring. Since the cutting tool is the direct executor during the metal cutting process, the occurrence of tool wear can affect the cutting force signal and can also be described by the cutting force signal. However, the captured cutting force signals are mixed by noise and vibration signals. To extract the useful information related to the tool wear from the captured cutting force signals, cutting force signals should be processed first. Until now, cutting force has been widely used to monitor tool wear in continuous cutting processes. However, due to the intermittent cutting property of UPRM, it is difficult to monitor tool wear using cutting force signals. As UPRM is a rotary cutting process with a relatively short duration, the cutting force is figured as a cutting force pulse and as such conveys little information about tool wear. Therefore conventional tool wear monitoring methods using cutting force and cutting force processing methods cannot be used to monitor tool wear in UPRM.

In the preliminary work for this study, a cutting force model was established to simulate the cutting force component in both feed direction and thrust direction. The cutting force model can be used to predict the cutting force components at different cutting depth, swing distance, and feed rate. Based on the elastic property of cutting force measuring system and the captured damped vibration signals, the cutting force measuring system was simplified as a second order vibration system. The imposed cutting force is simplified into a stimulus, which can stimulate the measuring system and lead to the free vibration of the dynamometer. Based on the theoretical and experimental results, the relationship between cutting force amplitude and the width of wear land is discussed. Through the power spectrum analysis, both the simulated
cutting force signals and the captured cutting force signals are transferred into a frequency domain. It is found that tool wear can lead to the increase of power spectrum density (PSD) at the characteristic frequencies of the dynamometer’s natural vibration and the first order modal vibration of the workpiece. Therefore, the two characteristic frequencies can be used to monitor tool wear.

Although the cutting force model has been developed and some useful results have been obtained, some other works need to be finished in the future. First, the relationship between tool wear characteristics and the PSD at the characteristic frequencies should be conducted. Currently, cutting force and its PSD characteristics can only reflect the occurrence of tool wear but not identify tool wear characteristics and tool wear level. The next step will be to conduct more experiments to explore the relationship between tool wear pattern and cutting force characteristics both in the time domain and frequency domain. A real-time tool wear monitoring system based on cutting force should be established to monitor tool wear through a Kistler 9256C1 dynamometer connected to a computer, in which the signal processing software can process the captured cutting force signal in real time to identify the tool wear characteristics.

(2) Study of chip formation mechanism at the critical cutting depth under the occurrence of tool wear

As mentioned above, the occurrence of tool flank wear can make the cutting chips truncated at both their tool entry and tool exit sides. However, through the comparison between the identified width of flank wear land based on the cutting chips
and the measured ones, it is found that the measured wear land width is a little bigger than the identified one. This phenomenon occurs due to the deviation between the thickness of cutting chips at the truncation position and the mapping height of flank wear land on the truncation plane. This deviation can be identified and even eliminated by studying the critical cutting depth under different tool wear levels.

To explore the critical cutting depth under different tool wear levels, a group of straight cutting will be conducted on a slope so that changeable cutting depths can be realized. The chip morphologies at different tool wear levels will be inspected and compared. In addition, the chip morphology at different slope angle and cutting speed will be compared so that useful conclusions can be drawn.

(3) Exploring cutting chip morphologies and their relations with tool wear at a wider range of cutting conditions.

Until now, cutting chip morphologies and their relations with tool wear have been investigated on different cutting depths (from 2um to 25 um). Although the geometric modelling shows those other cutting parameters like feed rate, spindle speed, step distance and swing distance have no effects on the tool wear evaluation method based on cutting chip morphologies, some material items caused by the changing of cutting parameters may affect the tool wear measurement accuracy, especially for tool flank wear evaluation. Therefore, in the future work, cutting experiments are conducted at a wider range of cutting parameter to explore the effect of cutting parameters on the cutting chip morphologies and the relations between
cutting chip morphologies and tool wear so as to extend the applicability of my research work.

