Research on Manufacturing and Application of Polycrystalline Diamond (PCD) Tools

A thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

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Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

Guangxian Li

25th June 2017
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Publications


7. Guangxian Li, Wencheng Pan, Songlin Ding, Shoujin Sun, John Mo, Experimental Investigation on Thrust Force and Hole Quality in Drilling Carbon Fiber Reinforced Plastic


12. **Guangxian Li**, Shuang Yi, Cuie Wen, Songlin Ding, Modeling and Investigation on Crater Wear of Different PCD tools. (in-draft)

13. **Guangxian Li**, Shuang Yi, Cuie Wen, Songlin Ding, Investigation on wear mechanism of PCD tools when cutting titanium alloy under high cutting speed. (in-draft)
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NOMENCLATURE

\( F_n \) Friction force at tool/chip interface (oblique coordinate), N;

\( F_m \) Force normal to the tool/chip contact interface (oblique coordinate), N;

\( F_l \) Force along the cutting edge direction (\(\vec{m}, \vec{n}, \vec{t}\) coordinate), N;

\( F_x \) Force measured in axial direction (axial force), N;

\( F_y \) Force measured in radial direction (thrust force), degree;

\( F_z \) Force measured in tangential direction (main cutting force), N;

\( \gamma_n \) Tool entering angle, degree;

\( \gamma_s \) Oblique angle, degree;

\( W_{uad} \) Tool material loss due to the adhesion per unit area, mm\(^3\);

\( N \) The number of the microwelds per unit area;

\( P \) Probability of forming a certain size of wear fragment;

\( h_{mw} \) The height of microwelds, mm;

\( A_{mw} \) The average cross area of the micro-weld, mm\(^2\);

\( F_{nf} \) Normal force exerted on the flank face, N;

\( A_{f,w} \) Total contact area on the worn tool flank face, mm\(^2\);

\( D \) Depth of cut, mm;

\( VB \) Width of flank wear, mm;

\( H_w \) Hardness of the softer material, MPa;

\( m \) Adhesive constant;

\( s \) Sliding distance, mm;
\( V \) Cutting speed, mm/min;
\( W_{ab}^{3-body} \) Tool material loss due to the three-body abrasion, mm³;
\( K \) Constant depending on the type of abrasion;
\( H_t \) Hardness of the cutting tool, MPa;
\( n \) Constants depending on the ratio of tool/workpiece hardness;
\( \theta \) Roughness angle in abrasive process, degree;
\( t_u \) Chip thickness, mm;
\( a_n \) Cutting depth, mm;
\( \sigma_w \) Exerted stress \( \sigma \), MPa;
\( r \) Fracture distance, mm;
\( K_{tc} \) Fracture toughness;
\( \gamma \) Tool clearance angle, degree;
\( \alpha \) Tool rake angle, degree;
\( W_{cad-cab} \) Crater wear amount due to adhesive-abrasive process, N;
\( W_{cab}^{3-body} \) Crater wear amount due to three-body abrasion of cutting tool and chip flow, N;
\( W_{cad} \) Crater wear amount due to adhesion process, N;
\( L_c \) Tool/chip contact length, mm;
\( F_{nc} \) Cutting force normal to the tool/chip interface, N;
\( V_c \) Speed of chip flow, mm/min;
\( J_{aw} \) Average diffusive flux, atoms/mm²s;
\( y \) Direction along the tool/chip interface;
\( c \) Diffusive flux rate, mm²/min;
\( D \) Diffusion coefficient, mm²/min;
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$D_0$</td>
<td>Diffusive coefficient related to the frequency of atomic oscillations, mm$^2$/min;</td>
</tr>
<tr>
<td>$Q$</td>
<td>Activation energy for diffusion, J/mol/K;</td>
</tr>
<tr>
<td>$R$</td>
<td>Constant of gas, J/mol/K;</td>
</tr>
<tr>
<td>$T_f$</td>
<td>Environment temperature, W/m;</td>
</tr>
<tr>
<td>$C_0$</td>
<td>Concentration of diffusing species at tool/chip interface, mm$^2$/min;</td>
</tr>
<tr>
<td>$m$</td>
<td>Automatic weight of diffusing species, g;</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density of diffusing species, g/mm$^3$;</td>
</tr>
<tr>
<td>$w$</td>
<td>Average chip width, mm;</td>
</tr>
<tr>
<td>$\Delta T_{rake}$</td>
<td>Temperature rise on the rake face of cutting tool, K;</td>
</tr>
<tr>
<td>$K_T$</td>
<td>Thermal conductivity of the tool material, W/m$\cdot$K;</td>
</tr>
<tr>
<td>$A$</td>
<td>Geometric factor, mm$^2$;</td>
</tr>
<tr>
<td>$Q_s$</td>
<td>The sum of the generated heat, J;</td>
</tr>
<tr>
<td>$Q_1$</td>
<td>Heat generated in primary deformation zone, J;</td>
</tr>
<tr>
<td>$Q_2$</td>
<td>Heat generated in secondary deformation zone, J;</td>
</tr>
<tr>
<td>$A_c$</td>
<td>Area of tool/chip interface, mm$^2$;</td>
</tr>
<tr>
<td>$R_s$</td>
<td>The fraction of heat in secondary deformation zone move into the chips, mm$^2$;</td>
</tr>
<tr>
<td>$K_{PCD}$</td>
<td>Thermal conductivity of PCD, W/m$\cdot$K;</td>
</tr>
<tr>
<td>$K_D$</td>
<td>Thermal conductivity of diamond, 1300 W/m$\cdot$K;</td>
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<tr>
<td>$K_B$</td>
<td>Thermal conductivity of binder material (cobalt in this study), 100 W/m$\cdot$K;</td>
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<td>$f_D$</td>
<td>Volume fraction of diamond;</td>
</tr>
<tr>
<td>$f_B$</td>
<td>Volume fraction of binder material;</td>
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<tr>
<td>$\sigma$</td>
<td>Residual stress, GPa;</td>
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<tr>
<td>$v_s$</td>
<td>The measured Raman shift value of the diamond, /cm;</td>
</tr>
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\( \nu_r \) The unstressed Raman shift value of diamond, /cm;

\( \chi \) The coefficient of stress-induced frequency shift, GPa/cm.
Abstract

Titanium alloys have been widely applied in industry, but they are difficult to machine due to the severe cutting conditions including high temperature at tool/chip interface and highly abrasive interaction at tool/workpiece interface. Polycrystalline diamond (PCD) has been gradually used for machining titanium alloy because of its high hardness and excellent thermal-conductivity. The in-depth understanding of wear behaviour and mechanisms of PCD tools which are made of different PCD materials and refined with different grinding methods is critical for the wide application of PCD tools in industry.

It is known that grain size and volume fraction of diamond in the PCD may have influences on the properties of PCD tools, which, in turn, will affect the wear mechanism of PCD tools. However, it is far from clear how these factors, or structure of different PCD materials, will affect the development of tool wear, and to what extent the affection will be. Through a series of cutting experiments, cutting forces, cutting temperatures, morphological characteristics of wear areas on tool surface, and the geometric parameters of chips were analysed to investigate the wear mechanisms, cutting performance, as well as the effects of material structure. It was found that adhesive-abrasive process and chemical diffusion were the main mechanism of wear of abrasively ground PCD tools. However, the wear processes of the three tools were different due to the difference in material structures. PCD tools made of uniformly sized diamond grains wear in a steady “spalling process”. In contrast, PCD tools made of mix-size diamond grains suffered from large-scale fracture at the tool tip. The shapes of chips and the related geometric parameters reflect different wear processes. Chip shapes changed from spiral to strip with the growing of crater wear, segment chips were generated because of the change of tool geometry caused by the fracture of the tool tip.

Since the wear of PCD materials is a complicated process, it is insufficient to limit the research to experimental analysis only, theoretical studies are necessary for the in-depth understanding of the wear mechanism of PCD tools. In this study, a new theoretical model was developed by
considering both abrasive and adhesive wear in order to investigate the wear processes and wear mechanisms of different PCD tools. The width of flank wear (VB) and depth of crater wear were calculated by solving the differential equation formulated to describe the rate of flank wear, the rate of crater wear and their relationship with cutting parameters and the properties of tool and workpiece material respectively. The data collected from experimental study was utilized to validate the analytical models. Calculation outcomes matched experimental results when tools made of uniformly sized diamond grains were used. Obvious deviation was found when the tool made of mix-size diamond grains was used due to the occurrence of large-scale fracture of tool tip in the cutting processes.

It is known that different grinding methods may result in different kinds of quality of tools. In this research, the quality and performance of PCD tools machined different grinding methods by were analysed. Comparisons between the ground tools (machined by abrasive grinding) and tools machined by electrical discharge grinding (EDG) are conducted, fundamental theories are investigated. After the grinding processes, sharpness of tool edges, roughness of machined surface and residual stress, were measured and investigated. Wear resistance was investigated by a series of cutting tests. By analyzing the experimental results, it was found that the wear and wear mechanism of eroded tools and ground tools were different. In ground PCD tools, compressive residual stress combined with external compressive stress led to the fracture of PCD structure around the tool tip. In contrast, the forming-removing cycle of build-up layer caused a steady adhesive-abrasive wear process, which was the main wear mechanism of eroded PCD tools. Also, residual stress and graphitization are the main factors that accelerated the wear of eroded tools. The stress at cobalt/diamond interface made the structure unstable and reduced the wear resistance of PCD tools. PCD inserts with bigger residual stress have larger worn area on the flank face after machining. The tool with less graphitization showed less worn in the machining of Titanium alloy.

**Keywords:** PCD, Ti6Al4V, wear mechanism, tool wear model, abrasive grinding, EDG, tool quality, cutting performance
Chapter 1 Introduction

1.1 Background

Titanium alloy Ti6Al4V is widely used in aviation industry, automobile engineering and biomechanical engineering, because of its outstanding physical, chemical and mechanical properties, including low density, high strength and good erosion resistance. However, many difficulties are encountered in the machining of titanium alloy with conventional tools due to its high chemical reactivity and low thermal conductivity, which leads to demand for new tool material with better cutting performance and longer tool life. In order to meet this demand, polycrystalline diamond (PCD) has been applied in addition to tungsten carbide (WC), ceramics, and polycrystalline cubic boron nitride (PCBN). Known as a hard and brittle material, PCD is manufactured by sintering the diamond grains and the binder material under high temperature and high pressure conditions (at temperatures of 1670K to 1770K and pressures of 5 GPa to 6 GPa). It has been applied widely in die and cutting tool applications due to the high hardness, better mechanical and thermal properties, and good chemical resistance to severe corrosive environments.

Tool wear analysis is one of the most important aspects associated with developing new tools. When cutting Ti6Al4V, the tool wear could appear in forms of chipping, built-up edge, chemical diffusion on PCD tools. Generally, experimental and theoretical investigations are two major research areas on analysing the mechanism and development of tool wear. Sliding tests and cutting tests were conducted to investigate the fracture mechanism of PCD structure and how cutting parameters affected the performance of PCD tools in different cutting processes (milling, turning and drilling). An accurate tool wear model is very important in predicting the development of tool wear, which in turn can help understand the wear mechanism of PCD tools comprehensively. The material loss in wear process caused by abrasion and adhesion on tool surface, and some analytical models were developed based on the adhesive-abrasive wear process considering the effect of the variation of cutting parameters. However, few studies were performed on the materials of PCD tools nor the influence from the micro-structure. Also, few
theoretical studies were conducted on the wear process of PCD tools, especially, the analytical models which consider the properties of different PCD tool materials was not proposed yet. As a result, the in-depth understanding of wear behaviour and mechanisms of PCD tools is critical for the wide application of PCD tools in industry.

As the hardest material, PCD tools is difficult to machine compared with cutting tools made by other materials. Also, the quality and performance of PCD inserts rely on the machining method and parameters used during the entire manufacturing process. As such, a systematic research about manufacturing process of PCD tools and their performance in titanium machining is pressingly needed. Conventional abrasive grinding, which removes the PCD material by the abrasion of a rotating diamond grinder wheel, has been adopted to refine the facial quality of PCD tools after brazing. However, low material removal rate and facial flaws induced by the large normal and shear stress during the process are inevitable problems although better surface roughness can be obtained by this grinding method. The non-contact machining methods, for example, electric discharge grinding (EDG), were developed due to its higher machining efficiency. Also, the material removal process eliminates large cutting forces exerted on the tool surface, and this made EDG a promising strategy in integrating the complicated geometric shape and superior properties of PCD for optimized process characteristics. However, the temperature of plasma generated in eroding process is up to 12000K, which could cause thermal damage to the machined surface including graphitization and residual stress. As a result, a comprehensive comparison on the tool quality and cutting performance between tools machined by abrasive grinding and tools machined by EDG is extensively required.

1.2 Research scope

This research will investigate polycrystalline diamond tools in three scopes. The first one is on the wear mechanism of tools made of different PCD materials. PCD with different diamond grain sizes and different volume proportions of binder material will be used as the tool materials in this study. Titanium alloy (Ti-6Al-4V) will be used to examine cutting performance of different kinds of tools. Turning processes will be applied to evaluate the cutting performances
of different tools under different speed levels. Wear development of tools made of different materials were investigated by analysing the change of cutting force and morphological characters of the worn areas.

The second aspect is on the quality and cutting performance of PCD tools machined by different grinding methods. Conventional abrasive grinding and EDG will be adopted to machine the surface of tools. Parameters including roughness of machined surface, radius of cutting edge and tool nose (sharpness) will be examined after the grinding processes. The condition of residual stress and graphitization will be measured after machining. Performance of different PCD tools will be tested by cutting hard-to-machine materials. Wear resistance and wear mechanism of both eroded tools and ground tools will be investigated in this study. The status and values of residual stress were measured, and taken into consideration when analysing the wear mechanism of the tools.

The third aspect is on theoretical analyse of the wear process of different PCD tools. Analytical models describing the flank wear and crater wear processes are going to be developed according to the adhesive-abrasive wear mechanism of PCD tools. In this model, the factors affecting the wear process in both micro-scale and macro-scale will be considered, including the sizes of diamond grains, volume proportion of binder material, the thermal and mechanical properties, and the dynamic cutting forces.

1.3 Research gap

With the development of aerospace material, the demand for high performance cutting tools is increasing. Synthesised by diamond grains and cobalt powder as the binder material under high pressure and high temperature, PCD, as an advanced tool material, has been widely used in manufacturing industry. The mechanical properties of different PCD materials vary significantly owing to the different sizes of diamond particles sintered in PCD and the different proportion of binding materials. This difference in material properties will result in a dramatic distinction in
the fracture of the polycrystalline structure in micro-scale, leading to the different wear process in macro-scale.

Some studies investigated the wear mechanism of different PCD tools in machining titanium alloys and other hard-to-machine materials by considering the effect of cutting parameters, the type of PCD materials and the methods of tool manufacture. However, it is far from clear how these factors will affect the quality of the tools and the performance in cutting processes, and to what extent the affection will be. The in-depth understanding of wear behaviour and mechanisms of PCD tools under different machining conditions is critical for the wide application of PCD tools in industry. It is known that grain size and volume fraction of diamond in the PCD may have influences on the properties of PCD tools, which, in turn, will affect the wear mechanism of PCD tools. The fundamental knowledge of the wear mechanism is critical for the wide application of PCD tools. Also, it is clear that research on the wear process of PCD tools so far is focused on experimental research which investigated the performance of PCD tools in turning, milling and drilling hard-to-machine materials under different cutting conditions. However, few theoretical studies were conducted on the wear process of PCD tools, especially, the analytical models which consider the properties of different PCD tool materials were not proposed yet.

Furthermore, because of its high hardness (over 8000HV), PCD tools are hard to machine. Currently, there are two different methods to grind PCD tool which are mainly adopted in industry: conventionally abrasive grinding which refines the tool surface by the abrasion of a rotating diamond grinder wheel and electrical discharge grinding (EDG) which is a variation of EDM process refining the tool surface by the erosion of generated high-temperature plasma. Because of the ultra-hardness of PCD, the efficiency of abrasive grinding is extremely low. In contrast, the latter method, EDG, is the more-efficient due to the erosion rate of diamond by the high-temperature sparks. However, there are still questions needed to be answered, especially the quality and performance of eroded PCD tools (tools refined by EDG processes). The quality of PCD tools machined with different grinding methods and their performance in cutting titanium alloys need to be understood comprehensively. Firstly, it is assumed that the values and status of residual stress within the PCD structure could be one of the reasons that affect the strength of
cutting edge and machined surface leading to the difference in wear resistance of different tools. Secondly, the comparison between the ground tools (tools machined by abrasive grinding) and eroded tools should be conducted. The strength of PCD structure is affected by different grinding method because of the difference in material removal mechanism of EDG and abrasive grinding. Especially for EDG, as a kind of non-contact machining, the theory of material removing is complex, defects and re-distribution of residual stress caused by the thermal effect needs to be investigated further.

1.4 Research questions and hypotheses

Although PCD has been used in industry for many years, the causes lead to different performance of PCD tools made by different methods and strategies are not fully understood. In this study, the questions needed to be answered can be generalized in three aspects:

Question 1: What factors affect the wear process of PCD tools made of different materials, how these factors will affect the quality of the tools, and the performance in cutting processes, and to what extend the affection will be?

In this research, three different PCD materials will be used, and the wear mechanism of tool made of these materials will be investigated. PCD is a kind of material sintered by diamond grains and binder material (cobalt in this study) under high pressure and high temperature. It is assumed that the mechanical properties are influenced by the size of diamond grains as well as the amount of the binder material used in the sintering process. The difference in the microstructure (grains size and volume fraction of binder material) of PCD materials is supposed to affect the mode of fracture of PCD structure when suffering external stress and high temperature, which leads to different performance in cutting processes. For example, the PCD material consisted of larger-size diamond grains and higher volume fraction of diamond is assumed to be more resistant to abrasion but more brittle when suffering external stress.

Question 2: What is the wear mechanism of PCD tools, and how it can be adopted in the
development of mathematical model of the wear process during the metal cutting process?

The wear mechanism of PCD is similar to that of ceramic and PCBN. On the flank face, facial materials are removed by the abrasion and adhesion caused by rotating workpiece surface. For crater wear, besides adhesive-abrasive wear process, chemical diffusion is supposed to be another dominant wear mechanism as the higher temperature at tool/chip interface activates the exchange of the elements from the cutting tool and chip flow. Also, the wear process of PCD tools is assumed to be affected by the micro-structure of different PCD materials, which should be considered in developing of the analytical model. Furthermore, the dynamic cutting force will influence the stress status on the tool surface, and variant cutting temperature can change the rate of chemical diffusion in cutting process. These two factors will be included when developing the analytical model.

**Question 3:** Will the tools machined by conventionally abrasive grinding and EDG have any difference in tool wear resistance, and what causes the difference in the performance of the ground and eroded tools in cutting processes?

Material removing mechanisms for abrasive grinding and EDG are different. Specifically, facial material is removed by the rotating diamond grinder wheel in abrasive grinding process. In contrast, EDG process erodes the PCD material by the generated high-temperature plasma which is the combined effects of physical explosion, chemical erosion, and thermal effect. As aforementioned in question 1, diamond grains and the cobalt (binder material) are combined by diamond-to-diamond bonds and diamond-to-cobalt bonds. It is supposed that the high temperature in EDG process will affect strength of these bonds leading to different wear mechanism of the eroded tools compared with the wear mechanism of ground tools. Furthermore, different from tungsten carbide or high speed steel tools, residual stress exists within the PCD layer because of the difference in thermal expansion coefficients of cobalt and PCD particles. It is assumed that the distributions of residual stress on the tools machined by abrasive grinding and EDG are different, which, in reverse, is going to affect the development of tool wear.
1.5 Research objectives and innovations

Based on the scopes and questions of the research, the overall objective is to investigate the wear mechanism of different PCD tools, and to compare the quality and performance of PCD tools refined by different grinding methods. The detailed information about the research objectives are introduced in three aspects:

1) To develop analytical models describing the wear process of different PCD in cutting titanium alloy Ti-6Al-4V.

The comprehensive analytical models on describe the flank wear and crater wear processes of PCD tools when cutting titanium alloys will be developed. The model, describing the flank wear and crater wear processes, is going to be developed according to the adhesive-abrasive wear mechanism of PCD tools. In this model, the factors affecting the wear process in both micro-scale and macro-scale will be considered, including the sizes of diamond grains, volume proportion of binder material, the thermal and mechanical properties, and the dynamic cutting forces.

2) To investigate the wear mechanism of tools made of different PCD materials when cutting titanium alloy Ti6Al4V.

Different from previous research in PCD tool wear which was focused on how machining parameters affected tool wear rate, in this study, the influence of the micro-structure of tool will be taken into consideration. This will include the effect of diamond grain sizes, the amount of binder material, and residual stress within PCD layers on the development of different types of tool wear including the wear on flank face, rake face and chipping on cutting edge.

3) To analyse the quality and performance of PCD tools machined with conventionally abrasive grinding and EDG.
Different cutting parameters were adopted to refine the tool surface, and the eroded PCD tools (tools machined by EDG) and ground PCD tools (tools machined by conventionally abrasive grinding) will be compared in the aspects of tool quality such as roughness of machined surface, sharpness of the cutting edge and thermal defects like residual stress and graphitization, as well as the wear resistance in cutting hard-to-machine materials.

### 1.6 Thesis outline

As presented in Figure 2, the research includes the study on manufacturing processes of different PCD tools and their wear mechanism. The thesis consists of six chapters which aim to investigate the wear mechanism, manufacturing processes and cutting performance of PCD tools:

1. **Chapter 1** is a generalized introduction to the content of the thesis, including the background, scopes, gaps and objectives of the research.

2. In **Chapter 2**, a comprehensive literature review is presented. Both experimental and theoretical results with respect to the manufacturing process, the performance and the wear mechanism of PCD tools are introduced.

3. **Chapter 3** presents the experimental investigation on the wear mechanism of PCD tools made of different PCD materials. Equipment and technique utilized in this research is introduced. In the cutting experiments, the PCD tools were used to turn titanium alloy Ti6Al4V in different speed levels. The variant of cutting forces, morphological character and the chips produced in the cutting processes were analyzed. A comprehensive wear mechanism considering the microstructure of PCD material was proposed.

4. In **Chapter 4**, the wear process of PCD tools is investigated theoretically. Analytical models to predict flank wear and crater wear processes of PCD tools when machining titanium alloy Ti6Al4V were developed. The models were developed based on the wear mechanism proposed...
in Chapter 3 which consider the dynamic cutting force and properties of different PCD materials. Finally, the models were validated by the experimental results from Chapter 3.

Chapter 5 introduces the different manufacturing processes of PCD tools and their quality. The two grinding methods, conventionally abrasive grinding and electrical discharge grinding (EDG), which are often adopted in industry were adopted. The selection of machining parameters for both abrasive grinding and EDG was presented. After grinding processes, the facial quality of the PCD tools (sharpness of cutting edge, roughness and residual stress on machined surface) were examined. Different cutting experiments were conducted to examine the cutting performance of both eroded and ground tools.

Finally, a conclusion including the findings and main contributions from this research, as well as future works related to this research are presented in Chapter 6.
Figure 1 Structure of the research
Chapter 2 Literature Review

This chapter presents a review of the current technology and issues associated with the results of manufacturing and application of PCD tools. As presented in Figure 2, the review covers four main aspects:

1) The development of tool materials. In this section, the development of tool materials from high speed steel (HSS) to PCD is introduced. A brief comparison of the performance of cutting tools made of these materials in cutting hard-to-machine materials was illustrated.

2) The introduction of PCD tools. This section introduces the manufacturing process of PCD material, and two major methods, conventionally abrasive grinding and electrical discharge grinding, to refine the tool surface. The material removal mechanism, advantages and disadvantages of both methods are presented.

3) The analysis on wear mechanism of PCD tools based on experimental studies. The investigation tool wear process in both micro-scale and macro-scale is presented in this section, including the wear mechanism of PCD tools in industrial machining, and the fracture mechanism of different PCD materials in sliding tests.

4) The theoretical research on wear mechanism of cutting tools. Models describing the wear process of PCD tools are scarce, as a result, the review of this section mainly introduces the statistic models, analytical models and finite element models on wear development of metallic tools and ceramic tools.
Titanium alloys have been widely applied in industry because of their excellent physical and mechanical properties such as high strength and low density. However, these materials are difficult to machine due to their low thermal conductivity (7 W/m.K) and highly chemical reactivity [1]. Severe cutting conditions including high temperature at tool/chip interface, highly abrasive interaction at tool/workpiece interface significantly accelerate the rate of tool wear, which adversely reduce tool life, cause premature tool failure, and eventually lead to very low efficiency [2].

Before the development of non-metallic cutting tools, high speed steel (HSS) and tungsten carbide (WC) tools and tools coated by chemical vapor deposition (CVD) are widely used in machining steel, cast and iron. However, the increase of cutting speed is the limitation when applying these tools to machine titanium alloy. In industry, the recommended cutting speed for the turning of TC4 (Ti6Al4V) with HSS and WC tools are around 30 m/min and 60 m/min respectively [3]. When applied in high speed cutting (larger than 100 m/min), the life of WC tools reduced dramatically, which can only last for a few minutes [4]. Sun et al. applied WC
tools with TiAlN coating in the end milling process of Ti6Al4V for studying the surface integrity [5]. The results show that the largest residual normal stress was obtained when the cutting speed was set to 80 m/min and the micro hardness of finished surface was 70-90 % larger than the bulk materials. Bhaumik et al. [6] tried the tools made of CBN in the turning process. The cooling method was the same as Sun’s experiment and excellent tool performance was found. Ezugwu et al. [7] applied the three different grains sizes of CBN tool material in the turning process of Ti6Al4V. The surface investigation showed that there was no adverse effect found on the finished surfaces. New tool materials were developed to meet the demands of the machining efficiency in titanium cutting processes. PCBN tools have been used in milling Titanium alloys with reasonable results at low cutting speed of less than 90 m/min, however, when they are applied at high cutting speed (larger than 100 m/min), the tool life becomes unacceptably short [8] [9].

Over past two decades, polycrystalline diamond (PCD) was gradually adopted for the fabrication of high-performance cutting tools because of its outstanding physical and mechanical properties. Shown in Table 1, the hardness of PCD is much higher than that of WC, which ensures the PCD tools to machine titanium alloys with relatively high cutting speeds. The extremely high hardness of PCD is about two times of the hardness of PCBN which makes PCD tools more resistant to abrasive wear. Furthermore, its excellent thermal-conductivity (5 times of those of WC and PCBN) reduces the temperature at the tool/chip and tool/workpiece interfaces during machining process which makes it a promising tool material for machining titanium alloy [10].

20 Table 1 Basic properties of different tool materials [4]

<table>
<thead>
<tr>
<th>Tool Material</th>
<th>Physical and Mechanical Properties</th>
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<tr>
<td></td>
<td>Knoop Hardness (GPa)</td>
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<tr>
<td>Tungsten Carbide (K10)</td>
<td>13</td>
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<tr>
<td>PCBN (Amborite)</td>
<td>28</td>
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<tr>
<td>PCD (CTB010)</td>
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There are studies about the performance of PCD tools when cutting materials used in aerospace industry. Compared with tungsten carbide tools, the tool wear resistance of PCD tools is better when machining composite materials, which had been proved by several experiments. In Park’s experiment [11], there was a comparison between PCD drill bits and WC drill bits when machining titanium/carbon fiber laminates. The results showed that, by using PCD drill bits, the increase of thrust force, which is the main factor of delamination [12], was not obvious when the number of drilled holes increased. Because the thrust force increase with tool wear development [13], Park’s results means that the cutting edges of PCD tools were more durable when machining laminate composites. Furthermore, the group found that the adhesion of titanium was less severe than the condition of adhesion WC tool surface owing to the high thermal conductivity and low friction of PCD [14]. In Sreejith’s experiment on machining of carbon/phenolic ablative composites, notching, spalling and cracking were found on tool surface. The reasons for these phenomena were oxidation, high temperature and tool tip oscillation, and degradation caused by thermal effect respectively [15]. According to some experimental results [16], the life of PCD tools were longer compared with tungsten carbide (WC) tools when machining Ti6Al4V with the cutting speeds 100m/min, 200m/min and 300m/min. However, the brittleness of PCD and high machining temperature because of the low thermal conductivity of titanium caused edge chipping and micro fracture on the cutting edge [17].

2.2 Introduction on the manufacturing of PCD tools

PCD was synthesised by diamond grains (Figure 3(a)) and metallic (usually cobalt) powder as the binding material (Figure 3(b)). There are several methods used to produce PCD, and the general method was to sinter the diamond grains and binder material together under high pressure (about 5 GPa) and high temperature (over 1500 °C) [18]. Cobalt powder was molten and infiltrated through the diamond grains, stimulating the formation of diamond to diamond bonds as a solvent-catalyst [19]. PCD could be manufactured into different shapes (Figure 3(c)) by the types of mould. The matrix distributed diamond phase and the pool shaped binder material were synthesized together as the polycrystalline phase (Figure 3(d)) which was sintered on a tungsten carbide substrate. Within the PCD structure, the diamond and binder materials was
combined with two kinds of bonds, specifically (Figure 3(e)), the diamond to cobalt bonds (D-Co) existed at the interface of diamond, and the diamond grains were combined by the diamond to diamond bonds (D-D). A PCD tool is usually fabricated by brazing PCD insert which is cut from a PCD disc on the tool shank (brazed PCD tool); more advanced method is packing diamond powder into grooves formed in the carbide body, sintering the diamond powders and then brazing the veined PCD blank to a tool shank (veined PCD tool) [20].

**Figure 3** The component of PCD before sintering (a) Dominant grains (b) Cobalt powder (c) PCD material after sintering (d) PCD surface (SEM) (e) Bonds within PCD
2.2.1 Abrasive grinding

Due to the ultra-hardness, the surface of PCD tools is difficult to refine. Conducted on the diamond grinding machine (Figure 4(a)), abrasive grinding is the conventional method which removes the material by the abrasion between the surfaces of the workpiece and a rotating diamond grinding wheel (Figure 4(b)). It was reported that this method provided a high surface quality and a long tool lifetime when the grinding parameters were adopted properly [21]. However, due to high hardness of PCD, the material removal rate of this method was extremely low, and the wear rate of grinder wheel (mainly the peel out of diamond grains on the grinder wheel) was relatively high (G ratio of 0.01 to 0.05) [22, 23]. Therefore, the high machining cost caused by low machining efficiency and high wear rate lead to the sky high cost of PCD: a brazed PCD tool is about 10 times expensive than a carbide tool, while the price of a vined PCD tool is about 20 times higher than the carbide ones [24]. Furthermore, the quality and performance of ground tools were strongly rely on the adopted cutting parameters and the types of the diamond grinder wheel. Based on Dold’s research, it was found that the size of grains had an effect on the quality of cutting edge, to be specific, larger chipping area was found on cutting edge of PCD sintered by small-size grains. This finally resulted in the formation of torn-out grains on the ground region [25]. In order to eliminate this defect, a secondary laser treatment was conducted to create a homogenous surface on cutting edge geometry. Refining by this method, a sharp cutting edge with sub-micro meters’ radius was obtained but the rate of machining was really low [26]. Also, the tool life of PCD inserts fabricated by conventional grinding was not ideal sometimes. According to Tsao’s investigation [27], defects such as facial cracks, fracture within local area and graphitization were reasons caused in abrasion process reduced the tool wear resistance of ground tools.
2.2.2 Electrical discharge grinding

The high manufacturing cost caused by the long machining time is the major impediment to the implementation of PCD tools. In order to increase the tool machining efficiency, electrical discharge grinding (EDG) is now gradually adopted by tool manufactures (Figure 5(a)). Different from abrasive grinding which removes the facial materials by physical abrasion, EDG is a noncontact thermal erosion process in which the facial material is removed by a series of recurring electrical discharges between the rotatory electrode and the electrically conductive workpiece, in the presence of a dielectric fluid (Figure 5(b)). The electric conductivity of PCD caused by the conductive binding material (Cobalt) makes it possible to machine PCD tools with EDG technology. However, the electrical conductivity is still poor, and this makes the EDG process is almost 3 times slower than electric discharge machining (EDM) of conductive metals [28].
Owning to the special structure of PCD, the EDM erosion process is very complex. The machining mechanism is distinctively different from conventional conductive material. The EDG machining of PCD is a thermal process and operates with discharge temperatures in the order of 8000 to 12000 °C. Unlike the thermal damage caused by spark erosion on the surface of metal-type workpieces which are generally localised because of the relatively low thermal conductivity, PCD is a good thermal conductor and very sensitive to heat. The quality of machined surface strongly relies on the states of discharges. Normally, EDM process has four main types of discharge status (Figure 6): normal discharge, open circuit, arc and short circuit. Except the first type which contributes to the removal of workpiece materials normally, other states are abnormal discharges.
To distinguish the status of the spark during the machining process, the discharge states can be classified by difference in ignition delay time [29]:

$$t_d \begin{cases} = 0 & \text{short circuit} \\ < t_a & \text{arc} \\ < t_e & \text{normal discharge} \\ = t_e & \text{open circuit} \end{cases}$$

where $t_d$, $t_e$, $t_a$ represents the ignition delay time, pulse duration, and the threshold time for arc identification, respectively. As presented in Figure 7, both short and open circuit reduced EDM erosion efficiency because effective plasma channel were not generated during the on-time period. With the characteristic of very short or no ignition delay time, an arc damages the surface finish because it deteriorate the gap status and make the EDM process instability [30, 31]. The ignition delay times show a big variation but the pulse on-time and off-time are the same [32].
2.2.3 Thermal defects

PCD is sensitive to heat, and the thermal defects caused by the heat generated in both abrasive and erosive processes were inevitable. The main problems confronting are graphitization and residual stress.

Residual stress (Figure 8) was caused by the mismatch of coefficient of thermal expansion between diamond particles and cobalt which plays a role of catalyzer in sintering process [24] [33]. It is believed that residual stress is accumulated in three processes: sintering process, brazing process, and grinding processes. The level of residual stress needs to be controlled within a range as larger residual stress can reduce the quality of PCD tools [34]. According to Yahiaoui’s research, tensile residual stress in PCD layer could lead to inner cracks, weaken the strength of diamond to diamond bonding and low the tool wear resistance [35]. The status and distribution of residual stress are affected by different factors. It was suggested that the thickness of PCD layer influenced the residual stress distribution in diamond layer [36]. In other words,
position of residual stress depends on the thickness ratio of PCD layer and tungsten carbide base. The size of PCD grains affects residual stress on machined surface as well. As PCD powder with different particle sizes are used during sintering process, larger compressive residual stress usually in PCD layers which were consisted of grains with big size (for example 30 µm) after cooling down [37].

Another thermal defect that cannot be avoided is graphitization. Carbon in nature usually has two allotropic forms. The chemical bonding between the carbon atoms in diamond is covalent with sp3 hybridization, which is metastable at room temperature and atmosphere pressure [38]. Under high temperature (1600 °C), the electronic configuration associated with surface atoms changes from sp3 to sp2 happened, which led to the structure of carbon transferred from body-centred cubic structure to lattice structure rapidly at under normal pressure (Figure 9) [39]. However, with cobalt as its catalyzer, graphitization happens when temperature reaches 973K which is easy to reach for both abrasive grinding and EDG. The conversion from diamond structure to graphite structure is harmful because it will weaken the strength of diamond and cause the irreversible expansion in volume [40, 41]. Based on experimental results [42], PCD would lose 36% of its original hardness when heated from normal temperature up to 500K which was ascribed to the graphitization process.
Normally, both graphitization and residual stress can be detected by using Raman Spectrum Analysis. The theory of this technique is based on the “Raman Effect” [43] which reflects the status of carbon of the crystalline diamond structure. As presented in Figure 10(a), when the PCD surface is irradiated by the light beam, a photon (electromagnetic radiation of a specific wavelength) interacts with a carbon atom, being in either the ground rovibronic state (lowest rotational and vibrational energy level of the ground electronic state) or an excited rovibronic state, in the mode of inelastic collision resulting in the emitting or scattering of the photon. Meanwhile, the carbon atom experienced this inelastic collision process rotates or vibrates in different states compared with the atom was originally. Reflected in the Raman spectroscopy, the difference in energy between the original rovibronic state and this resulting rovibronic state leads to a shift in the emitted photon's frequency away from the excitation wavelength. When suffering external stress, this shift could be left-ward or right-ward as the status of the carbon atoms was changed by the reduced (Figure 10(b)) or extended (Figure 10(c)) atom distance.
Figure 10 Mechanism of Raman effect (a) Natural status (b) Compressive status (c) Tensile status

The shift of peak value of different phase of carbon can indicate the existence of these matters and help to calculate the residual stress within the scanned region [44]. As is shown in Figure 11, that three kinds of lattice exists in PCD: raw polycrystalline diamond (1330/cm), stressed polycrystalline diamond (1332/cm), nanocrystalline diamond (1250/cm), and graphite (1600/cm) [45]. The shift of diamond peak (1332/cm) indicates that residual stress exists within the PCD layer.
2.3 PCD wear mechanism

In metal cutting process, three deformation zones are formed at workpiece/chip contact face (primary deformation zone), tool/chip interface (secondary deformation zone) and tool/workpiece interface (tertiary deformation zone) respectively (Figure 12(a)). The tool surface was exposed to an environment with huge pressure, severe abrasion and extremely high temperature, which causes various types of tool wear (Figure 12(b)) which strongly influences the tool life. The development of tool wear is affected by duplicate reasons including physical, chemical and thermal factors. To be specific, flank wear is caused by the abrasion of tool flank face and the moving workpiece surface [47]; formation of build-up edge along the cutting edge and build-up layer (BUL) on tool surface is initiated by the diffusion of workpiece material [48]; the excessive load exerted by flowing chips tends to cause chipping and notching along cutting edge [49]. Other tool wear types such as fracture of tool nose, plastic deformation of cutting edge and oxidation on tool surface were often found on metallic cutting tools. Otherwise, one type of tool wear can be affected by more than one factor. For instance, when turning titanium alloy with WC tools, the crater wear found on the tool rake face was the combine effect of high temperature and abrasion at tool/chip interface.
Among these types of tool wear, the development of flank wear is used as the indicator to reflect life of different cutting tools. The change of width of flank wear (“VB” a value used to reflect the condition of flank wear) was plotted as tool life curve to describe the development of tool wear and indicate the effective tool life of cutting tools [50]. Shown in Figure 13, the development of flank wear is divided into three stages: the initial wear process, the steady wear process and the intensive wear process, according to the rate of the increment of VB. The VB increased rapidly to a value in the initial wear process, and the increase became stable and linear in the steady wear process. VB increased drastically in the intensive wear process which also stands for the end of tool life.

Figure 13 Tool life curve according to the development of flank wear width
2.3.1 Wear mechanism of PCD in macro-scale

Different types of tool wear were found when machining titanium alloys with PCD tools. Titanium alloy is active and affinity to many kinds of tool material [51]. The cutting tools can be worn by abrasion, adhesion, chemical erosion, diffusion, and other wear modes [4]. Chipping and fracture are often found on the cutting edges especially in the milling process [4]. Amin et al. [52] investigated the wear process of PCD tools in milling titanium alloy TC4 (Ti6Al4V). According to their results, the fracture of tool nose, abrasion on flank face and notching along the cutting edge were the main wear types found on the surface of PCD tools (Figure 14(a)). Honghua et al. [53] conducted a milling experiment of TA15 using PCD end mills with the cutting speed of 350 m/min. They assumed that the reduced yield strength of PCD tool caused by high cutting temperature in combination with the dynamic shock on the cutting tools led to the appearance of chipping and adhesion (Figure 14(b)). In the milling experiment conducted by Li et al. [54], the cutting speed was increased up to 375 m/min, which was the upper limit of the cutting speed for PCD tools. The large scale of chipping found along the cutting edge indicated that PCD was vulnerable to the high-frequency changed dynamic force under such a high cutting speed (Figure 14(c)). Oosthuizen et al [16] investigated the effect of coolant in high-speed milling process of titanium alloy with PCD tools. Adhesion and thermal cracks found on the tool surface without the application of coolant reflected that the structure of PCD became extremely unstable under high cutting temperature and severe abrasion without the application of coolant (Figure 14(d)).