(4) Find tool wear characteristics by spindle vibration signals

Beyond the methods proposed in this thesis, I would like to conduct some research on the relationship between tool wear and spindle vibration. In ultra-precision machine tools, spindle is an important component since it can convey the rotary motion and realize the cutting process. In general, the spindle is supported by conventional bearings, hydraulic bearings and gas pressure bearings, in which gas pressure bearings can realize high accuracy, high stability and high rotatory speed. Therefore, gas pressure bearings are the most used bearings in ultra-precision machine tools. In the UPRM process, the diamond tool is installed on the spindle and rotates with the spindle. Therefore, vibration of the spindle can directly affect the cutting process, and vice versa. The effect of spindle vibration on the surface generation in UPRM has been conducted previously. However, a study of the effect of tool wear on the spindle vibration in UPRM has not been performed before. In my future work, the effect of tool wear on spindle vibration will be conducted. A spindle analyzer will be used to capture the spindle displacement signal in $x$, $y$ and $z$ direction under different tool wear levels, and the captured signals processed by power spectrum analysis. Theoretically, the cutting force can cause spindle vibration. However, the occurrence of tool wear can enlarge the cutting force in the thrust direction and lead to a more serious vibration, thus tool wear levels can be monitored by spindle vibration signals.
Appendices

Appendix I Precitech Freeform 705G Ultra-precision Raster Milling Machine

Freeform 705G CNC ultra-precision raster milling (UPRM) machine is a high precision machining machine, which is a product of the Precitech Inc. (USA). The appearance of UPRM machine and the general experimental setup for cutting is shown in Figure I-1.

![Figure I-1](image.png)

Figure I-1 The appearance of UPRM machine (a) and its cutting system (b)

Freeform 705G UPRM machine can realize three-axis non rotational symmetric freeform grinding and milling, and 2-axis diamond turning, as is illustrated in Figure I-2. It can be used to directly mill freeform surfaces and micro-structures such as micro prism, micro pyramid, V-groove and F-theta lenses with supper mirror surface finish and sub-micrometric form accuracy. Besides, there is an optional grinding system for grinding optical products made from non-diamond-turntable materials like ceramics, steels and other ferrous materials.
In UPRM, there are two common cutting strategies: vertical cutting and horizontal cutting. In each cutting strategy, the feed direction and step direction are perpendicular to each other. Both the two directions in the vertical cutting are opposite to that in the horizontal cutting, as is shown in Figure I-3. The theoretical surface roughness is slightly different in different cutting strategies.

Figure I-2 Schematic diagram of the kinematic structure of the UPRM machine

Figure I-3 Cutting strategies in UPRM: (a) horizontal cutting and (b) vertical cutting
According to the manual of Freeform 705G UPRM machine, the UPRM machine has the following key features:

(1). Sealed natural granite base eliminating machine contamination.

(2). Self-leveling dual chamber isolation system minimizing vibration influences during machine operation.

(3). Linear motor driven, hydrostatic oil bearing slideways with advanced stiffness characteristics for the ultimate in performance.

(4). 8.6 or 1.4nm feedback resolution for improved velocity control.

(5). Slot-type thrust bearing spindle design available up to 5,000 RPM.

(6). Qnx ® real time OS for advanced programming capacity, 1.0nm programming resolution for increased throughput.

(7). Optional rotational axes and grinding spindles available for advanced capabilities.

Kinematics information about Freeform 705G UPRM machine (Manual of Freeform 705G):

(1). Slide Travel: X-350mm (14") Y-150mm (6") Z-250mm (10")

(2). Maximum Feedrate: 1500mm/min. (59"/min.)

(3). Process Capability:

(4). Water Tight Machine Grinding X, Z

(5). Water Tight Machine SPDT X, Z

(6). Raster Milling X, Y, Z, B

(7). Linear Grooving X, Y, Z

(8). Diamond Ruling X, Y, Z
Available product options (Manual of Freeform 705G):

(1). Adjustable & Flycutting Toolholders Milling Attachments;

(2). Aspheric grinding systems 50,000/15,000 RPM On-Machine Gage & Amplifier;

(3). Aspheric Programming Software Optical and LVDT Tool Setting Systems;

(4). FTS Fast Tool Servo Slow Tool Servo Positioning C-Axis

(5). HydroRound Rotary B-Axis UltraComp™ On-Machine Metrology
Appendix II Wyko NT 8000 Optical Profiling System

The introduction of the Wyko NT 8000 Optical Profiling System is based on the product’s datasheet and manual.