As for the turning process, its main difference from milling is that the influence of heat generated by the continuous cutting is more significant, although the dynamic force exerted on tool surfaces are not as severe as those in the interrupted cutting (milling) processes. Results of relevant experiments showed that, in addition to flank wear caused by the abrasion at tool/workpiece interface, thermal activated wear including chemical diffusion and BUL also existed [55]. Based on the experiments on turning Ti6Al4V with different cutting parameters, In Rosemar’s experiment, tool life and wear mechanism of PCD inserts were learned [56]. In experiment, PCD tools were used to turning Ti6Al4V in different cutting speeds with coolant. After machining, severe crater wear and adhesion were found on worn area. He thought the results of experiment could be attributed to a combination of attrition and diffusion-adhesion mechanism (Figure 14(e)). To be specific, adhesion wear occurred between the surfaces of workpiece which has chemical
affinity and tool clearance face. Then high cutting temperature accelerated the rate of this chemical diffusion and this process resulted in a layer of titanium-carbide layer [57, 58]. Finally this layer and amount of tool material were removed by plucking action, thus accelerated tool wear on rake face.

Figure 14 Wear of PCD tools found in milling tests (a) Results of Amin et al. [52] (b) Results of Honghua et al. [53] (c) Results of Li et al. [54] (d) Results of Oosthuizen et al. [16] (e) Results of da Silva et al. [56]
2.3.2 Wear mechanism in micro-scale

Being a kind of sintered material, PCD is manufactured with diamond grains and binding materials under high pressure and temperature [27]. In the PCD structure, three kinds of bonds exist simultaneously, which include diamond-diamond bonding, cobalt-diamond bonding and C-C bonding within the diamond grains. The wear process in micro scale was the breakage of these bonds. Generally, inter-granular (Figure 15(a)) and trans-granular fracture (Figure 15(b)) were the two kinds of fracture mechanism of polycrystalline materials [59]. Inter-granular fracture was the typical fracture mechanism of most sintered materials when they are subject to quasi-static load as the grain-grain bonding formed after the sintering process is weak [60, 61]. For PCD, the strength of the diamond-diamond bonding is known to be strong, both inter-granular and trans-granular fracture were expected to happen because of the low energy cleavage planes within polycrystalline diamond structure (diamond-diamond bonds) and the weak bonds at the interface of diamond and binder material [62].

Figure 15 (a) Simplified mechanism of inter-granular fracture (b) simplified mechanism of trans-granular fracture

McNamara et al. conducted a series of experiments [63-65] to investigate the fracture toughness of PCD structure. Their results (Figure 16(a)) showed that the fracture toughness of PCD was affected by the size of diamond grains, status of secondary phase (binding material) and the
residual stress after sintering process. Inter-granular fracture was the mode of damage for the PCD consisted of fine grain size diamond (≤ 4 µm) under quasi-static load. While, trans-granular fracture usually happened within the structure of PCD consisted of coarse grains (≥ 20 µm) suffering dynamic force. Some experiments have been conducted aiming to investigate the stability of PCD microstructure at different temperatures. Based on the results of a sliding wear test, Deng et al. [66] proposed that the friction behaviour of PCD changed with the increase of ambient temperature. The friction coefficient decreased with the increase of environment temperature. Furthermore, micro-cracks along grain boundaries increased because the binder material cobalt was molten by the high temperature and extrude out by the grinder (Figure 16(b)). Jaworska et al. tested the oxidation, graphitization and thermal resistance of PCD materials with different secondary phase at 800 °C by the sliding test [67]. According to their results, the degradation of hardness of different PCD structures was influenced by the materials of secondary phase (Figure 16(c)). In terms of the friction coefficient, Jaworska et al. found that the friction coefficient increased with the increase of environment temperature and became fluctuated when the environment temperature was around 600 °C. Westraadt et al. investigated the thermal degradation of PCD properties when the temperature was up to 800 °C [68], they found that the conversion from diamond to graphite (Figure 16(d)) resulted in the formation of facial cracks, which was different from the hypothesis that cracking was solely caused by thermal expansion and the extrusion of cobalt. Kai et al. [69] utilized simulation to investigate the wear mechanism of PCD in nano-scale. It is found that high cutting temperature reduced the cohesive energy of carbon and weakened the C-C bond of diamond, which reduced the strength of the microstructure within diamond grains (Figure 16(e)).
Figure 16 (a) Results of McNamara et al. [63-65] (b) Results of Dent et al. [66] (c) Results of Jaworska et al. [67] (d) Results of Westraadt et al. [68] (e) Results from the simulation of Kai et al. [69]
2.3.2 Wear mechanism in micro-scale

According to the aforementioned introduction, the research on wear of PCD tools includes studies on different wear processes in macro-scale and the wear mechanisms in micro-scale. As shown in Figure 17, thermal crack, tool/chip and tool/workpiece abrasion, tool tip fracture, spalling of facial material, BUE and BUL caused by adhesion, and chipping of cutting edge were the wear processes of PCD tools in metal cutting. Micro-cracks caused by inter-granular fracture and trans-granular fracture, the graphitization under high temperature and reduction in properties were the wear mechanism of PCD tools in micro-scale.

Figure 17 Studies on wear process and wear mechanism of PCD tools
2.4 Tool wear model

2.4.1 Analytical model

Analytical models were developed to investigate the wear mechanism and predict the development of wear processes of different tools theoretically. In order to describe the relationship between tool life and cutting parameters, Taylor proposed an empirical equation which defined an exponential relationship between the tool life and the cutting speed [70], which can be written as followed:

\[ t = AV^{-B} \]  \hspace{1cm} (2.1)

where \( t \) is tool life, \( V \) stands for cutting speed and \( A, B \) are constants. This formula has been applied in metal machining using WC, PCBN and PCD tools although it was first developed for predicting tool life of HSS [71]. In fact, it has been proved that cutting speed influences tool wear rate by affecting cutting temperature. As a result, a modified model was proposed by Taylor himself which defined the tool life as a function of cutting temperature. This empirical formula is often used to explain the relationship between tool life and cutting temperature [72]:

\[ t = CT^{-D} \]  \hspace{1cm} (2.2)

where \( T \) is cutting temperature, and \( A, B \) are constants. However, both of Taylor’s models only provided a general method to predict the time without considering the tool material, workpiece material, and the types of tool wear.

In industry, flank wear is an important indicator about tool life. For predicting its condition, Takeyama and Murata developed a model to explain the relationship between tool temperature and the lost mass on flank face. In this model, they considered that flank wear was caused by abrasion which was proportional to the cutting distance and independent of tool temperature. This relationship was given by following equation [73]:

[Continue]
\[ \frac{dW}{dt} = De^{-\frac{E}{RT}} \]  

where \( W \) stands for mass loss due to flank wear, \( D \) and \( K \) are constants, \( E \) is activation energy and \( T \) is tool temperature.

In Attanasio’s simulation [74], flank and crater wear evolution was predicted utilizing a diffusion wear model implemented into an Arbitranean Lagrangian Eulerian (ALE) numerical formulation. Considering the effect of diffusive-adhesive wear, the author used a modified Takeyama and Murata model:

\[ \frac{\partial W}{\partial t} = D \exp\left(-\frac{E}{RT}\right) \]  

where \( D \) is a material constant, \( E \) is the activation energy and \( R \) is the gas constant and \( T \) is the tool temperature. Furthermore, temperature prediction was obtained by Eulerian step of the analysis considering the global heat transfer coefficient at the tool-chip interface with following equation [75]:

\[ T = 442 - 2.36V_c - 7950f + 0.0276V_c^2 + 40600f^2 \]  

where \( h \) which is a function of both the normal pressure and the temperature along the contact length, is the function cutting speed \( V \) and feed rate \( f \). The results showed that the error was 6%~10% for both flank wear and crater wear.

With the gradually comprehensive understanding of tool wear, analytical models considering the properties of tool materials, workpiece materials and different types of wear mechanism were developed. For abrasive wear, the analytical model proposed by Rabinowicz was most widely used [76, 77]. Material loss due to two types of abrasion were considered and modeled respectively. Two-body abrasion was caused by the pure friction between the abrasive surfaces, and the material loss due to this abrasion was influenced by the sliding distance and the hardness of the harder material (Eq 2.6). Three-body abrasion considered the influence of the released hard particles from the harder surface, and the wear amount was supposed to have relationship with the ratio of the hardness of the softer material and the hard material (Eq 2.7).
Bhattacharya et al. proposed a wear model considering the effect of adhesion [78]. In this model, the definition of temperature sensitive zone (TSZ) and temperature insensitive zone (TIZ) was proposed. Tested by conducting dry turning experiment, they found that within the TSZ, the adhesive wear was more severe and was the function of cutting speed and types of material removing during the cutting process.

In the tool wear model developed by Choudhury et al. [79], the development of tool wear in turning process was described by a mathematically statistic model (Eq 2.8). The Wear amount was exponential relationship with the cutting parameters including feed rate, cutting speed and cutting depth. The model was validated by turning C45 steel using HSS tools under normal cutting speed.

\[
V_{\text{two-body}} = \frac{Lt\tan\theta}{\pi P_t} x
\]  
(2.6)

\[
V_{\text{three-body}} = \frac{K_1 x N}{K} \times \frac{P_t^{n-1}}{P_t^n}
\]  
(2.7)

Wong et al. investigated the wear of coated WC tools [80], they assumed that the adhesive wear was the predominant wear type for flank wear. They developed the empirical model (Eq 2.9) by considering the abrasive wear and adhesive wear was combined together. The model of wear rate was developed and concluded as a function of the hardness of tool. An empirical coefficient was obtained by cutting test with different parameters. However, the effect of abrasion and adhesion was not shown in the equation directly.

\[
h_f = 0.0238 \times N^{3.666} f^{1.34} d^{0.664} D_w^{4.466}
\]  
(2.8)

\[
\frac{dL}{dt} = 9 \times 10^8 \frac{A}{P_t}
\]  
(2.9)
With the development of synthetic materials, models were developed to investigate the wear process of ceramic tools and PCBN tools. Dawson and Kurfess reported a model on the development of flank wear for uncoated and coated PCBN tools. In this model (Eq 2.10 and Eq 2.11), the flank wear width was described as the function of cutting parameters and the geometric characteristics of the cutting tools [81].

\[
VB^u = (0.0561v^{0.68}f^{0.29}) \times \frac{v}{\sqrt{R \left[ \cos^{-1}\left(\frac{R - a_p}{R}\right) + \sin^{-1}\left(\frac{f}{2a}\right) \right] \left[ \frac{\tan\beta}{2(\tan\alpha + \tan\beta + 1)} \right]}}
\]

\[\text{Eq 2.10}\]

\[
VB^c = (0.0559v^{0.61}f^{0.31}) \times \frac{v}{\sqrt{R \left[ \cos^{-1}\left(\frac{R - a_p}{R}\right) + \sin^{-1}\left(\frac{f}{2a}\right) \right] \left[ \frac{\tan\beta}{2(\tan\alpha + \tan\beta + 1)} \right]}}
\]

\[\text{Eq 2.11}\]

Huang et al. developed a model (Eq 2.12) considering the adhesion as the main mechanism for flank wear process of the PCBN tools, which was validated by tests of AISI 52100 bearing steel cutting [82].

\[
\frac{dL}{dt} = \frac{(\cot\alpha + \tan\gamma)R}{VB(R - VB\tan\alpha)} \times \left\{ 0.0295 \left( \frac{p^{-1}}{p_t} \right) V_cV_B\sigma + 1.4761 \times 10^{-14} e^{9.0313 \times 10^{-4}T} V_c\sigma + 5.7204 \times \sqrt{V_cV_B\sigma^{20460 T + 273}} \right\}
\]

\[\text{Eq 2.12}\]
2.4.2 FEM simulations

Mechanism of tool wear was also investigated by using finite element method (FEM), and some advantages make the method suitable for the simulation of tool wear process. Compared with analytical model, the calculation process is more convenient because the processing method had been already programmed into software. By inputting the cutting parameters and properties of the materials, the accurate results of stress, strain, deformation and temperature fields can be obtained.

Kagnaya et al. [83] simulated the crater wear process using Deform 2D. The results of force in different directions showed good agreement with the experimental results, the main cutting force and feed force decrease with the increasing of depth of crater wear (KT) and width of flank wear (VB). As well as the temperature (Figure 18), it increased with KT and VB significantly. The effect of BUL on cutting process variables is highly depicted. BUL promoted the increase of the workpiece surface temperature whereas decreasing tool flank wear land temperature.

Figure 18 Results from the simulation of Kagnaya et al.: the distribution of temperature on worn surfaces [83]
Malakizadi et al. [84] predicted the rate of flank wear evolution for uncoated cemented carbide tools in longitudinal turning processes via FEA combined with response surface methodology. Force, stress and temperatures were investigated under different wear conditions (Figure 19). A fairly good agreement was observed between the flank wear simulations and experimental measurements within the range of the cutting conditions presented in this study. In-depth analyses of the cutting edges revealed the abrasion and adhesion mechanisms on the flank surfaces. The simulated mean interface temperatures were below 750 °C, which is well below the interface temperature of about 850–900 °C under which the thermally activated physico-chemical mechanisms are supposed to be dominant.

![Figure 19 Results from the simulation of Malakizadi et al.: nodal force, distribution of normal pressure and temperature on worn surfaces [84]](image)

### 2.5 Limitation of reviewed studies

It can be generalized that PCD is becoming widely applied in cutting hard-to-machine materials because of its outstanding properties. However, the tools made of PCD materials are difficult to fabricate due to its extremely high hardness. In industry, the surface of PCD tools can be refined by conventional abrasive grinding and discharge grinding. Both methods have their advantages but the thermal defects such as residual stress and graphitization are inevitable. Wear processes of cutting tools had been learned both experimentally and mathematically. By conducting experiments, wear mechanism of PCD tools was investigated in both micro-scale and macro-scale. Analytical models, statistic models and finite element models were developed to describe
the wear process of tools under different cutting conditions. However, there are still limitations of these finished works, and deeper investigation is needed in following aspects.

Firstly, it is far from clear how the micro-structure of different PCD materials will affect the quality of tools and the performance in industrial cutting processes, and to what extent the affection will be. The relationship between the micro-structure including size of diamond grains and the development of fracture had been revealed under sliding tests. However, these theories had never been considered in the wear process of PCD tools in industrial machining. Furthermore, the quality of PCD tools machined with different grinding methods and their performance in cutting titanium alloys need to be understood comprehensively. There are no studies on comparison of the quality and performance of eroded tools and ground tools. Also, research proved that residual stress existed within the PCD structure, however, the influence of this factor had never been considered when investigating the wear process of PCD tools. Also, few theoretical studies were conducted on the wear process of PCD tools, especially, the analytical models which considering the properties of different PCD tool materials were not proposed yet.

2.6 Summary

This chapter presents a review of manufacturing and application of PCD tools in different aspects including the development of cutting tools, the introduction of PCD materials, the manufacturing processes of PCD tools, and the experimental and theoretical studies on wear mechanism of cutting tools. Also, limitations of the reviewed research are given at the end of this chapter.
Chapter 3 Experimental Studies on Wear Mechanism of Different PCD Tools

In this chapter, wear mechanism of tools made of different PCD materials is investigated experimentally. Cutting forces in different directions were recorded during each process of turning, width of flank wear were measured after each turning test, and morphological characters of worn areas were observed through SEM to investigate the wear mechanism of PCD tools in micro-scale. Shape and morphological characters of chips were analyzed.

3.1 Experimental setup and data processing

This section introduces the setup of the turning experiments, including the preparation of cutting tools, the selection of cutting parameters and machined tools, and the measurement as well as the processing of experimental data.

3.1.1 Preparation of cutting tools

Three types of PCD materials CTB002 (Figure 20(a)), CTB010 (Figure 20(b)), CTM302 (Figure 20(c)), manufactured by Element Six were used. These PCD materials were sintered with different-sized diamond grains and pre-defined volume percentages of cobalt powder. Specifically, CTB002 and CTB010 consist of uniformly sized diamond grains, 2 µm and 10 µm grains respectively. The sizes of diamond grains consisting of CTM302 range from 2 µm to 30 µm, and the diamond of CTM302 occupies 91.4% of the total volume of the PCD layer. The basic physical and mechanical properties of each PCD material are listed in Table 2. It is found the values of Poisson’s ratio and overall hardness of these three materials are similar, however, other properties such as density and elastic modulus are different because of the difference in diamond fraction (volume percentage of diamond).
Table 2 Basic properties of PCD tool materials [21]

<table>
<thead>
<tr>
<th>Material</th>
<th>CTB002</th>
<th>CTB010</th>
<th>CTB302</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain size (µm)</td>
<td>2</td>
<td>10</td>
<td>2 to 30</td>
</tr>
<tr>
<td>Binder material</td>
<td>cobalt</td>
<td>cobalt</td>
<td>cobalt</td>
</tr>
<tr>
<td>Diamond fraction (%)</td>
<td>84.8 / 68.6</td>
<td>89.7 / 77.4</td>
<td>91.4 / 80.6</td>
</tr>
<tr>
<td>Density (g/mm³)</td>
<td>4.35</td>
<td>4.08</td>
<td>3.99</td>
</tr>
<tr>
<td>Young’s modulus (Gpa)</td>
<td>883</td>
<td>1000</td>
<td>901</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.1</td>
<td>0.1</td>
<td>0.11</td>
</tr>
<tr>
<td>Hardness (Gpa)</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>

Figure 20 Raw PCD materials (a) CTB002 (b) CTB010 (c) CTM302
The tool inserts were firstly cut from PCD discs into cubic shapes (7 mm x 7 mm) by wire-cut EDM (Figure 21). After EDM machining, a “heat-affect zone” (HAZ) was formed within certain depth from the machined surface. In HAZ, thermal defects caused by the high-temperature plasma including graphitization and residual stress were significant, which affected the wear resistance of PCD tools in cutting processes. Therefore, flank faces of the inserts were refined by conventional abrasive grinding. The grinding in-feed was pre-set as 100 µm to ensure the complete removal of HAZs.

![Figure 21 Setup of EDM wire-cut](image)

The tool quality after the grinding process was examined to avoid any flaws on the tool surface (Figure 22). The sharpness and surface roughness of the machined surface of six tools were measured by the Alicona (IF-EdgeMaster) 3D microscope fit with a 50x lens. The sharpness was defined as the average value of the cutting edge radiuses of the four cutting edges. The roughness was the average of that of the four machined surfaces (Table 3). It is found that the values of sharpness of all the inserts are around 6 µm, and the values of roughness of the machined surface are within the range of 110 nm to 130 nm. As a result, the effect from different tool surface quality on the wear development of cutting tools is minimized.
Figure 22 Cutting tools after grinding processes (a) tools made of CTB002 (b) tools made of CTB010 (c) tools made of CTM302

Table 3 Sharpness of cutting edge and roughness of machined surface

<table>
<thead>
<tr>
<th>Tool No.</th>
<th>Material</th>
<th>Cutting condition</th>
<th>Sharpness (µm)</th>
<th>Roughness (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T002N</td>
<td>CTB002</td>
<td>160 m/min</td>
<td>5.42</td>
<td>111</td>
</tr>
<tr>
<td>T010N</td>
<td>CTB010</td>
<td>160 m/min</td>
<td>5.92</td>
<td>121</td>
</tr>
<tr>
<td>T302N</td>
<td>CTM302</td>
<td>160 m/min</td>
<td>6.48</td>
<td>129</td>
</tr>
<tr>
<td>T002H</td>
<td>CTB002</td>
<td>240 m/min</td>
<td>5.77</td>
<td>125</td>
</tr>
<tr>
<td>T010H</td>
<td>CTB010</td>
<td>240 m/min</td>
<td>5.95</td>
<td>119</td>
</tr>
<tr>
<td>T302H</td>
<td>CTM302</td>
<td>240 m/min</td>
<td>6.21</td>
<td>128</td>
</tr>
</tbody>
</table>

Since tool inserts were shaped into cuboids, the angles of the cutting tool were characterized by the tool holder KORLOY DSDNN2020 K-12 (Figure 23(a)) with a -10 degree rake angle and a 10 degree relief angle. A customized fixture was designed and manufactured with aluminium alloy to clamp the dynamometer and the cutting tool as a rigid body (Figure 23(b)).
Figure 23 (a) the tool holder KORLOY DSDNN2020 K-12 (b) the customized fixture

3.1.2 Workpiece material

The workpiece used in this study were Ti alloy rods made of Ti-6Al-4V (Figure 24(a)) Grade 5 with the dimension of 300 mm (L) × 50 mm (D). As a kind of α+β phase (Figure 24(b)) titanium alloy, Ti6Al4V has higher strength and good plasticity which makes its mechanical properties better than purely alpha phase or beta phase titanium. The basic physical properties and composition of the material are listed in Table 4.

Figure 24 Workpiece material (a) the Ti6Al4V rod (b) optical microstructure of Ti6Al4V
Table 4 Sharpness and roughness after grinding [11]

<table>
<thead>
<tr>
<th>Mechanical properties</th>
<th>Chemical composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>4.43 g/mm³</td>
</tr>
<tr>
<td>Hardness</td>
<td>3730 MPa</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>113.8 GPa</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.342</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>6.7 W/m·K</td>
</tr>
<tr>
<td>Ti</td>
<td>88.3%</td>
</tr>
<tr>
<td>Al</td>
<td>6.5%</td>
</tr>
<tr>
<td>V</td>
<td>4.3%</td>
</tr>
<tr>
<td>C</td>
<td>0.1%</td>
</tr>
<tr>
<td>O</td>
<td>0.3%</td>
</tr>
</tbody>
</table>

3.2.3 Experimental setup and data processing

As shown in Figure 25(a) and Figure 25(b), the turning experiment was conducted on a CNC lathe OKUMA GENOS L200E-M which provided the feed rate ranged from 0.001 – 1000 mm/rev and the spindle speed ranged from 75 – 3000 rev/min. The CNC lathe can automatically change the spindle speed according to the dynamically reducing radius of the workpiece during the cutting processes. The entire experiment was divided into six groups (Table 5), the workpiece would be machined with one type of PCD inserts in each group. Figure 25(c) presents the simplified turning processes, fixed cutting depth (0.2 mm) and feed rate (0.15 mm/rev) were selected which were practically used in semi-finishing processes in industry [85] were applied in all experiments. Two cutting speeds, 160 m/min which is the normal cutting speed for turning titanium alloys with PCD cutters and 240 m/min which is the upper limitation of the cutting speeds for PCD tools, were selected to investigate the wear mechanism of PCD tools under different speed levels. To avoid the excessively thermal damage of cutting tools, every turning process was conducted with the application of 8 MPa fluid coolant which is often used for turning Grade 5 titanium alloy. For each cutting process, forces in 3 directions were recorded: the feed force (axial direction of the machine coordinate, X direction of the coordinate of dynamometer), the thrust force (radial direction of the machine coordinate, Y direction of the coordinate of dynamometer) and the main cutting force (tangential direction of the machine coordinate, Z direction of the coordinate of dynamometer).
Table 5 Cutting tests and cutting conditions

<table>
<thead>
<tr>
<th>Cutting conditions</th>
<th>Normal Speed</th>
<th>High speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting speed</td>
<td>160 m/min</td>
<td>240 m/min</td>
</tr>
<tr>
<td>Feed rate</td>
<td>0.15 mm/rev</td>
<td>0.15 mm/rev</td>
</tr>
<tr>
<td>Cutting depth</td>
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<td>0.2 mm</td>
</tr>
<tr>
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<td>35 seconds</td>
</tr>
<tr>
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<td>4160 mm³</td>
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<td>Coolant</td>
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<td>8 MPa</td>
</tr>
<tr>
<td>Tool no.</td>
<td>T002N</td>
<td>T010N</td>
</tr>
<tr>
<td></td>
<td>T302N</td>
<td>T002H</td>
</tr>
<tr>
<td></td>
<td></td>
<td>T010H</td>
</tr>
<tr>
<td></td>
<td></td>
<td>T302H</td>
</tr>
</tbody>
</table>

(a) (b) (c)
Figure 25 (a) the CNC lathe OKUMA GENOS L200E-M (b) Experimental setup (c) description of turning processes

Figure 26(a) presents the process of data collection and filtering of noise signals. For each cutting process, force were firstly acquired by the dynamometer PCB260A01 (Figure 26(b)) and transmitted as analog signal (voltage) and amplified by the coupler Kistler 9527B (Figure 26(c)); an I/O connecter CB-68LPR and a DAQ card National Instrument 6036E (Figure 26(d) and Figure 26(e)) was used to moderate the signal and complete the A/D conversion.

SignalExpress is the software used to present and collect the force signals (Figure 27). Three channels were selected to record the signals of forces in three directions respectively; cutting forces were recorded in the type of analog signals (voltage). Rate of the data collection and the sample to read was pre-set as 10000 and 1000 respectively, which means that 10 thousand data
of cutting force would be recorded per second, and the software would select 1000 from the data to present on the interface. During the cutting process, both force signals and noise were acquired and presented in the oscilloscope of SignalExpress.

![Configuration and Voltage Input Setup of SignalExpress](image1)

**Figure 27** Data record and presentation in SignalExpress (a) setup for data collection (b) acquired signals presented in the oscilloscope of SignalExpress

The acquired signals (Figure 28(a)) were filtered to remove the high-frequency noise during the recording processes. As a result, the collected data were processed by a low-pass digital filter in
MatLab. Generally, the Type I Chebyshev Filter which has a roll-off steeper and a pass band ripple was adopted as the low-pass filter as the filter could minimize the error between the idealized values and the characteristics of the actual signals. Mathematically, the filter is developed based the orthogonal functions of Chebyshev polynomial,

\[ G_n(\omega) = \frac{1}{\sqrt{1 + \varepsilon^2 T_n^2 \left( \frac{\omega}{\omega_0} \right)}} \]  

(3.1)

Where, 
\( \omega \)  
Angular frequency, positive stands for “clockwise rotating” Hz; 
\( \varepsilon \)  
Ripple factor; 
\( \omega_0 \)  
Stop-band frequency; 
\( T_n \)  
Chebyshev polynomial of the nth order, which could be presented as following,

\[ T_n(\omega) = \cos \left( n \cdot \cos^{-1}(\omega) \right) \quad -1 \leq \omega \leq 1 \]  

(3.2)

\[ T_n(\omega) = \frac{e^{\ln(\omega+\sqrt{\omega^2-1})} + e^{-\ln(\omega+\sqrt{\omega^2-1})}}{2} \]  
\[ \omega \leq -1, \omega \geq 1 \]  

(3.3)

The function of Chebyshev filters in MatLab is presented as following:

\[ y = lowp(X, f_1, f_3, r_p, r_s, F_s) \]  

(3.4)

Where, 
\( X \)  
Signal data; 
\( f_1 \)  
Stop-band frequency, Hz; 
\( f_3 \)  
Pass-band frequency, Hz; 
\( r_p, r_s \)  
Parameters on the trend of the curve; 
\( F_s \)  
Frequency of sampling;

The signals after filtering are plotted in MatLab, and as shown in Figure 28 Voltage signal after filtering, two peaks are found during the cutting process. The PCB260A01 is a kind of
A dynamometer which reflects the change of pre-tightening force. The force would have a sudden increase when the tool inserts start to cut the workpiece material and went down to zero if there were no drastically force increment, and a sudden decrease when the forces exerted on the dynamometer were released which were the cutting forces at the end of cutting. As a result, the cutting forces at the end of the cutting process are the production of the voltage when the cutting was finished and the sensitivities of the dynamometer in each direction:

- X-axis: $1000 \times 0.4195$ mV;
- Y-axis: $1000 \times 0.4459$ mV;
- Z-axis: $1000 \times 1.9876$ mV;

![Figure 28 Voltage signal after filtering](image)

3.2.4 Measurement of width of flank wear

The maximum width of flank wear (VB) was used as the indicator of flank wear development after each cutting test (Figure 29). The VBs were measured by an optical microscope with the magnification 50× (Alicona 3D scanner). Tools would be rejected if the flank wear land (width of maximum flank wear) was over 300 um according to the tool failure criteria in ISO 3685-1993.
3.2 Result of experiments

3.2.1 Change of cutting forces and development of flank wear under 160 m/min

As shown from Figure 30(a) to Figure 30(c), the evolution of cutting forces of the tools under the cutting speed 160 m/min increased with the accumulative cutting processes. The main cutting forces of T002N and T010N increased from 70 N to 320 N with similar trend in the first 7 cutting processes, and the force increment of T010N was smaller than that of T002N in the...
following cutting processes. The main cutting force was 120 N less than which was the smallest after the 14\textsuperscript{th} cutting process when T302N was used, and the force did not increase in strict linear trend. Specifically, the sudden increase of the force at the 7\textsuperscript{th} process and 12\textsuperscript{th} cutting process was found, while, the increments of cutting force were insignificant during the periods 1\textsuperscript{st} to 4\textsuperscript{th} cutting processes, 8\textsuperscript{th} to 11\textsuperscript{th} cutting processes and 13\textsuperscript{th} to 14\textsuperscript{th} cutting processes. The trends of feed force are similar to that of main cutting force. They increased linearly from around 20 N to 91 N and 77 N respectively when T002N and T010N were used. The feed force of T302N was the smallest and it experienced a sudden increase in the 13\textsuperscript{th} cutting process. The thrust force increased linearly for all three tools, the forces of T002N and T010N increased with a steeper gradient from the beginning to the 8\textsuperscript{th} cutting process, and it experienced insignificant increase afterwards. In contrast, the thrust force of T302N had a different trend, it was only 10 N after the 8\textsuperscript{th} cutting process, and there was an obvious increase when the cutting ran from the 8\textsuperscript{th} cutting to the 10\textsuperscript{th} cutting. The force became stable again afterwards. The change of VB (Figure 30(d)) reflected the development of flank wear in the cutting process. The VB of T002N increased linearly from 69 \(\mu\text{m}\) to 193 \(\mu\text{m}\), which was the biggest among all three tools. Similarly, the VB of T010N increased linearly from 50 \(\mu\text{m}\) to 93 \(\mu\text{m}\) during the first 6 cutting processes, and this value finally reached 137.5 \(\mu\text{m}\) with a smaller increase rate in the following 8 cutting processes. Fluctuation of VB, which was similar to the change of cutting force when using T302N, was found during the 2\textsuperscript{nd}, 8\textsuperscript{th} and 13\textsuperscript{th} cutting processes.
Figure 30 Change of cutting forces and VBs under the cutting speed 160 m/min (a) main cutting forces (b) feed forces (c) thrust forces (d) widths of flank wear (VB)
3.2.2 Change of cutting forces and development of flank wear under 240 m/min

Figure 31(a) to Figure 31(c) present the change of cutting forces during the high-speed cutting tests in three directions. The cutting forces of T002H, T010H and T302H were similar to the forces under the normal cutting speed when cutting edges of the tools were sharp, and the increments of the forces were more significant at the end of the high-speed cutting tests. The main cutting forces of T002H, T010H and T302H experienced drastically larger increment under the cutting speed 240 m/min, all of which increased linearly from about 90 N to 640 N, 540 N and 390 N respectively in 6 cutting processes. The development of feed forces of the tools was similar to the change of main cutting forces. Feed forces of all three tools were around 18 N when the edges were sharp. Feed forces of T002H and T010H experienced an increment of 90 N, while the force increment of T302H was only 30 N. The forces of T002H and T010H were nearly the same, both of which increased to around 60 N in steep linear trend. The thrust force of T302H was one third less than that of T002H and T010H. Drastic increase was found in the first 3 cutting process, and the increment was insignificant in the following 3 cutting processes. The trends of feed force are similar to that of main cutting force. On the part of the development of width of flank wear (Figure 31(d)), VBs of T002H, T010H and T302H increased over 190 µm after 6 cutting processes which were nearly triple of the VBs generated under the cutting speed 160 m/min after 6 cutting processes. To be specific, the VBs of T002H and T010H were 342 µm and 284 µm respectively, which were larger than that of T302H (196 µm). Considering the error of measurement, both tools reached the rejection criteria according to ISO 3685-1993.
Figure 31 Change of cutting forces and VBs under 240 m/min (a) main cutting forces (b) feed forces (c) thrust forces (d) widths of flank wear (VB)
3.3 Discussion on wear mechanism

It has been proved that the “diffusive-abrasive” interaction at tool/workpiece interface was the main wear mechanism in machining titanium alloys [56]. The similar phenomenon was found on the worn surfaces of PCD tools after the turning process based on the aforementioned experimental results in literature review. Furthermore, PCD materials consisted of diamond grains and cobalt as the catalyzer, and these two materials were combined by diamond grains and diamond-diamond bonds after sintering [86]. As a result, the wear of PCD tools is influenced by the microstructure of the PCD materials (Figure 32 Wear process of PCD tools in micro-scale, which is different from the wear process of metallic tools such as WC tools. It has been proved that the nature of the wear process of PCD tools was the breakage of the existed bonds within PCD structure in micro-scale. The structure of tool material collapsed when the bonds were broken, and this led to the removal of facial tool material during the cutting process leading to the development of tool wear. When cutting metallic materials, the 2\textsuperscript{nd} deformation zone and the 3\textsuperscript{rd} deformation zone respectively were formed at tool/chip and tool/workpiece interfaces respectively. A large amount of heat was generated and huge pressure was exerted on the tool surface at the same time, which led to the increase of temperature and stress around these areas. The high temperature at the contact surfaces caused the appearance and propagation of thermal cracks along the crystallographic planes [66]. On the other hand, compressive residual stress distributed on the surface of PCD after abrasive grinding [87], which would lead to the instability of PCD structure. With the combined influence of high pressure, high temperature and residual stress, the diamond-diamond bond and diamond-cobalt bond were prone to break down, a proportion of PCD materials would be removed by the abrasion causing material loss on tool surfaces.

However, the size of diamond grains and the volume proportion of the binding material are different for types of PCD materials, and it is known that grain size and volume fraction of diamond in the PCD may have influences on the properties of PCD tools. In this section, the wear mechanism of tools made of three different PCD materials will be investigated, and the
influence of grain size and volume fraction of diamond in the PCD on wear process will be discussed.

Figure 32 Wear process of PCD tools in micro-scale

3.3.1 Discussion on wear mechanism of tools under the cutting speed 160 m/min

3.3.1.1 Analysis of flank wear process

Detailed morphological characters of worn areas on flank faces were obtained by the Scanning Electron Microscope Philips XL30. As for tools made of CTB002 and CTB010 (Figure 33(a) and Figure 33(c)), the worn areas after 6 cutting processes on the flank face can be divided into two regions, a rectangular worn area with exposed PCD surface near the tool tip and a triangular “adhesion-rich” area scaled with layers of adhered titanium alloy. The enlarged images (Figure 33(b) and Figure 33(d)) show that rectangular worn areas of T002N and T010N were scaled by partial workpiece material. Near the tool noses, a clear boundary between the exposed area and adhesion-rich area was found on the flank face of T010N. Also, it was found that partial adhered material with scratches adhered on the worn surface of T002N. These morphological characteristics proved that a layer of adhesion was ever formed but it was partially removed together with some tool materials in the cutting process. As for the tool made of CTM302 (Figure
33(e) and 33(f)), large-scale fracture of PCD structure happened during the cutting process, this is different from the wear mechanism of the tools made of CTB002 and CTB010. In the enlarged image, it was found that the tool tip was totally removed leaving a coarse surface at the position where the tool tip used to be.
In turning titanium alloy, the flank wear process of PCD tools was dominated by the “adhesive-abrasive” mechanism. Subjected to quasi-static shear stress and high cutting temperature near the tool tip, micro-cutting, scoring, ploughing and grooving at tool/workpiece interface [88] could remove the adhered material as well as some bonded tool material. As for tools made of CTB002 and CTB010 which were made of uniformly sized diamond grains, tool material with adhered workpiece material was prone to being removed by the tool/workpiece abrasion as a “spalling” process [89]. This “spalling” process was steady which could be proved by the linearly increased main cutting force and VBs. In micro-scale, this spalling was caused by the breakage of diamond-diamond bonds and cobalt-diamond bonds, and this led to inter-granular fracture [89] at the cobalt-diamond boundary and the interface of sintered grains. Compared with CTB002, the fracture toughness of CTB010 is higher, and this makes T010N more resistant to the spalling caused by the tool/workpiece abrasion. Because the temperature near tool nose was higher, a rectangular worn surface with freshly exposed PCD was created, which indicated that the spalling process at this area was serious.

Different from CTB002 and CTB010, CTM302 is sintered with the mixture of diamond grains sized from 2 to 30 µm, and the diamond fraction of CTM302 is the highest among the three types of PCD tools, and the tool made of this material is more resistant to abrasion. However, high volume fraction of diamond makes PCD structure of CTM302 more brittle at the tool tip, and the high brittleness would result in relatively large-scale fracture at the tool tip under high stress in the cutting processes. In micro-scale, the fracture was the combined effects of inter-granular and trans-granular fracture [89]. As was presented by the development of VB of T302N, it increased dramatically after the 1st and 2nd cutting processes but increased slightly in the following cutting tests, this was a clear evidence proved that the tool tip fracture happened at the early stage of the turning. Also, the limitation of flank wear area could be ascribed to the change of tool geometry caused by the fracture of the tip of T302N. Specifically, a slope with bigger rake and clearance angles in the worn area was formed. The increase of clearance angle reduced the tool/workpiece
contact region, as a result, the adhesion was constrained in a small area on the tool flank face, which shows that the development of flank wear was restricted by this geometric change.
Figure 34 Morphology of worn areas after 14 cutting processes (a) Worn area on the flank face of T002N 1000× (b) Detailed character of the worn area of T002N 2000× (c) Worn area on the flank face of T010N 1000× (d) Detailed character of the worn area of T010N 2000× (e) Worn area on the flank face of T302N 1000× (f) Detailed character of the worn area of T302N 2000×

Different morphological characteristics of worn areas on the flank face were found after 14 cutting processes. Specifically, strip-like BULs were found on the flank faces of the T002N and T010N (Figure 34(a) and Figure 34(c)). Titanium alloy stacks on the tool tips and scales along the cutting edges of T002N and T010N, and the BUL of titanium alloy was thicker (Figure 34(b)). This reflected that the cutting temperature was higher than that in the first 6 cutting processes. The laminated character indicated that the thicker layer of adhesion was accumulated during the cutting processes (Figure 34(d)). However, the increment of VB during the following 8 cutting processes was smaller than the VB increment during the first 6 cutting processes. With the development of wear process, tool materials within HAZ were removed gradually (10 µm from flank face when the aforementioned grinding parameters were adopted [46]), and therefore the large residual stress which was original in the HAZ zone was released. Owing to the reduction of residual stress, strength of PCD structure beneath the BUL was strong enough to prevent the aforementioned “spalling of PCD material” from occurring. Also, the preserve of BUL on the tool surface could prevent the generated heat transferring to the cutting tool [90], which reduced the rate of flank wear development. In the following 8 cutting processes, the flank wear of T302N was developing in the type of fracture in a large scale (Figure 34(e)). As shown in Figure 34(f), trans-granular fracture happened at the tip of. The thick layer of titanium which adhered to the tool at the boundary of fracture indicated that diffusive-abrasive wear process happened before the fracture of tool tip.