The Wyko NT8000 is an efficient optical profiler which can realize the non-contact evaluation and measurement of surface roughness, microstructure heights, and machined surface topography of wafers, metals, precision lenses, semiconductors and optics. The appearance of Wyko NT8000 and the surface structure measured by it is shown in Figure II-1, it can realize non-contact 3D measurement with the range from 0.1 nm to 8 mm and with resolution down to sub-nanometer level. This device can self-calibrate over the entire scan range with the help of internal reference signal. The Wyko NT8000 can realize fast scan at the scan speed of 100μm/sec.

Figure II-1 Wyko NT 8000 Optical Profiling System and the surface structure measured by it

The Wyko NT8000 system provides a fast, easy and reliable way to measure and evaluate different kinds of surface structures and samples. The Wyko NT8000 system consists of several key components working together to provide service, which
Appendices

includes:

(1). A Wyko Profiler head mounted on a z-axis and automated tip/tilt cradle

(2). Various magnification objectives mounted on a turret

(3). A vibration-isolation table

(4). A motorized x/y sample stage

(5). An IBM-compatible computer, preloaded with Microsoft® Windows XP® and Wyko Vision software.

For Wyko NT8000 system, there are two available basic types of measurements: phase-shifting interferometry (PSI) and vertical scanning interferometry (VSI). In phase-shifting interferometry (PSI), a mechanical system is used to precisely change the length of the optical path of the test beam. The change of optical path leads to a lateral shift in a form of fringe pattern. The shifted fringes are then periodically recorded by the camera and used to produce the interferograms. The surface height profile can be determined by the combination of computerized calculations and the series of interferograms. In vertical scanning interferometry (VSI), as the camera periodically records frames, an internal translator scans downward during the measurement process. As focusing each point on the surface, the modulation on that point reaches a maximum, then tapers off as the translator passes through focus. The system can determine the height of each pixel through recording the height of the translator at maximum modulation. The maximum scan depth for a VSI scan is 8mm.
Appendix III Hitachi Tabletop Microscope TM-3000 SEM

The following statement and introduction of the Hitachi TM-3000 SEM is based on the product’s datasheet and manual.

Hitachi TM-3000 is a specialized Scanning Electron Microscope (SEM) that mainly uses backscattered electrons rather than secondary electrons to image the specimen, the latter usually need a better vacuum work condition. Hitachi TM-3000 is a truly tabletop SEM, it has relative small size and is portable. The working mechanism makes it needed for the minimal preparation of the specimens. The TM3000 is an effective and alternative choice to stereo microscopes, optical microscopes and confocal laser scanning microscopes. Until now, Hitachi TM-3000 has been widely applied for many industrial fields including food, life science, healthcare, cosmetics, textiles, materials science etc..

In this study, TM-3000 was used to measure the 3D image of cutting chips because the TM-3000 is easy to be operated and can realize fast measurement. In addition, it has some other advantages:

(1). Compact — Energy-saving design and size

(2). No special power requirements needed. Uses standard outlet

(3). No special table required

(4). No coating required
(5). High magnification  
(6). High resolution  
(7). Simple maintenance  
(8). EDS (EDX) can be attached  
(9). EDS Elemental Mapping is optional  
(10). Auto-focus, auto-brightness and auto-contrast functions  
(11). Smaller, compact and lightweight design  
(12). Easier to operate - One button auto start  
(13). Larger stage, larger samples  
(14). Motorization package  
(15). Variable accelerating voltage (enhanced sample surface observation)  
(16). Beam current control  
(17). No other facilities required  
(18). Includes PC with Windows® 7  

**Characteristics of the Hitachi TM3000 SEM:**  

(1). Accelerating voltage: 5 or 15 kV, tungsten source  
(2). Magnification: X 15 to X 30,000  
(3). 30 nm resolution  
(4). Backscattered detector only  
(5). Charge reduction mode (which uses higher chamber pressure) allows imaging of uncoated samples  
(6). Easy to use and portable
Hitachi TM-3000 has a 3-dimensional image display/measurement function, this function is used to measure the ridges’ cross-sectional shape on the cutting chips in this thesis.