3.3.1.2 Analysis of crater wear process

Crater wear was caused by the interaction between tool rake face and chip surface in the 2nd deformation zone [91]. Compared with the cutting conditions at tool/workpiece interface, the temperature and shear stress within the 2nd deformation zone were higher. Although coolant had been applied in this study, the temperature at tool/chip interface near the tool tip was still nearly as high as the temperature in dry cutting condition because the coolant flow could hardly reach the tool/chip interface near the tool tip. As a result, chemical diffusion as well as the adhesion-abrasion interaction at tool/chip interface were the dominant mechanisms for crater wear. Figure
33 illustrates worn morphology on the rake surfaces of all three tools which were obtained after the 6th cutting process and the 14th cutting processes. It could be seen that scattered workpiece material scaled on the rake faces of T002N (Figure 35(a)) and T010N (Figure 35(c)), and little titanium was found near the tool tips. 100 µm away from the tool tip, the titanium alloy, which stacked along the cutting edge and formed obvious BUE, reduced the sharpness of the cutting edges. In contrast, the tip of T302N (Figure 35(e)) was fractured leaving a coarse surface, and a thick BUL was scaled on the rake face of the tool. After another 8 cutting processes, titanium alloy tended to stack at tool nose and along cutting edge of T002N (Figure 35(b)) and T010N (Figure 35(d)), fresh PCD was exposed in the areas where titanium alloy used to be scaled on. During the following turning process, fracture of the tip of T302N (Figure 35(f)) kept happening, and part of the BUL near the cutting edge was removed. The rest of BUL became scattered leaving an area of exposed PCD surface near the cutting edge.
To investigate the wear mechanism of crater wear comprehensively, the worn area on rake face is separated into three regions (Figure 36) based on the distribution of normal stress, shear stress and temperature [48]. Region I is a narrowly strip area locates near the cutting edge, which is defined as “sticking zone”. The stresses at the tool/chip interface were the highest among all three regions. In Region II, both velocity of the chip flow and the shear stress become stable. The tool/chip abrasion in this region is intensive, and the contact status changes from sticking to sliding. Furthermore, the effect of coolant is insignificant due to the intensive contact of tool surface and chip surface, based on numerical and analytical models about the temperature distribution on rake face, the temperature within this region reached its highest. With the combined effect of the exerted stresses, the maximum depth of crater wear can be found within this region. In region III, the shear stress at tool/chip interface became less significant, while the adhesive wear became predominant. Rosemar et al. concluded that a part of workpiece adhesion and its bonded tool material was removed by the “plucking action” of chip flow [56], and similar morphological characters was found on the worn rake face of T002N, T010N and T302N.
In Region I, under the high temperature caused by the heat generated in primary deformation zone, adhesion of workpiece material along the cutting edge was significant which led to the formation of build-up edge (BUE) along the cutting edges. As shown in Figure 35, the length of the BUE was around 300 µm which was equal to the tool/workpiece contact length for T002N and T010N. BUE near the tip of T302N was not reserved because of the large-scale fracture.
Morphology of tool wear in Region I after 14 cutting processes (a) T002N (b) T010N (c) T302N

In Region II, cracks were found on the rake faces of tools made of CTB002 and CTB010. As for T002N and T010N, the distribution of micro-cracks was intensive and mesh-like (Figure 38(a) and Figure 38(b)). CTB002 and CTB010 have higher volume proportion of cobalt, and the D-Co bonds were prone to be broken when suffering high temperature [67]. This stimulated the occurrence and the development of the inter-granular fracture at cobalt-diamond interface, which destabilized the local PCD structure and caused the micro-cracks. Then, the fractured tool material was prone to be removed by the chip flow leaving a crater on within this Region. In contrast, no obvious thermal cracks were found on T302N (Figure 38(c)), instead, the tool/chip abrasion left some tiny scratches in region II, reflecting better thermal resistance of CTB010 under normal cutting speed. This was ascribed to the better local thermal conductivity of CTM302 which was the material for both tools. Due to the mixture of diamond grains with different sizes, the distribution of cobalt in CTM302 was concentrated pools, which was different from the evenly distributed cobalt in CTB002 and CTB010. As a result, heat was easier to be transferred away at the tool/chip interfaces of T302N. The model developed by List et al. [92] was applied to calculate the average temperature at tool/chip contact areas. In region II, coolant effect was minor due to the intensive abrasion of tool surface and chip surface, which made the temperature at the tool/chip interface was as high as that of under dry cutting condition. The results were listed in Table 6 Average temperatures at tool/chip interface, and it is found that the temperature at the tool/chip interface of the T302N was lower.
Figure 38 Morphology of tool wear in Region II after 14 cutting processes (a) T002N (b) T010N (c) T302N

Table 6 Average temperatures at tool/chip interface

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>CTB002</th>
<th>CTB010</th>
<th>CTM302</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>603</td>
<td>589</td>
<td>437</td>
</tr>
<tr>
<td>2nd</td>
<td>682</td>
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</table>

Adhesive wear in Region III was significant (Figure 39). When the high-temperature chip flow entered into region III, the stresses became lower but the temperature was still high enough to stimulate the formation of microwelds were between the asperities on chip surface and tool
surface. When the chip flow started to leave the rake face, material from the chip side could be adhered on the tool surface forming obvious adhesion. Also, the influence of applied coolant was better in the region III compared with the other two regions, materials from the chip flow was partially adhered on the tool surface due to the chip ploughing phenomenon. Meanwhile, some PCD grains were plucked and removed by the chip flow, leaving some holes on the rake faces. As for T002N and T010N, the effects of ploughing and plucking action were obvious. In contrast, the adhesion in region III for T302N was thicker without any drop-like titanium alloy preserved. This was explained by the change of tool geometry caused by the large-scale fracture of tool tip. Specifically, a coarse follow area was formed which prevented the movement of chip flow and changed its direction as well. Therefore, the softened chip was stacked at the fractured area and was extruded into a thicker layer in region III of T302N.

Figure 39 Morphology of tool wear in Region III after 14 cutting processes (a) T002N (b) T010N (c) T302N
3.2.2 Discussion on wear mechanism of tools under the cutting speed 160 m/min

3.3.2.1 Analysis of flank wear process

Different from strip-like worn areas on T002N, T010N and T302N after 14 cutting processes, the triangular worn areas (Figure 40(a) to Figure 40(c)) are found on the flank faces of T002H, T010H and T302H after 6 cutting processes. Based on the conclusion of Thomsen [93], the worn area on flank face could be divided as two regions, plastic contact region and elastic contact region, based on the contact properties of the workpiece surface and flank face. Near the cutting edge, the plastic flow of the workpiece contacted the flank face leading to the adhesive were on the tool flank face. This was proved by the strip-like adhesion areas on the PCD tools under the cutting speed 160 m/min. When the cutting speed became higher, both shear stress and the temperature at tool/workpiece interface were higher. Therefore, the adhered material was not only stacked within the plastic contact region, and was enlarged into the elastic contact region by the high speed workpiece flow. The lamella of the BUL proved that the layer was accumulated gradually with the increase of cutting processes (Figure 40(d)).
As was shown in Figure 41, chipping was found near the tips of all three tools. In comparison, the condition of the chipping was not as severe as the large-scale fracture found at the tip of T302N. The chipping condition of T002H was less severe, however, the cracks under the adhered material indicated that the PCD structure near the tool tip of T002H was destabilized which was prone to causing large-scale fracture. The fracture of T010H and T302H was significant leaving a coarse worn surface at the chip areas. Especially for the fractured area on T302H, it proved that trans-granular fracture of the PCD consisting of large-size diamond grains happened during the cutting process.
Figure 41 Chipping and fracture at tool tips 2000× (a) T002H (b) T010H (c) T302H

Figure 42 presents the morphology of the worn areas of the elastic contact region. In this region, abrasion dominated the wear process, and it was found cracks distributed within this area. As for T302H, the cracks were obvious near the adhered layer and worn area reflecting the spalling of workpiece material during the flank wear process. In comparison, cracks on T010H and T002H were slender and branch-like, and it could be found two obvious cracks were formed at the boundaries of the worn areas of both T002H and T010H. Tiny scratches were left within the worn area of T010H.
3.3.2.2 Analysis of crater wear mechanism

On rake faces, the three regions within the worn areas of T002H, T010H and T302H were distributed distinctively (Figure 43 and Figure 44). In Region I, build-up edge (BUE) was formed along the cutting edges of T002H, T010H and T302H after 6 cutting processes, however, no obvious BUE was found on the cutting edges near the tool tips. As was known [90], the stability of BUE was influenced by the cutting temperature. The distribution of BUE on the edges of T002H, T010H and T302H was interpreted as that the workpiece material near the tool tip could hardly be preserved because of the severe abrasion caused by higher cutting speed. Intensive and mesh-like micro-cracks were found on the worn areas of T002H and T010H, and these cracks were more significant compared with the cracks in Region II of T002N and T010N. As the cutting temperature had a drastic increase under the cutting speed 240 m/min, cobalt was easier to be softened and squeezed out causing thermal cracks. As for T302H, similar to T302N, only some tiny scratches were left on the rake face in the Region II, no obvious thermal cracks were found. The area of Regions III on the worn areas of T002H, T010H and T302H were larger compared with the tools used under normal cutting speed. The shape and amount of adhesion of workpiece material in region III was influenced by the adoption of cutting parameters as well as tool geometric characteristics. With regard to T002H and T010H, the temperature was still high enough to cause the inter-granular cracks which led to the collapse of PCD strcuture. As a result, some fractured PCD was plucked and removed by the chip flow, leaving some holes on the rake faces. Also, materials from the chip flow were easier to be adhered on the tool surface due to the
high temperature under the higher cutting speed, the adhered material was squeezed forming larger layer of adhesion in regions III of T002H and T010H. The BUL in region III of T302H was smaller in comparison, which indicated that the temperature in this region was lower.

Figure 43 Morphology of worn areas on the crater faces (a) T002H (b) T010H (c) T302H
Figure 44 Detailed worn morphology in different regions (a) Region I & Region II of T002H (b) Region I & Region II of T010H (c) Region II of T302H (d) Region III

3.4 Analysis of residual elements on worn surface

It is known that higher temperature may accelerate the chemical diffusion at the tool/chip interface [94]. The residual elements caused by diffusive wear within the worn area (from the rake surface down to 5 µm below) of each tool were analysed by Energy Dispersive X-ray Spectroscopy (EDS). It is found that C, Ti, V, Al and O consisted of 98% of the total elements (Figure 45), and the results of mapping scanning are presented in Figure 46 to Figure 47.

The atomic percentage of titanium is listed in Table 7. After 6 cutting processes, the atom percentages of titanium atom on the rake faces of T002N and T010N were 11.3%, 9.5% respectively. The temperatures near tool tip which increased from around 500 K to 700 K was high enough to destabilize the BUL [90], and the BUL on the rake face were scattered due to the abrasion caused by the high temperature chip flows. For T302N, the atom percentage of titanium was the highest (14.6%) because of the preserve of an intact BUL. Due to the fracture of tool tip, a slope with bigger rake angle was
formed. This change of tool geometry changed the direction of chip flow, and it led to the stack of workpiece material on the rake face near the fractured area. After another 8 cutting processes, the amount of adhered titanium alloy increased to 14.2%, 11.3%, 16% respectively, but the distribution was different from that of after 6 cutting processes. Only T302N had thick BUL on its rake face, titanium alloy tended to stack at tool noses or along cutting edges of tools made of CTB010 and CTB002. From the distribution of titanium on worn rake faces of T002H, T010H and T302H, it was found that the workpiece material was prone to adhered in region I and region III due to the formation of BUE and the adhesive wear mechanism. While the adhesion condition in region II was insignificant because, the abrasive process was intensive which did not provided an environment to stabilize the existence of adhesion.

Cobalt was the binder material of the PCD used in this study. The atomic percentages of cobalt of the three tools were in accordance with the cobalt fraction of the three PCD materials (Table 8). The maps showed that the distribution was more intensive within the sliding zones of T002N and T010N. According to the results of sliding test [66], cobalt could be molten when the temperature was over, and was extrude out by the constant abrasion. The cobalt in region II was extruded in the turning process, and this process was more significant after 14 cutting processes. Compared with T010N, higher atomic percentage of cobalt was found on the worn surface of T002N because the fraction of cobalt in the PCD layer of the cutting tool was higher, and the cobalt was easier to be squeezed out during the cutting process. In comparison, concentrated cobalt was found at the fractured area of the tool CTM302, which was influenced by the softening of these concentrated cobalt pools at the tool tip.

In addition to the elements from the workpiece material and tool material, oxygen was found on the rake faces. According to the map of oxygen, the atoms distributed scattered in region II due to the intensive contact of tool surface and chip surface, oxygen can hardly reach this area. Furthermore, some of the oxygen atom concentrated along the main cutting edge and the sub cutting edge. The atom percentages of oxygen atom were within 10% on the worn areas of T002N, T0110N and T302N respectively (Table 9). As was known, oxygen could react with titanium, carbon and cobalt under high temperature. However, since the temperatures at tool/chip interface, which were in the range of 550 K to 800 K, were not high enough to activate the
oxidation of cobalt (over 900 K [66]), and the products of the oxidation of diamond were
gaseous, which were released during the cutting process, as a result, the existence of oxygen
could be caused by the chemical reaction between the titanium alloy and oxygen: \( Ti + O_2 = TiO_2 \). Higher temperature stimulated the rate of chemical reaction between oxygen and titanium
alloy, and this made the atom percentage of oxygen on the T002N and T010N higher than that of
T302N.

![Figure 45 Elements found on the worn crater faces of tools under the cutting speed 160 m/min](image)

**Table 7 The amount of titanium after the 6th and the 14th cutting porcesses**

<table>
<thead>
<tr>
<th>Tool No.</th>
<th>T002N</th>
<th>CTB010</th>
<th>CTM302</th>
</tr>
</thead>
<tbody>
<tr>
<td>6th cutting</td>
<td>11.3 %</td>
<td>9.5 %</td>
<td>14.6 %</td>
</tr>
<tr>
<td>14th cutting</td>
<td>14.2 %</td>
<td>11.3 %</td>
<td>16 %</td>
</tr>
</tbody>
</table>

**Table 8 The amount of cobalt after the 6th and the 14th cutting porcesses**

<table>
<thead>
<tr>
<th>Tool No.</th>
<th>T002N</th>
<th>T010N</th>
<th>T302N</th>
</tr>
</thead>
<tbody>
<tr>
<td>6th cutting</td>
<td>2.9 %</td>
<td>1.8 %</td>
<td>0.7 %</td>
</tr>
<tr>
<td>14th cutting</td>
<td>4.1 %</td>
<td>2.3 %</td>
<td>1.4 %</td>
</tr>
</tbody>
</table>

**Table 9 The amount of oxygen after the 6th and the 14th cutting porcesses**

<table>
<thead>
<tr>
<th>Tool No.</th>
<th>T002N</th>
<th>T010N</th>
<th>T302N</th>
</tr>
</thead>
<tbody>
<tr>
<td>6th cutting</td>
<td>8.6 %</td>
<td>6.8 %</td>
<td>5.4 %</td>
</tr>
<tr>
<td>14th cutting</td>
<td>9.2 %</td>
<td>7 %</td>
<td>5.7 %</td>
</tr>
</tbody>
</table>

**Table 10 The amount of titanium, cobalt and oxygen after the 6th cutting porcess**
<table>
<thead>
<tr>
<th>Tool No.</th>
<th>T002H</th>
<th>T010H</th>
<th>T302H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titanium</td>
<td>9.8%</td>
<td>5.3%</td>
<td>5.3%</td>
</tr>
<tr>
<td>Cobalt</td>
<td>3.0%</td>
<td>1.9%</td>
<td>2.4%</td>
</tr>
<tr>
<td>Oxygen</td>
<td>6.4%</td>
<td>3.8%</td>
<td>2.7%</td>
</tr>
</tbody>
</table>

Figure 46 Distribution of titanium, cobalt and oxygen within worn areas after 6 cutting processes
Figure 47 Distribution of titanium, cobalt and oxygen within worn areas after 14 cutting processes
Figure 48: Distribution of titanium, cobalt and oxygen within worn areas after 6 cutting processes.
3.5 Discussion on chips produced by different PCD tools

The change of chip shape and the detailed characteristics on chip surface were used to indicate the development of tool wear [95, 96]. When cutting metallic materials, chips with different shapes were produced due to the material deformation at primary deformation zone, including as segment chips, continuous chips and serrated chips (also known as saw-tooth chips). Serrated chips are typical chips produced when machining the workpiece materials with high hardness and low thermal conductivity, such as titanium alloys, nickel alloys and hardened steels at different critical cutting speeds for the onset of segmentation. Serrated chip formation during cutting results in high cyclical cutting forces and severe crater wear that leads to a decrease in tool life, and a rough surface finish as a result of tool vibration and chatter.

3.4.1 Analysis of geometric characters of chips

The development of wear on rake face is indicated by the change of chip shapes, for example, the radius of chip curl increases when the tool/chip contact area becomes larger [97]. As was found in Figure 49, the shapes of chips machined by three different tools were different and they kept changing during the cutting process. At the beginning of the cutting process, chips were shaped and segmented as small-radius curls for all three tools as the tool/chip contact length was short. After the first cutting process, the chips generated by T002N and T010N became continuous and the radius of curled chips was bigger due to the increase of tool/chip contact length caused by the development of crater wear. After the cutting run for 6 processes, the shape of chips became strip, when using tools made of CTB002 and CTB010 respectively, because of the development of crater wear. Chips scattered in large-radius curls were found by using T002N and T010N after 14 cutting processes. With the development of tool wear, the temperature of chip was higher than it was in the previous cutting process. The chip was softened by the high temperature and became easier to break. As a result, the chips broke down by the combination of exerted pressure of coolant and the weight themselves.
Figure 49 Shape of chips after different cutting processes (a) T002N after the first cutting process (b) T002N after 6 cutting processes (c) T002N after 14 cutting processes (d) T010N after the first cutting process (e) T010N after 6 cutting processes (f) T010N after 14 cutting processes

For the chips produced by T302N (Figure 50), it can be seen that helical chips with smaller curl radius were generated in the first cutting process, which indicated that the situation of crater wear was less serious. The chip shape changed from continuous to segment in the following 5 cutting processes because of the change of tool geometric caused by the fracture of tool nose during the cutting process. Specifically, a sharp and new cutting edge with bigger rake angle and clearance angle at the worn area was formed (Figure 51(a)). The increase of clearance angle reduced the tool/workpiece contact area, as a result, the fractured area became a “chipbreaker” which reduced the tool/chip contact length stimulating the generation of the fractured chips. During these cutting processes, the fractured area on the rake face became flat due to the tool/chip abrasion. Also, the loss of tool material on the rake face caused the reduction of both the clearance angle and rake angle in the tool geometry, which increased the tool/workpiece contact area at the same time (Figure 51(b)). Therefore, the chips became continuous which proved the flattening of the fractured area by the chip flow from 7th cutting to 11th cutting. Large-scale fracture kept happening during the following 3 cutting processes, and this made the chips generated in last three cutting processes became fragment, which were similar to the chips generated in the previous cutting processes (2nd to 6th).
Figure 50 Shape variation of chips during the cutting process generated by T302N after different cutting processes.

Figure 51 Change of tool geometric after different cutting processes when using T302N (a) after 6 cutting processes (b) after 14 cutting processes.

Figure 52 presents the chips generated by T002H, T010H and T302H after the first cutting processes and the 6th processes respectively. Under the cutting speed 240 m/min, the shapes of chips machined by three different tools were continuous throughout the cutting processes. This reflected that the wear process of the tools under high speed cutting developed gradually, and no large-scale fracture of the tool tips happened.
Figure 52 Shape variation of chips produced by different tools (a) T002H after the first cutting process (b) T010H after the first cutting process (c) T302H after the first cutting process (d) T002H after 6 cutting processes (e) T010H after 6 cutting processes (f) T302H after 6 cutting processes

The friction coefficients at tool/chip interface $\mu$ was an indicator which can reflect the friction status at the tool/chip interface, and the value was calculated using the following equation,

$$
\mu = \frac{F_m}{F_n}
$$

where,

$F_n$ Friction force at tool/chip interface (oblique coordinate), N;

$F_m$ Force normal to the tool/chip contact interface (oblique coordinate), N;

To determine the force normal to the rake face and the friction force, a conversion need to be conducted to translate the cutting forces from global coordinate system to the oblique coordinate system. In the oblique coordinate, $\vec{m}, \vec{n}, \vec{l}$ are the direction of cutting, the direction normal to tool/chip interface, and the direction parallel to cutting edge respectively,

$$
\begin{bmatrix}
F_m \\
F_n \\
F_l
\end{bmatrix} = [TM]_x [TM]_y
\begin{bmatrix}
F_x \\
F_y \\
F_z
\end{bmatrix} =
\begin{bmatrix}
\cos \gamma_n & 0 & -\sin \gamma_n \\
-\sin \gamma_n \sin \gamma_s & \cos \gamma_s & -\sin \gamma_s \cos \gamma_n \\
\cos \gamma_n \sin \gamma_s & \sin \gamma_s & \cos \gamma_s \cos \gamma_n
\end{bmatrix}
\begin{bmatrix}
F_x \\
F_y \\
F_z
\end{bmatrix}
$$

(3.6)
where,

\[ F_1 \] Force along the cutting edge direction (\( \vec{m}, \vec{n}, \vec{t} \) coordinate), N;

\[ F_x \] Force measured in axial direction (axial force), N;

\[ F_y \] Force measured in radial direction (thrust force), degree;

\[ F_z \] Force measured in tangential direction (main cutting force), N;

\( \gamma_n \) Fool entering angle, degree;

\( \gamma_s \) Oblique angle, degree;

As a result, the forces in oblique system were calculated by the forces in global coordinate,

\[
F_1 = -F_x \sin \gamma_s \sin \gamma_n + F_y \cos \gamma_s - F_z \sin \gamma_s \cos \gamma_n \quad (3.7)
\]

\[
F_m = F_x \cos \gamma_s \sin \gamma_n + F_y \sin \gamma_s + F_z \cos \gamma_s \sin \gamma_n \quad (3.8)
\]

\[
F_n = F_x \cos \gamma_n - F_z \sin \gamma_n \quad (3.9)
\]

and, the friction coefficient at tool/chip interface is rephrased as

\[
\mu = \frac{F_x \cos \gamma_n - F_z \sin \gamma_n}{F_x \cos \gamma_s \sin \gamma_n + F_y \sin \gamma_s + F_z \cos \gamma_s \sin \gamma_n} \quad (3.10)
\]

The results of calculation show that the friction coefficient at initial cutting stage (first six cutting processes) was different for the three tools under the cutting speed 160 m/min, and did not change tool much in the following cutting processes (Figure 53(a)). The friction coefficients at tool chip interfaces of T002N and T010N fluctuated within the range from 0.02 to 0.05, which were smaller than the friction coefficient of PCD (0.05 to 0.1). This phenomenon could be explained by the formation of the tribology film on the tool rake surface [68]. The cobalt fraction of CTB002 was higher, during the cutting process, being softened and extruded by the high temperature and shear stress, the cobalt could lubricate the tool/chip friction. Compared with T002N and T010N, the friction coefficient on at the tool/chip interface of T302N fluctuated...
significantly from the 1\textsuperscript{st} cutting to the 7\textsuperscript{th} cutting, and the change of the friction coefficient in following cutting processes was similar to those of T010N and T002N. As was mentioned in previous sections, the tip of T302N suffered large-scale fracture which changed as well as the geometric parameters of the cutting tool in the first 6 cutting processes. The coarse worn surface significantly affected the status of tool/chip abrasion causing significant change of the friction coefficient. The change of friction coefficients of tools under high cutting speed is presented in Figure 53(b), and it is found that the value gradually decreased without any obvious fluctuation. This was agree with by the change of cutting forces and flank wear widths as wear process of PCD tools under high cutting speeds which changed gradually and steadily. Also, larger sliding zones without severe adhesion were found on the rake faces of T002H, T010H and T302H, which means that the chip flowed on the PCD surface without influence of the BUL. As a result, the coefficients of friction were close to 0.05.

![Figure 53 Calculated friction coefficients of different PCD tools (a) the tools under 160 m/min (b) the tools under 240 m/min](image)

3.4.2 Analysis of morphological characters on chip surface

Both front surfaces and back surfaces of the chips were examined via SEM to analyse their detailed facial characters. Serrated characters (Figure 54(a)) were found on the chip back surface when cutting titanium alloy under high cutting speeds, and the simplified mechanism of chip formation was presented in Figure 54(b). Under the shear cutting force, a crack P-O in front of the cutting edge was initiated and propagated along the cutting direction. This phenomenon
appeared before the shear formation of the serrated shape on the back surface of chips. Due to the low thermal conductivity of Ti6Al4V, the heat was prone to be accumulated zone softening the material around the shear plane B-B’ in primary deformation. Also, the strain rate of the workpiece material was larger than the transmission of the temperature generated in primary deformation zone, and this led to the large-scale shear deformation of the chip along the shear plane B-B’ forming the serrated shape on chip back surface A-B (Figure 54(c)). As found by shoujin et al. [95, 96], some plastic deformation dimples could be found on the back surface of chips was the combined efforts of the adiabatic shear, initiation and growth of cracks during the chip formation (Figure 54(d)).

**Figure 54** (a) Serrated shape of chips (b) Simplified mechanism of the formation of serrated chip (c) Simplified mechanism of the formation of the dimples (d) Periodical plastic deformation dimples on the back surface of chips
Surfaces of chips were examined via SEM to analyse their detailed facial characters. When titanium alloy was cut with a sharp tool (Figure 55(a) to Figure 55(c)), these voids caused by the formation of crack (P-O) on workpiece surface were elongated by the sharp cutting edge and developed into plastic deformation dimples on the surface of chips. With the progressive development of tool wear, the shear stress at the 1st deformation zone was larger due to the blunt of cutting edge which led to the rising of temperature in this area. When the condition of tool wear was severe, the temperature in the 1st deformation zone was high enough to soften the titanium alloy and made the material prone to shear rather than crack. Hence, the formation of serrated characters on chip back surface could be considered as the squeeze of the material along the shear band at high temperature, no obvious plastic deformation dimple was observed on the slipping surface. As shown in the SEM images, dimples were found on the back surface became insignificant after 14 cutting processes (Figure 55(d) to Figure 55(f)). This phenomenon indicates that the condition of flank wear became severe.

Figure 55 Plastic dimples on front surface of chips (a) T002N after the first cutting process (b) T002N after 6 cutting processes (c) T002N after 14 cutting processes (d) T010N after the first cutting process (e) T010N after 6 cutting processes (f) T010N after 14 c

Figure 56 presents morphology of the front surface of the chips which contacted the rake face during the cutting processes. The results of EDS (line-scan) proved that debris of diamond grains
was adhered on the chip flow which proved that the PCD structure consisted by 2 um diamond grains was easier to collapse down in tool/chip abrasion and to be removed by the chip flow. The dimples on the front surface of the chip produced by the tools made of CTB010 and CTM302 reflected that titanium alloys adhered on the rake faces of the CTB010 tool and the CTM302 tool, which proved that PCD structures stability of CTB010 and CTM302 had better resistance to collapse of PCD structure.

---

**Figure 56** Morphological characters on front surface of chips (a) chips produced by the tools made of CTB002 (b) chips produced by the tools made of CTB010 (c) chips produced by the tools made of CTM302
3.5 Summary

Cutting forces, morphology of worn areas, elements within worn areas and chips produced in the cutting processes were analysed to investigate the wear mechanism of PCD tools made of different materials under normal and high cutting speed levels. It was found the wear mechanism of tools made of three PCD materials were different. On the flank face of tools made of CTB002 and CTB010 (T002N/H and T010N/H), facial material was removed by the spalling layerly and steadily in wear process. In micro-scale, this process was caused by the breakage of bonds due to fracture at the interface of diamond grains as well as the diamond/cobalt interface in micro-scale. Large-scale fracture was the wear mechanism of the tool consisting of CTM302 (T302N) throughout the entire cutting process, which was reflected by the development of cutting forces and VBs. On the rake faces, the adhesive-abrasive wear was more severe, and chemical diffusion was significant due to the higher temperature at tool/chip interface. Morphological characters and the distribution of residual material within the worn areas were different. The development of tool wear was reflected by the change of chip shapes and the morphological characters.
Chapter 4 Theoretical Investigation on Wear Process of Different PCD Tools

In this chapter, the wear process of PCD tools is investigated theoretically by developing analytical models of flank wear and crater wear. The models were developed based on the wear mechanism proposed in Chapter 3 which considering the dynamic cutting force and properties of different PCD materials. Then, the models were validated by the experimental results (the data of T002N, T010N and T302N) from Chapter 3.

4.1 Development of flank wear model

It has been proved that the “diffusive-abrasive” interaction at tool/workpiece interface was the main wear mechanism in machining titanium alloys when using metallic tools [56]. In adhesive wear, huge amount of heat is generated due to the deformation of the workpiece material. Under the combined effect of normal stress and high temperature, micro-welds [90] are formed between the asperities on both tool flank face and workpiece surface (Figure 57(a)). Then, the shear of joint could happen on both tool side and workpiece side when suffering from external shear stress. Workpiece materials would adhere on the tool surface when the joint shear appears on the workpiece side, while, tool material would be removed if the shear of joint happens on the tool side.

Although PCD is the one of the hardest tool materials known so far, the binding material (cobalt in this study) which acts as both the bridge and boundary of the sintered diamond structure could be softened under high temperature. Combined with the tool/workpiece abrasion, the cobalt-diamond bonds could break, and initiated cracks could be developed at the cobalt-diamond boundaries, leading to the collapse of PCD structure [53]. As a result, joint shear is prone to happening on the tool side and causes material loss on the tool flank face (Figure 57(b)).
Abrasive wear is the facial damage caused by scratching of either the sliding of hard asperities or the rolling of hard particles at tool/workpiece interface. The types of abrasion could be classified as two-body mode and three-body mode according to the status of the abrasion. For two-body abrasion, asperities on the harder side, or strongly constrained hard particles, scratch on the softer side leading to the loss of material on this side. For PCD tools, diamond grains or fractured sintered diamond structure could be released in the tool wear processes (Figure 57(c)). These hard particles roll or slide together with the titanium alloy at the tool/workpiece interface, and could cause further release of hard particles or material loss on the softer surface which is known as three-body abrasion (Figure 57(d)).

Figure 57 Simplified mechanism of adhesive wear and abrasive wear processes (a) formation of micro-welds (b) material loss due to adhesive wear (c) status of three-body abrasion (d) material loss due to abrasive wear
In this research, it was found that the material loss in the flank wear process of PCD tools was caused by the combined effect of adhesion and abrasion at tool/workpiece interface.

### 4.1.1 Tool material loss due to adhesive process

The material loss due to the adhesive process is mainly the removal of micro-welds. The amount of adhesive wear per unit area can be calculated with the following equation:

\[
W_{uad} = N \times A_{mw} \times h_{mw} \times P
\]

where:

- \( W_{uad} \): Tool material loss due to the adhesion per unit area, \(\text{mm}^3\);
- \( N \): The number of the microwelds per unit area;
- \( P \): Probability of forming a certain size of wear fragment;
- \( h_{mw} \): The height of microwelds, mm;
- \( A_{mw} \): The average cross area of the micro-weld, \(\text{mm}^2\);

According to Huang et al. [82], the hardness of the softer material could be defined as the actual contact pressure. The contact pressure at the cross section of the micro-welds, \( P_{ac} \), could be calculated as follows:

\[
P_{ac} = \frac{F_{nf}^m}{A_{mw} \times N \times A_{fw}} = \frac{F_{nf}^m}{A_{mw} \times N \times D \times VB} = H_w
\]

where

- \( F_{nf} \): Normal force exerted on the flank face, N;
- \( A_{fw} \): Total contact area on the worn tool flank face, which equals to the product of width of flank wear and the cutting depth, \(\text{mm}^2\);
- \( D \): Depth of cut, mm;
- \( VB \): Width of flank wear, mm;
$H_w$ Hardness of the softer material, MPa;

$m$ Adhesive constant depending on the type of deformation during the wear process (Table 11).

Table 11 Adhesive constant [98]

<table>
<thead>
<tr>
<th>Deformation type</th>
<th>Shape of adhesion</th>
<th>$m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic</td>
<td>Layer</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>Lump</td>
<td>0.8</td>
</tr>
<tr>
<td>Plastic</td>
<td>Layer</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>Lump</td>
<td>1</td>
</tr>
</tbody>
</table>

The volume of material loss per unit area caused by adhesive process is expressed as

$$W_{uad} = NA_{mw}h_{mw}P = \frac{F_{nf}^m \times N \times P \times h_{mw}}{H_w \times N \times D \times VB} = \frac{F_{nf}^m ph_{mw}}{H_wDV}$$  \hspace{1cm} (4.3)

where: the average cross-section area of each micro-weld is:

$$A_{mw} = \frac{F_{nf}^m}{H_w \times N \times D \times VB}$$  \hspace{1cm} (4.4)

Considering that the tool/workpiece contact area in time $dt$ is the sliding area during this period of machining time, as a result, the rate of material loss caused by adhesive process in $dt$ is expressed as

$$\frac{dW_{uad}}{dt} = \frac{ds \times (D \times W_{uad})}{dt} = VDW_{uad} = \frac{F_{nf}Vph_{mw}}{H_wVB}$$  \hspace{1cm} (4.5)

where

$s$ Sliding distance, mm;

$V$ Cutting speed, mm/min;
1 \[ dt \] Time period (second);

2 **4.1.2 Tool material loss due to abrasion process**

3 Based on the empirical-quantitative model proposed by Rabinowicz et al. [76, 77], the volume of
4 material loss caused by three-body abrasion can be calculated with the following equation:

\[
W_{ab}^{3-body} = \frac{s \times F_{nf} \times tan\theta}{K} \times \frac{H_w^{n-1}}{H_t^n}
\]  \hspace{1cm} (4.6)

5 where:

6 \( W_{ab}^{3-body} \) Tool material loss due to the three-body abrasion, mm³;
7 \( K \) Constant depending on the type of abrasion;
8 \( H_w \) Hardness of the workpiece, MPa;
9 \( H_t \) Hardness of the cutting tool, MPa;
10 \( n \) Constants depending on the ratio of tool/workpiece hardness;
11 \( F_{nf} \) Normal force exerted on the flank face, N;
12 \( \theta \) Roughness angle in abrasive process, degree.

7 Parameters \( K \) and \( n \) were selected based on the ratio of tool hardness and workpiece hardness
9 (Table 12). By taking the roughness angle as 45 degree, the rate of material loss caused by
10 abrasive process during \( dt \) can be described as:

\[
\frac{dW_{ab}}{dt} = \frac{dW_{ab}^{3-body}}{dt} = \frac{V \times F_n}{2.43} \times \frac{H_w^6}{H_t^7}
\]  \hspace{1cm} (4.7)

12 **Table 12 The constants \( K \) and \( n \) [79]**

<table>
<thead>
<tr>
<th>Hardness Ratio</th>
<th>( K )</th>
<th>( n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H_t/H_w \leq 0.8 )</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>( 0.8 \leq H_t/H_w \leq 1.25 )</td>
<td>5.3</td>
<td>3.5</td>
</tr>
<tr>
<td>( H_t/H_w \geq 1.25 )</td>
<td>2.43</td>
<td>7</td>
</tr>
</tbody>
</table>
4.1.3 Modeling of force normal to flank face

Since the normal force is changing in accordance with the development of flank wear, it is critical to develop an accurate model to calculate the normal force in each cutting period. According to the general statistic force model [99], regardless tool wear, the normal force $F_{ns}$ was mainly exerted on the sharp cutting edge (Figure 58(a)), which can be determined using the following equation:

$$F_{ns} = K_f A_c \cos \alpha + K_n A_c \sin \alpha$$ (4.8)

$K_n$ and $K_f$ are specific cutting energy of normal force ($J/mm^3$) and specific cutting energy of cutting force ($J/mm^3$) respectively, which were generally determined by cutting tests. The relationship between the cutting parameters and $K_n$, $K_f$ can be determined practically with the following equations:

$$\ln K_n = a_0 + a_1 \ln f + a_2 \ln V + a_3 D + a_4 \ln V \ln f$$ (4.9)

$$\ln K_f = b_0 + b_1 \ln f + b_2 \ln V + b_3 D + b_4 \ln V \ln f$$ (4.10)

where:

- $f$ Feed rate, mm;
- $V$ Cutting speed, N;
- $D$ Cutting depth, mm;
- $a_0 \sim a_4, b_0 \sim b_4$ Constants used to determine $K_n$ and $K_f$ respectively. They were solved linearly by adopting the cutting parameters and measured force [100].

With the development of flank wear, the cutting force on a worn tool could be regarded as the sum of the normal force exerted on the blunt cutting edge which was considered to be the same value as $F_{ns}$, and the component force exerted the flank wear area, $F_{nw}$ (Figure 58(b)). The force
exerted on the flank wear area, $F_{nw}$, is calculated by the product of the normal stress $\sigma_w$ and the flank wear area $A_w$:

$$F_{nw} = A_w \sigma_w = D \cdot VB \cdot \sigma_w$$  \hspace{1cm} (4.11)

To estimate stress $\sigma_w$ exerted on the worn surface, the fracture of PCD has to be taken into account. Because tool material loss in wear process is caused by the fracture of PCD structure when it suffers from external stress, the relationship among exerted stress $\sigma$, fracture length $r$ and the fracture toughness $K_{ic}$ can be described as follows [101]:

$$\sigma = \frac{K_{ic}}{\sqrt{2\pi r}}$$  \hspace{1cm} (4.12)

![Cutting Direction](image)

**Figure 58** Force normal to the tool/workpiece interface (a) normal force when the cutting edge is sharp (b) normal force when the cutting edge is worn

The geometric relationship between fracture length $r$ and increment of flank wear width was developed, as was shown in Figure 59. The parameter $r$ was defined to be equal to the thickness of the removed tool material layer ($h_2 - h_1$) in the wear process of the time period $dt$. According to the geometric relationship, $h_1$ and $h_2$ can be calculated as,

$$h_1 = (VB_1 - h_1 \cdot \tan \alpha) \times \tan \gamma$$  \hspace{1cm} (4.13)

$$h_2 = (VB_2 - h_2 \cdot \tan \alpha) \times \tan \gamma$$  \hspace{1cm} (4.14)
As a result,

\[ r = h_2 - h_1 = \tan \gamma \times [(V B_2 - V B_1) - \tan \alpha \times (h_2 - h_1)] \]

\[ = \frac{d V B \times \tan \alpha}{1 - \tan \alpha \times \tan \gamma} \] (4.15)

where

\( d V B \) Increment of flank wear landing in time interval \( dt \);

\( V B_1 \) Flank wear landing before cutting;

\( V B_2 \) Flank wear landing after the time interval \( dt \);

\( \gamma \) Tool clearance angle, degree;

\( \alpha \) Tool rake angle, degree;

---

**Figure 59** Geometric relationship between VB and wear volume

---

4.1.4 Modeling of flank wear rate

According to the geometric relationship shown in Figure 59, the volume of material loss \( d V \) caused by flank wear after \( dt \) can be described with the following equation:
\[ dV = D \times \frac{1}{2} \times (VB_1 + VB_2) \times (h_2 - h_1) \]  
(4.16)

As a result, the increment of wear amount during the time period \( dt \) could be written as,

\[ dV = D \times \frac{1}{2} \times (2VB_2 - VB) \times r \approx D \times VB \times r = \frac{D \times dVB \times VB \times \tan \alpha}{1 - \tan \alpha \times \tan \gamma} \]  
(4.17)

where

- \( \alpha \) Tool rake angle
- \( \gamma \) Tool clearance angle

The total volume of material loss due to the adhesive-abrasive wear process which consists of adhesion and three-body abrasion during the time interval could be expressed as

\[ dV = \omega dW_{ad} + (1 - \omega) dW_{ab} \]  
(4.18)

where

- \( \omega \) Proportion of normal force exerted on the sum area of the micro-welds cross section

Considering the time differential of the amount of flank wear, the above equation (4.18) could be re-written as follows,

\[
\frac{dV}{dt} = \omega \frac{dW_{ad}}{dt} + (1 - \omega) \frac{dW_{ad}}{dt}
\]

Therefore, the flank wear rate could be presented with the following equation,

\[
\frac{dVB}{dt} = \frac{C_1}{VB} + \frac{C_2}{VB^2}
\]  
(4.19)

where

- \( C_1 = (1 - \omega) \frac{F_{nj} VH_{w}^{n-1}}{KH_i^n D \frac{\tan \alpha}{1 - \tan \alpha \times \tan \gamma}} \)
- \( C_2 = \frac{\omega F_{nj}^m VRh_{pw}}{H_{w} D \frac{\tan \alpha}{1 - \tan \alpha \times \tan \gamma}} \)
4.2 Development of crater wear model

Crater wear was the caused by the relative movement of rake face and the chip surface. Figure 60 presents the simplified mechanism of the facial material loss during the crater wear. The adhesive-abrasive wear at the tool/chip interface was similar to the wear process of flank wear. The temperature at tool/chip interface is extremely high which would melt the binder material which would weak the D-Co bonds and stimulated the release of diamond grains. Therefore, 3-body abrasion was assumed to be the status of the friction at tool/chip interface. Huge amount of heat generated in 1st deformation zone (shear plane near the tool tip) and 2nd deformation zone (tool/chip interface) stimulate the formation of micro-welds at tool/chip interface. When the micro-welds were removed by the fast chip flow, the facial PCD could be removed together leading to the material loss caused by adhesive wear. As for diffusive wear, the atoms from both tool surface and chip surface could diffuse into each other depending on the relative affinity of the elements on each side under high pressure and high temperature. The chemical diffusion happened only within a narrow zone, and in the modelling of flank wear process, the material loss due to this wear mechanism was ignored. However, compared with flank wear, chemical diffusion was more significant in crater wear because of the higher temperature at tool/chip interface. As a result, the material loss in crater wear process was considered as the combined influence of three-body abrasion, adhesion and chemical diffusion.