In the 3-dimensional model establishing process, the 4-channel backscattered electron detector are used to acquire signals in each segment, then by combining the 4 directional surface profiles, a 3-dimensional model can be generated without sample tilting and alignment, as is shown in Figure III-1.

Figure III-1 Schematic illustration of the measurement principle of the Hitachi TM-3000 3D module

In user observer, the 3-dimensional model can be rotated and zoomed freely, and the rotational operation of the 3-dimensional model can be recorded in an animation file (in AVI format). Figure III-2 shows the application of the 3-dimensional image display/measurement function of Hitachi TM-3000 on the measurement of 3D structure of a structured surface.
Figure III-2 Surface structure measured by the 3D module of Hitachi TM 3000
Appendix IV Kistler 9256C1 Dynamometer

The statement and introduction of the Kistler 9256C1 dynamometer comes from its datasheet and instruction manual.

Kistler 9256C1 dynamometer is quite suitable to measure cutting force in ultra-precision machining process, this is because:

(1). The 3-component dynamometer is used for the quasi static and dynamic measurement of the 3 orthogonal force components acting on the top plate ($F_x$, $F_y$ and $F_z$).

(2). The dynamometer is characterized by high rigidity and therefore has a high natural frequency.

(3). Its high resolution makes it possible to measure tiny dynamic changes in large forces.

(4). Its low threshold permits the measurement of quite small forces.

(5). The dynamometer can measure the active force independently.

(6). Measurement can be made both of the average force and the dynamic changes in force.

(7). The useful frequency range depends mainly on the natural frequency of the entire measuring system.

(8). Small temperature error

Kistler 9256 C1 dynamometer has been widely used in both conventional machining and ultra-precision machining process. Figure IV-1 shows the photograph of Kistler 9256 C1 dynamometer and its application in the metal cutting process.
Figure IV-1 Photos of Kistler 9256C1 dynamometer (a) and its application in machining (b)

Product Description

The Kistler 9256C1 dynamometer is composed of four 3-component force sensors installed between the cover plate and two base plates under high preload. This special mounting of the sensors allows its low thermal error. Each sensor contains three crystal rings: one is sensitive to the pressure comes from the y-direction while the two others are sensitive to the shear in the x- and z-directions. The forces in different directions are measured practically without delay. The four force sensors are ground-isolated so that it can eliminate ground loop problems. The dynamometer is suitable for the force measurement in process since it is corrosion-resistant and protected against penetration by cutting fluid or splashing water.

Applications of Kistler 9256C1 dynamometer:

(1). Cutting force measurement in precision machining, such as: cutting metals, diamond turning, high speed machining

(2). Ultra-high precision machining of brittle hard materials

(3). Multicomponent force measurement of small forces

(4). Force measurement in confined spaces
Appendix V Simulation of UPRM process in Solidworks

The UPRM process can be simulated by using Solidworks software. In Solidworks, there is a command call ‘revolved cut’, the command can realize the similar function of rotary cutting. If we design the tool nose profile in the sketch and give the revolved axis, then the desired structures can be obtained through the revolve cut. In the following part, a rotary cutting at the central place of a workpiece bulk with its length of 50 mm, width of 25 mm and height of 5mm is simulated. Due to the accuracy limited, to realize the rotary cutting process, all the cutting parameters are enlarged 10 times. Therefore, the cutting parameters used in this simulation are tool nose radius of 6.31mm, swing distance of 283.5mm, step distance of 0.25mm cutting depth of 0.3mm. The simulation steps are summarized in below:

**Step 1:** Establishing a rectangular solid with its length, width and height equal to the real dimension of the workpiece by using the ‘Extruded Boss/Base command’, as is shown in Figure V-1.