Figure 60 Material loss on crater face due to abrasive wear, diffusive wear and chemical diffusion
4.2.1 Tool material loss due to abrasive-adhesive process

The abrasive-adhesive wear process on rake face was caused by the tool/chip relative movement. The abrasion of high-speed chip flow on tool surface raised the temperature of interface, which both molten the facial binder material and stimulated the formation of micro-welds. According to the geometric relationship on rake face (Figure 61), the volume of material loss $dV$ caused by flank wear after $dt$ was expressed as the following equation,

$$
\frac{dW_{cad-cab}}{dt} = \frac{dW_{3-body}^{3-body}}{dt} + \frac{dW_{cad}}{dt} = \frac{F_{nc}V_cP_{hw}}{H_wL_c} + \frac{V_c\tan\theta}{K} \times \frac{H_w^{n-1}}{H_t^n} \quad (4.20)
$$

where

- $W_{cad-cab}$ Crater wear amount due to adhesive-abrasive process, N;
- $W_{3-body}$ Crater wear amount due to three-body abrasion of cutting tool and chip flow, N;
- $W_{cad}$ Crater wear amount due to adhesion process, N;
- $L_c$ Tool/chip contact length, mm;
- $F_{nc}$ Cutting force normal to the tool/chip interface, N;
- $V_c$ Speed of chip flow, mm/min;

$$
V_c = \frac{\sin\theta \cdot V}{\cos(\theta - \alpha)} \quad (4.22)
$$

where

- $\theta$ Shear angle, degree;

Therefore, the rate of removal material amount of crater wear could be rephrased as,

$$
\frac{dW_{ad-ab}}{dt} = \left( \frac{P_{hw}}{H_wL_c} + \frac{\tan\theta H_w^{n-1}}{KH_t^n} \right) \times \frac{\sin\phi \cdot V}{\cos(\theta - \alpha)} \times (F_t \sin\alpha + F_a \cos\alpha) \quad (4.23)
$$
4.2.2 Tool material loss due to chemical diffusion

As aforementioned, chemical diffusion in crater wear process was caused by the exchange of elements between the rake face and chip back surface. The average flux rate of diffusion was expressed according to Fick's first law \([53]\) describing the diffusive flux under the assumption of steady state. It postulates that the flux goes from regions of high concentration to regions of low concentration with a magnitude which is proportional to the concentration gradient (spatial derivative). In simplistic terms, the diffusive process is expressed mathematically using the following equation,

\[
J_{av} = -D \frac{\partial c}{\partial y}
\]  (4.24)

where
- \(J_{av}\) Average diffusive flux, atoms/mm²s;
- \(y\) Direction along the tool/chip interface;
- \(c\) Diffusive flux rate, mm²/min;
Diffusion coefficient, $D$;  

$$D = D_0 e^{-Q/RT_f} \quad (4.25)$$

where  

$D_0$ Diffusive coefficient related to the frequency of atomic oscillations, mm$^2$/min;  
$Q$ Activation energy for diffusion, J/mol/K;  
$R$ Constant of gas, J/mol/K;  
$T_f$ Environment temperature, K.

To simplify the case in this study, the temperature as well as the diffusive flux concentration at tool/chip interface was considered as uniformly distributed. As a result, the average gradient concentration of the diffusive flux is expressed mathematically,

$$\left. \frac{\partial c}{\partial y} \right|_{y=0} = -C_0 \sqrt{\frac{V_c}{\pi D \cdot L_c}} \quad (4.26)$$

where  

$C_0$ Concentration of diffusing species at tool/chip interface, mm$^2$/min;  

As a result, the mathematical expression of the Fick’s law could be rephrased as the following equation:

$$J_{av} = -D \frac{\partial c}{\partial y} = 2C_0 \sqrt{\frac{V_c D}{\pi \cdot L_c}} \left( \frac{\text{atoms}}{\text{mm}^2 \cdot \text{s}} \right) \quad (4.27)$$

Wear of material in unit time by diffusion $W_{udi}$ is expressed as,

$$W_{udi} = J_{av} \cdot w \cdot L_c \left( \text{atoms} \right) = \frac{m}{\rho} J_{av} \cdot w \cdot L_c \left( \text{mm}^3 \right) \quad (4.28)$$

where  

$m$ Automatic weight of diffusing species, g;  
$\rho$ Density of diffusing species, g/mm$^3$.  


A

1. Tool wear in time interval due to diffusion can be written as,

\[ dW_{dt} = W_{udt} dt \] (4.29)

2. Amount of tool material diffused across the interface is expressed as,

\[ dW_{dt} = \frac{m}{\rho} 2C_0 \sqrt{\frac{V_c D}{\pi L_c}} L_c w dt = K_4 \sqrt{\frac{V_c}{q}} L_c dt \] (4.30)

3. where

\[ K_4 = \frac{m}{\rho} 2C_0 \sqrt{\frac{D_0}{\pi}} w \] (4.31)

4. To predict the temperature rise at the tool/chip interface, the model developed by List et al. [92] was applied to calculate the tool/chip contact temperature around the tool tip, which is presented with following equation

\[ \Delta T_{rake} = \frac{q_T L_c}{2K_T} \cdot G \] (4.32)

5. where

\[ \Delta T_{rake} \] Temperature rise on the rake face of cutting tool, K;

\[ K_T \] Thermal conductivity of the tool material, W/m·K;

\[ A \] Geometric factor, mm²;

\[ G = \frac{\pi}{2} \left[ \ln \left( \frac{2w}{L_c} \right) + \frac{1}{3} \left( \frac{L_c}{w} \right) + \frac{1}{2} \right] \] (4.34)
As is shown in Figure 62, $q_T$ stands for the heat flux (W/m) transmitted into the cutting tool via the tool/chip interface. The heat source was the combined influence of the deformation of workpiece material in primary deformation zone and the tool/chip friction in secondary deformation zone. Specifically, shear deformation of the workpiece material happened at the shear plane within primary deformation zone. This generated huge amount of heat and made the initial temperature of the chip flow extremely high. On the other hand, the interaction of the tool rake face and high-speed chip flow formed the secondary deformation zone, and a proportion of generated heat was translated to the tool side. Therefore, the sum of the heat resources could be presented as,

$$q_T = \frac{Q_s}{A_c} = \frac{(1 - R_s)(Q_2 + Q_1)}{A_c}$$  \hspace{1cm} (4.35)

where

$Q_s$ \hspace{1cm} The sum of the generated heat, J;

$Q_1$ \hspace{1cm} Heat generated in primary deformation zone, J;

$Q_2$ \hspace{1cm} Heat generated in secondary deformation zone, J;

$A_c$ \hspace{1cm} Area of tool/chip interface, mm$^2$;

$R_s$ \hspace{1cm} The fraction of heat in secondary deformation zone move into the chips, mm$^2$.

$$R_s = \frac{1}{1 + 0.754 \left( \frac{K_{PCD}}{K_WA} \right) \sqrt{\frac{a}{V_cL_c}}}$$  \hspace{1cm} (4.36)

$K_{PCD}$ \hspace{1cm} Thermal conductivity of PCD, W/m$ \cdot $ K, which could be calculated using the Maxwell equation:

$$K_{PCD} = K_D \cdot \frac{2K_D + K_B - 2f_B(K_D - K_B)}{2K_D + K_B + f_B(K_D - K_B)}$$  \hspace{1cm} (4.37)

where,

$K_D$ \hspace{1cm} Thermal conductivity of diamond, 1300 W/m$ \cdot $ K;
\( K_B \)  \hspace{1cm} \text{Thermal conductivity of binder material (cobalt in this study), 100 W/m \cdot K;}

\( f_D \)  \hspace{1cm} \text{Volume fraction of diamond;}

\( f_B \)  \hspace{1cm} \text{Volume fraction of binder material.}

1. As \( Q_1 \) was generated by the shear deformation, it is calculated by the production of the shear force and shear speed,

\[ Q_1 = F_s V_s \quad (4.38) \]

2. where, \( \tau, A_s, \) and \( V_s \) stand for the shear stress at the shear plane, the area of the shear plane and the shear speed at the shear plane. The values of these parameters were calculated via the following equations,

\[ F_s = F_c \cos \theta - F_t \sin \theta \quad (4.39) \]

\[ V_s = V \sin \theta \quad (4.40) \]

3. For the heat resource \( Q_2 \), it was calculated by the production of the friction force at tool/chip interface and the friction velocity,

\[ Q_2 = F_m V_c \quad (4.41) \]
4.2.3 Modeling of crater wear rate

The volume of material loss during crater wear process is the volume of the crater on rake face. According to the geometric relationship presented in Figure 63, the volume is the production of the chip width $w$ and the shaded area, which is calculated with the following equation,

$$
S_c = \frac{\delta}{2}\pi R^2 - \frac{1}{2} L_c R \cos \frac{\delta}{2} = \frac{\delta R^2}{2} - \frac{1}{2} R \cos \frac{\delta}{2} \cdot 2 R \sin \frac{\delta}{2} = \frac{R^2}{2} (\delta - \sin \delta) \quad (4.42)
$$

where,

- $S_c$ Area of the cross-section of the crater;
- $\delta$ The angle between the centre line and the radius;
- $L_c$ Length of the crater;
- $R$ Radius of the arc boundary of the crater, which was calculated with the following equation
where VC stands for the depth of crater wear.

![Geometric relationship of crater wear](image)

**Figure 63 Geometric relationship of crater wear**

By simplifying equation (4.42) and equation (4.43), R is rephrased as,

\[
R = \frac{\left(\frac{L_c}{2}\right)^2 + VC^2}{2D_c}
\]  

and, \( \delta \) is expressed as,

\[
\delta = \arcsin \left( \frac{L_c}{2R} \right) = \arcsin \left( \frac{L_c VC}{\left(\frac{L_c}{2}\right)^2 + VC^2} \right)
\]

Therefore, the volume of material loss on crater face \( V_{crater} \) is calculated with the equation as follows:
\[ V_{\text{crater}} = w \left( \frac{D}{2VC} \right)^2 \left( \arcsin \left( \frac{F}{D} \right) - \frac{E \cdot F}{D^2} \right) \]  

(4.46)

where \( A = \left( \frac{L_c}{2} \right)^2 + VC^2 \), \( B = \left( \frac{L_c}{2} \right)^2 - VC^2 \), \( C = L_c VC \).

Considering the time differential of the amount of flank wear,

\[
\frac{dV_{\text{wear}}}{dVC} = \frac{dV_{\text{wear}}}{dt} \cdot \frac{dt}{dVC} \tag{4.47}
\]

The crater wear rate \( \frac{dvc}{dt} \) is shown in the following equation

\[
\frac{dVC}{dt} = \frac{dV_{\text{wear}}}{dt} \cdot \frac{dVC}{dV_{\text{wear}}} = \frac{dVC}{dV_{\text{wear}}} \cdot \frac{d}{dt} (W_{\text{cad-cab}} + W_{\text{di}})
\]

\[
= \left[ K_4 \left( \frac{V_c L_c}{Q} h_f \right) + \left( \frac{P h_m w}{H w L_c} + \frac{\tan \theta H_{\omega}^{n-1}}{K H_t^{n-1}} \right) \times \frac{\sin \varphi \cdot V_c}{\cos (\varphi - \alpha)} \times (F_t \sin \alpha + F_a \cos \alpha) \right] \cdot \frac{1}{wD(VC)} \tag{4.48}
\]

where

\[
D(VC) = \frac{A \left( \arcsin \left( \frac{C}{A} \right) - \frac{B \cdot C}{A^2} \right)}{VC} - \frac{1}{2} \frac{wA^2 \left( \arcsin \left( \frac{C}{A} \right) - \frac{B \cdot C}{A^2} \right)}{VC^2}
\]

\[
+ \omega A^2 \left( \frac{L_c}{A} - 2 \frac{VC \cdot C}{A^2} \right) - \frac{L_c C}{A^3} + \frac{4B \cdot C \cdot VC}{A^3} + \frac{2VC \cdot C}{A^2}
\]

\[
+ \frac{1}{4} \frac{\left[ \sqrt{1 - \left( \frac{C}{A} \right)^2} \right]}{VC^3} \tag{4.49}
\]
4.3 Calculation processes

The calculation was conducted by using MatLab2016R. The flow chart of the calculation of flank wear is shown in 未找到引用源。. Initially, the cutting force of sharp tools was calculated by using the pre-set cutting parameters. Using the properties of PCD material, the amounts of material loss due to both adhesive wear and abrasive wear were calculated and the differential equation describing the relationship between the flank wear rate and wear volume was developed. The flank wear in the fixed time interval could be obtained by solving the differential equation, and this value was used to calculate the normal force in next time interval.

The calculation of crater wear rate was conducted via the software MatLab2016R according to the following flow chart (未找到引用源。). By adopting the properties of the PCD material and cutting parameters, the amounts of material loss due to adhesive-abrasive wear and chemical diffusion were calculated. To determine the rate of chemical diffusion, the average temperature at tool/chip interface was calculated by adopting the measured force in each cutting process. The increment of crater wear in each cutting process could be obtained by solving the differential equation describing the relationship between crater wear rate and wear volume.
Figure 64 Calculation process of flank wear
Figure 65 Calculation process of crater wear

1. Calculate the material loss due to adhesive wear
2. Calculate the material loss due to abrasive wear
3. Calculate the material loss due to chemical diffusion
4. Develop the geometric model of material loss due to flank wear
5. Develop the model and calculate cutting temperature
6. Conducting cutting test with the parameters used in the model, measure the cutting forces
7. Validate the model by comparing the calculated result and experimental result
4.4 Model validation

4.4.1 Validation of flank wear model

The results calculated with the proposed model and the VBs measured in the cutting experiments are listed in Table 13 to Table 15, and the values are plotted in Figure 66 to show the development of flank wear. It can be seen that the measured VBs of all three tools increased steadily in a linear trend, and the development of tool wear caused by abrasive process was steeper than the increase of flank wear due to adhesive process. The VBs were measured after each 50-second cutting process and plotted with the same time interval (cutting process). The largest VBs were found when the tool CTB002 was used (186 µm), followed by the VBs of CTB010 tool (133 µm). The tool made of CTM302 showed the best resistance to flank wear because of the lowest VB after 14 cutting processes (124 µm). The measured VBs increased linearly, this trend matches the trend of calculated results when tools CTB002 and CTB010 were used. As for the tool CTM302, sudden increments of VB were found after the first, the 9th and the 14th cutting processes respectively. The increments of VBs in the 5th to the 8th cutting processes and the 10th to the 13th cutting processes were insignificant, which were 5 µm and 9 µm respectively. To validate the model and to investigate the wear process of the three different types of tools, comparison between the calculated values and experimental results were presented by the relative deviation which was calculated with the following equation:

$$\text{Relative deviation} = \left| \frac{VB_{\text{calculated}} - VB_{\text{measured}}}{VB_{\text{measured}}} \right| \times 100\%$$

(4.50)

As listed in Table 6, the deviations of CTB002, CTB010 and CTM302 are generally below 10% except for a few abnormal results which are caused by special reasons explained in Section 4.2. The experimental results of tool CTB010 distributed along the linearly calculated results indicating that the development of flank wear was dominated by adhesive-abrasive process. The measured VBs were larger than the calculated results considering adhesive-abrasive wear when
The tool CTB002 was used, indicating that the abrasive wear contributed more in the material loss process of flank wear. In contrast, the deviations of tool CTM302 were bigger and the fluctuation irregularly.