![Building up the 3D model of workpiece bulk](image)

**Step 2:** Generating the previous cutting plane through the command ‘extruded cut’
The depth of the extruded cut should be equal to the cutting depth, as is shown in Figure V-2.

Figure V-2 The generation of machined surface

**Step 3:** Simulating the previous step cutting to generate previous step surface. To realize this operation, ‘extruded cut’ commend in Solidworks is used. In the ‘extruded cut’ option, the sketch is a circle with its diameter of 12.62 mm to simulate the 6.31 mm tool nose radius, as is shown in Figure V-3(a). After the extruded cut, the step surface is formed as shown in Figure V-3(b).

Figure V-3 Previous step cutting realization

**Step 4:** Similarly, another ‘extruded cut’ operation is used to realize the current step cutting, as is shown in Figure V-4. This operation is the basis to realize the rotary cutting.
Step 5: Based on the previous ‘extruded cutting’, the entire previous surface has been generated. To realize the rotary cutting process, ‘revolved cut’ commend is used in this time, therefore, the rotary cutting process is realized, as is shown in Figure V-5.

Theoretically, all the step surfaces should be finished by the repeated ‘revolved cut’ in Solidworks software. However, for easily, it is acceptable that the previous step surfaces are simulated by the ‘extruded cut’ since the existing error is quite small.
Appendix VI Simulation of Cutting Chip Formation in Solidworks

The Solidworks software can also be used to simulate the cutting chips generation in UPRM. Similar to the simulation of the rotary cutting process, the cutting chips generation is realized by using commands of ‘extruded cut’ and ‘revolved cut’.

In the UPRM process, cutting chips are generated from three cutting steps: previous step cutting, previous rotary cutting and current rotary cutting. Therefore, the cutting chip is enveloped by four surfaces include: the rough surface, the surfaces formed by previous rotary cutting (previous rotary surface), current rotary cutting (current rotary surface), and previous step cutting (previous step surface). The simulation of cutting chips generation in Solidworks 2012 can be divided into the following steps:

**Step 1:** Generating a 3D solid, the cross-sectional sketch of the 3D solid is enveloped by two circles and a horizontal line. The radiuses of the two circles are determined 6.31mm to simulate the tool nose radius, while the distance between the two circles’ center points is fixed as 0.25mm to simulate the feed rate in a rotation circle. The straight distance between the lowest point of the circles and the horizontal line is defined as 0.3mm to simulate the cutting depth. The sketch figure is shown in Figure VI-1(a), by using ‘extruded cut’ command , the 3D solid profile is established and shown in Figure VI-1(b).
Step 2: Simulating the previous rotary cutting. To realize the previous rotary cutting, the cross-sectional sketch is defined as the cross-sectional profile of the 3D solid established by Step 1, as is shown in Figure VI-2 (a). The rotation radius equals to the swing distance, as is shown in Figure VI-2 (b). By using the ‘revolved cut’ commend, the simulated rotary cutting profile is shown in Figure VI-2 (c).
Step 3: Establishing a reference plane, the distance between the reference plane and original plane should be equal to the feed rate in a rotary cutting. The reference plane is used to realize a new rotary cutting, as is shown in Figure VI-3 (a).

Step 4: Simulating the current rotary cutting through the revolved cut commend in SolidWorks. Similar to Step 2, the cross-sectional sketch of this operation is defined as the cross-sectional profile of the 3D solid established by Step 1, as is shown in Figure VI-3 (b). The rotation radius of the revolved cut is equal to the swing distance, as is illustrated in Figure VI-3 (c).

Figure VI-3 Schematic illustration of the surface generation in current rotary cutting

Based on the simulation steps 1-4, a cutting chip is generated and shown in Figure VI-4. Through the comparison with the captured cutting chips, the simulated
cutting chip is found agreed well with the captured one.

Figure VI-4 Simulated cutting chip morphology by using Solidworks
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