![Graph (a)](image1)

![Graph (b)](image2)
Figure 66 Development of flank wear of different PCD tools (a) the tool made of CTB002 (b) the tool made of CTB010 (c) the tool made of CTM302

Table 13 Calculated and experimental results of the tool T002N

<table>
<thead>
<tr>
<th>Cutting Process No.</th>
<th>Calculated (µm)</th>
<th>Experimental (µm)</th>
<th>Deviation (%)</th>
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<td>Totally abrasive</td>
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<th>Experimental (µm)</th>
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3

Table 15 Calculated and experimental results of the tool T302N

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<th>Deviation (%)</th>
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</table>
### 4.4.2 Validation of crater wear model

Figure 67, and Table 16 to Table 18 present the validation of crater wear model. Compared with width of flank wear (VB), VC after 14 cutting process were smaller, because the stress at tool/chip interface was not as severe as the stress status at tool/workpiece interface. It was shown that both measured and calculated values of the depth of crater wear (VC) of the tools made of CTB002 and CTB010 increased linearly. This agrees to the wear mechanism proposed in Chapter 3 that the crater wear processes of the tools made of uniformly-sized grains were steady. Compared with the VC of tool CTB010 (12.5 µm), the VC of tool CTB002 (15.2 µm) after 14 cutting processes was higher. The reason is ascribed to the higher temperature at tool/chip interface and the larger normal force which accelerated both adhesive-abrasive process as well as diffusive process. The deviation of crater wear depth was calculated using the Eq 4.50, and the results show that the deviations of tools made of CTB002 and CTB010 fluctuate within the range of 10% to 20% which are larger the deviation of flank wear width. Furthermore, the measured VCs are larger than the calculated results when the tools CTB002 and CTB010 were used. As for the tool made of CTM302, the development of VC experienced sudden increase during the 1\textsuperscript{st}, 5\textsuperscript{th} and 12\textsuperscript{th} cutting processes. Due to the large-scale fracture of the PCD near the tip of the tool.
made of CTM302, geometric characters of crater the tool tip was changed significantly and irregularly, which caused the obvious fluctuation of the deviations of the CTM302 tool.
Figure 67 Development of crater wear of different PCD tools (a) the tool made of CTB002 (b) the tool made of CTB010 (c) the tool made of CTM302

Table 16 Calculated and experimental results of the tool T002N

<table>
<thead>
<tr>
<th>Cutting Process No.</th>
<th>Calculated (µm)</th>
<th>Experimental (µm)</th>
<th>Deviation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Adhesive-abrasive</td>
<td>Diffusive</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3.9</td>
<td>0.6</td>
<td>5.2</td>
</tr>
<tr>
<td>2</td>
<td>4.3</td>
<td>0.8</td>
<td>6.3</td>
</tr>
<tr>
<td>3</td>
<td>4.6</td>
<td>1.0</td>
<td>6.9</td>
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<td>4</td>
<td>4.9</td>
<td>1.3</td>
<td>7.4</td>
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<tr>
<td>5</td>
<td>5.1</td>
<td>1.4</td>
<td>7.9</td>
</tr>
<tr>
<td>6</td>
<td>5.3</td>
<td>1.6</td>
<td>8.5</td>
</tr>
<tr>
<td>7</td>
<td>5.6</td>
<td>1.8</td>
<td>9.8</td>
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<tr>
<td>8</td>
<td>6.2</td>
<td>2.2</td>
<td>10.5</td>
</tr>
<tr>
<td>9</td>
<td>7.4</td>
<td>2.4</td>
<td>11.2</td>
</tr>
<tr>
<td>10</td>
<td>7.9</td>
<td>2.5</td>
<td>12.6</td>
</tr>
<tr>
<td>11</td>
<td>8.3</td>
<td>2.6</td>
<td>13.2</td>
</tr>
<tr>
<td>Cutting Process No.</td>
<td>Calculated (µm)</td>
<td>Experimental (µm)</td>
<td>Deviation (%)</td>
</tr>
<tr>
<td>--------------------</td>
<td>----------------</td>
<td>------------------</td>
<td>---------------</td>
</tr>
<tr>
<td></td>
<td>Adhesive-abrasive</td>
<td>Diffusive</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3.5</td>
<td>0.5</td>
<td>4.8</td>
</tr>
<tr>
<td>2</td>
<td>3.9</td>
<td>0.6</td>
<td>5.3</td>
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<td>3</td>
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<td>4</td>
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<td>1.1</td>
<td>6.4</td>
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<td>4.6</td>
<td>1.4</td>
<td>6.9</td>
</tr>
<tr>
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<td>7.6</td>
<td>3.0</td>
<td>11.6</td>
</tr>
<tr>
<td>14</td>
<td>8.1</td>
<td>3.1</td>
<td>12.5</td>
</tr>
<tr>
<td>Average</td>
<td>5.49</td>
<td>1.92</td>
<td>8.37</td>
</tr>
</tbody>
</table>

Table 17 Calculated and experimental results of the tool T010N

<table>
<thead>
<tr>
<th>Cutting Process No.</th>
<th>Calculated (µm)</th>
<th>Experimental (µm)</th>
<th>Deviation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Adhesive-abrasive</td>
<td>Diffusive</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2.7</td>
<td>0.5</td>
<td>2.8</td>
</tr>
<tr>
<td>2</td>
<td>4.5</td>
<td>0.7</td>
<td>5.5</td>
</tr>
<tr>
<td>3</td>
<td>4.7</td>
<td>0.8</td>
<td>6.8</td>
</tr>
<tr>
<td>4</td>
<td>4.8</td>
<td>1</td>
<td>7.6</td>
</tr>
</tbody>
</table>

Table 18 Calculated and experimental results of the tool T302N
### 4.5 Summary

Analytical models predicting flank wear process and crater wear process were developed based on the wear mechanisms proposed in Chapter 3. The material loss during the flank wear process was caused by the combined influence of adhesive wear and 3-body abrasive wear. In addition to the adhesive-abrasive wear, diffusive wear was considered in the material loss process of crater wear. Differential equations were developed which describing the increasing rate of VB and VC respectively. By adopting the tool geometric parameters, cutting parameters and physical properties of workpiece and tool materials, tool wear amount after the time periods were obtained via solving the differential equations. The model was validated by the experimental results of the turning tests in Chapter 3, and the results of calculation agree with the experimental results.
Chapter 5 Investigation on Quality and Performance of PCD tools
Refined by Abrasive Grinding and Electrical Discharge Grinding

In this section, a comparison of quality and performance of the PCD tools machined two different grinding methods was conducted experimentally. The PCD materials used in this section were CTB002, CTB010 and CTM302 manufactured by ElementSix. The raw PCD were firstly cut into cubic shapes by wire-cut. Then the inserts were divided into two groups, and their flank faces were refined by the abrasive grinding and electrical discharge grinding respectively with different grinding parameters. Facial quality including roughness of machined surface, sharpness of cutting edge and the residual stress were examined after the grinding processes, and the tools with lowest surface roughness, cutting edge radius and residual stress were selected to test their performance by conducting the cutting experiments, including short-distance grooving cutting tests and long-distance turning tests. Cutting forces and morphology of worn surfaces of the tools were analysed to investigate the wear resistance of tools refined by the two grinding methods.

5.1 Preparation of cutting tools

5.1.1 PCD tools machined by abrasive grinding

The setup of abrasive grinding is presented in Figure 68. The grinding process was conducted on a CNC diamond grinder COBORN RG6-FE. In the grinding process, a PCD insert was mounted on a fixture, and the facial material was removed by the abrasion of a rotating diamond grinder wheel. Water-based coolant was adopted during the grinding process to avoid surface damage caused by the grinding temperature. As a kind of sintered material, PCD is brittle although it is one of the hardest tool materials, the grinder wheel should be selected properly, and the force exerted on the tool surface should be controlled to avoid excessive flaws caused by the large-scale fracture of PCD in grinding process. For this purpose, the removal of PCD material should
follow the principle of “ductile fracture for brittle materials” [102]. The breakdown behaviour (Table 19) for both ductile and brittle materials due to the localized loading was generalized by Alkin [103]. As was shown in Table 18, ductile fracture for the brittle material could be achieved when the radius of the indenter was small, and this helped to the selection of the grinder wheel with appropriate grain size. A vitrified bond D17 diamond grinder wheel made by Trochilics Ltd was equipped on the spindle of the CNC diamond grinder. The average size of the abrasive grains on the wheel is 17 µm, which is small enough to control the ductile fracture of the PCD structure with an acceptable scale. Furthermore, the stress exerted on the tool surface should be satisfied with Eq 5.1 and Eq 5.2, which ensures the initiation of the dislocation of PCD structure,

\[
\tau_c = \left[\frac{2G}{1-2\nu}\right]e^{-\left(\frac{2\pi\omega}{b}\right)}
\] (5.1)

\[
\sigma_c = \left[\frac{2\gamma E}{\pi c}\right]
\] (5.2)

where

\(\tau_c\)  Shear stress exerted on workpiece surface, MPa;

\(\sigma_c\)  Critical stress to cause the ductile fracture for brittle material, MPa;

\(G\)  Elastic shear modulus of PCD, GPa;

\(E\)  Longitudinal elastic modulus of PCD, GPa;

\(c\)  Crack length, mm;

\(\gamma\)  Surface energy density, \(J/m^2\);

\(\nu\)  Poisson’s ratio;

\(\omega\)  Width of the dislocation region, mm;

\(b\)  Magnitude of the burger’s vector in the slip direction, mm;
Figure 68 Equipment for abrasive grinding of PCD (a) CNC diamond grinder (b) grinding setup

Table 19 Breakdown behaviour for different materials

<table>
<thead>
<tr>
<th>Abrasive geometry</th>
<th>Brittle material</th>
<th>Ductile material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large radius of tip (more than the grain size of work-piece)</td>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
</tr>
<tr>
<td>Small radius with lower tip load (P) (radius of tip &lt; grain size of the work-piece)</td>
<td><img src="image3" alt="Diagram" /></td>
<td><img src="image4" alt="Diagram" /></td>
</tr>
<tr>
<td>Small radius of with high tip load (P) (radius of tip &lt; grain size of the work-piece)</td>
<td><img src="image5" alt="Diagram" /></td>
<td><img src="image6" alt="Diagram" /></td>
</tr>
</tbody>
</table>

Figure 69 presents the simplified mechanism and parameters for abrasive grinding of PCD tools.

Perpendicular grinding method rather than parallel grinding method was adopted in order to
reduce the normal stress which could limit cracks caused by the fracture of diamond in the grinding process. During the grinding process, the grinding wheel moved back and forth in the axial direction, and touched the PCD surface with a certain frequency. The grinding in-feed was pre-set as 100 µm to completely remove the “heat affect zone” (HAZ) caused by the wire-cut EDM. When selecting of contact load and grid depth of grinding, their values should be sufficiently small to obtain ductile fracture of brittle materials. The grid depth of grinding could be calculated using the following equation [102],

\[ g_m = \left( 2a \cdot \frac{V_{osc}}{V_{whe}} \cdot \sqrt{\frac{\Delta/k}{D}} \right) \]  

(5.3)

where,

- \( g_m \) Grid depth of grinding, mm;
- \( 2a \) Distance between the successive grains (16 µm for D16 diamond grinder wheel), mm;
- \( V_{osc} \) Wheel oscillation speed, 15 mm/s;
- \( V_{whe} \) Wheel velocity, 10 m/s;
- \( D \) Wheel diameter, mm;
- \( \Delta \) Grinding in-feed, mm;
- \( k \) Hardness ratio between the PCD and resin bond of the wheel;

The normal contact load was preset by using the following equation [102]:

\[ F_n = \tan \alpha \times \frac{\pi V_{osc} d}{2V} \times C_p \]  

(5.4)

where,

- \( F_n \) Contact load, N;
- \( C_p \) Specific grinding energy for PCD;
- \( d \) Oscillation distance;
- \( \alpha \) Half of the included angle of diamond grain;
A relatively large range of cutting speeds and feed rates could be adopted in abrasive grinding of PCD surface in industry. In this chapter, the following machining parameters were selected and arranged orthogonally to in total 18 cutting tools (Table 20), grinding feed rate of 0.2 and 0.5 mm/min and wheel velocity of 10, 20, and 30 m/s, to investigate their effects on the roughness of machined surfaces, the sharpness of cutting edges and the level of residual stress.

**Table 20** PCD materials and machining parameters of abrasive grinding

<table>
<thead>
<tr>
<th>Tool number</th>
<th>Tool material</th>
<th>Feed rate (mm/min)</th>
<th>Cutting speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TA01</td>
<td>CTB002</td>
<td>0.2</td>
<td>10</td>
</tr>
<tr>
<td>TA02</td>
<td>CTB002</td>
<td>0.2</td>
<td>20</td>
</tr>
<tr>
<td>TA03</td>
<td>CTB002</td>
<td>0.2</td>
<td>30</td>
</tr>
<tr>
<td>TA04</td>
<td>CTB002</td>
<td>0.5</td>
<td>10</td>
</tr>
<tr>
<td>TA05</td>
<td>CTB002</td>
<td>0.5</td>
<td>20</td>
</tr>
<tr>
<td>TA06</td>
<td>CTB002</td>
<td>0.5</td>
<td>30</td>
</tr>
<tr>
<td>TA07</td>
<td>CTB010</td>
<td>0.2</td>
<td>10</td>
</tr>
<tr>
<td>TA08</td>
<td>CTB010</td>
<td>0.2</td>
<td>20</td>
</tr>
<tr>
<td>TA09</td>
<td>CTB010</td>
<td>0.2</td>
<td>30</td>
</tr>
<tr>
<td>TA10</td>
<td>CTB010</td>
<td>0.5</td>
<td>10</td>
</tr>
</tbody>
</table>
The EDG process was conducted on a commercial EDG machine ANCA EDGe RX7 (Figure 70(a)). The insert was held on a customized holder as one of the electrodes in eroding process. A tungsten-copper wheel electrode with a rotational speed of 2 m/s was used as the other electrode (Figure 70(b)). In this study, a 2-step machining method was adopted including a roughing process and a finishing process. As was shown in Figure 71, electrical parameters used in each process were selected based on the values optimized in our previous studies to ensure the quality of machined surface. The open-circuit voltage was constant (120 V) throughout the eroding process for every tool. As for the roughing process, longer pulse duration (time-on, µs), short pulse interval (time-off, µs) and larger current were adopted intending to remove the material rapidly. The in-feed was 100 µm for all the inserts in roughing processes. With regard to finishing process, the shorter time-on, longer time-off and smaller current were suitable for the finishing process which could remove the HAZ formed in roughing process without inducing further thermal defects like residual stress and graphitization. Four finishing in-feeds were implemented to further investigate the influence of this machining parameter on the surface quality and residual stress distribution of PCD tools (Table 21). It is expected that higher in-feed of finishing reduced the total residual stress after machining as the increased eroding depth machined with finishing parameters removed the HAZ generated by rough erosion thoroughly. As was found by Rahim et al. [104], the average crater depth generated in the roughing operation
was about 0.01 mm, therefore, 0.01 mm was pre-set as the minimum in-feed (lowest finishing depth).

Figure 70 Equipment for Electrical discharge grinding (a) the EDG machine ANCA EDGe RX7 (b) experimental setup of EDG

Figure 71 Simplified mechanism and machining parameters in electrical discharge grinding (a) roughing process (b) finishing process
Table 21 PCD materials and machining parameters of EDG

<table>
<thead>
<tr>
<th>Tool number</th>
<th>Tool material</th>
<th>Finishing in-feed (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE01</td>
<td>CTB002</td>
<td>10</td>
</tr>
<tr>
<td>TE02</td>
<td>CTB002</td>
<td>20</td>
</tr>
<tr>
<td>TE03</td>
<td>CTB002</td>
<td>30</td>
</tr>
<tr>
<td>TE04</td>
<td>CTB002</td>
<td>40</td>
</tr>
<tr>
<td>TE05</td>
<td>CTB010</td>
<td>10</td>
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<tr>
<td>TE06</td>
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<td>CTM302</td>
<td>20</td>
</tr>
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</tr>
<tr>
<td>TE12</td>
<td>CTM302</td>
<td>40</td>
</tr>
</tbody>
</table>

5.2 Examination of tool quality

5.2.1 Surface examination

After grinding processes, the sharpness and surface roughness of the machined surface were measured by the Alicona 3D scanner (IF EdgeMaster ×50). The sharpness was the average value of the cutting edge radiuses of the four cutting edges, and the roughness was the average value of the roughness of four machined surfaces. The surface roughness (Ra) of the three types of PCD inserts machined with abrasive grinding and EDG was shown in Figure 72(a). With the selected machining parameters, it was found that the roughness of all the ground was controlled basically within 0.3 µm. Specifically, the surface roughness of ground tools made of CTM302 was the largest (over 250 nm), followed by tools made of CTB010 and CTB002 respectively (below 200
nm). As introduced in aforementioned chapter, the hardness of CTM302 was the highest due to the existence of large-size diamond grains as well as the lowest volume fraction of cobalt. Also, compared with CTB002 and CTB010, CTM302 consisted of the mix of diamond grains in different sizes, which led to the micro-fracture in large scale during the grinding process. These led to rougher finish surfaces of the ground CTM302 tools. Furthermore, for the tools made of same PCD material, the roughness increased with the increase of cutting speed and feed rate. This indicates that conservative cutting parameters were recommended to obtain better surface roughness.

The surface roughness of eroded PCD inserts was lower compared with that of the ground tools (Figure 72(b)). Specifically, average surface roughness of the eroded tools made of CTB002 and CTB010 was approximately 140 nm. This value was closely similar to the smallest surface roughness of the ground tools made of same PCD materials. As for eroded tools made of CTM302, the average roughness was 166 nm which was much smaller than the smallest roughness of the ground tools. The reduction in surface roughness was ascribed to the material removal mechanism of EDG. In eroding process, PCD material was removed without any physical contact which was different from the conventionally abrasive process. Compared with abrasive grinding, the PCD material was graphitized by the high temperature plasma which was generated between the PCD surface and rotating grinder wheel, and then removed by the coolant flow. Therefore, the eroding process was steady if the electrical characters of the EDG machine were stable. Furthermore, change of surface roughness was irregular with the increase of finishing in-feed, which means that the influence of finishing in-feed on the roughness of eroded surface was insignificant. Different cobalt fractions of the three materials led to the difference in the conductivity which directly affected the results of erosion. Also, the debris could be another reason contributed to the fluctuation in surface roughness as the graphite in coolant flow could change the status of plasma resulting in the fluctuation of surface roughness.
Figure 72 Roughness (\textit{nm}) of machined surface (a) tools machined by abrasive grinding (b) tools machined by EDG

Figure 73 presents the sharpness of the cutting edges. It was found that the sharpness of both eroded and ground tools ranged from 4.5 µm to 6 µm. The values of ground tools increased with
the adoption of higher cutting speeds and larger feed rates. The obvious difference could only be observed on the tools made of CTB010 and CTM302 machined with high wheel velocities and feed rates. Specifically, the increment of sharpness was 1.5 µm for the ground tools made of CTM302, and the sharpness increased about 1 µm for the ground CTB010 tools when the largest feed rate and wheel speed were adopted. However, the feed rates and grinding speeds contributed insignificantly to the edge radius of the CTB002 PCD tools. This is explained as the fracture character of different PCD materials, for the PCD consists of large-size diamond grains, the fracture scale is more difficult to control compared with the PCD made of small-size diamond grains. The influence of finishing in-feed on the sharpness of eroded tools was not obvious which is similar to the results of roughness measurement. The values were fluctuated around 5 µm which reach to the lowest sharpness of the ground tools.

![Graph showing sharpness results for CTB002, CTB010, and CTM302](image)
5.2.2 Residual stress analysis

PerkinElmer Raman Station 400F (Figure 74) was utilized to measure residual stress. According to the Raman spectrum of the finished surface, residual stress is reflected by the shift of the peak which stands for the existence of certain material [105]. In this research, the Raman spectrum of each insert was acquired with a 100 µm laser spot to analyse the types of carbon and status of residual stress on the machined surface.
The values of residual stress were calculated according to the results of peak shift in Raman spectroscopy of the PCD tools. In Raman spectrum of PCD, different carbon phases are presented by Raman peaks in different wave numbers, for example, peak value of unstressed diamond is $1330/\text{cm}$. The shift of diamond peak indicates that residual stress exists within the diamond structure at scanned area. The value of residual stress within PCD layer can be calculated based on the following equation [106]:

$$
\sigma = -\frac{v_s - v_r}{\chi}
$$

where

- $\sigma$ Residual stress, GPa;
- $v_s$ The measured Raman shift value of the diamond, $/\text{cm}$;
- $v_r$ The unstressed Raman shift value of diamond, $/\text{cm}$;
- $\chi$ The coefficient of stress-induced frequency shift, GPa/$\text{cm}$.

Figure 75 shows the calculated results of residual stress of the eroded tools and ground tools. It was found that compressive residual stress existed on the machined surface of the ground tools,
which matched the results achieved by Erasmus et al. [107]. During the machining process of abrasive grinding, the material of PCD insert was removed by a PCD grinding wheel. Huge pressure exerted on the machined surface led to compressive residual stress both within the bonded diamond structure and at the cobalt/diamond boundary. The significant difference in largest residual stress of PCD tools consisted by different PCD materials, specifically, the maximum residual stress of CTB002 tools was 2.23 Gpa which was 1.5 times and twice of the maximum value of tools made of CTB010 and CTM302 respectively. This indicates that residual stress was strongly affected by the size of diamond grains. With regard to the influence of cutting parameters, feed rate did not exert significant effects on residual stress except when the cutting speed is low (10 m/s). For the tools consisting of CTB002 and CTB010, residual stress increased drastically when the cutting speeds became higher. In the cases of eroded tools, the erosion process stressed the surface in a tensile direction. Different from the insignificant changes of sharpness and roughness, the difference in the magnitudes of residual stress of the eroded tools with different finishing in-feed was noticeable. The values decreased about 75 % when the in-feed increased up to 40 µm, which means that larger finishing in-feed was prone to refine the stress status on finished surface. Similar to the ground tools, smallest residual stress was found on the surfaces of CTM302 tool.
Figure 75 Residual stress after different grinding processes (a) tools machined by abrasive grinding (b) tools machined by EDG

It has been proven that the thermal stress generated by the roughing process is the main contributor to the final residual stress on the surface, and a finishing process is required to remove the stressed region. As shown in Figure 76(a), in the roughing process, the tungsten-cooper wheel was the cathode and the PCD inserts played the role of the anode, and the plasma was generated to erode the materials on the surface of PCD inserts. The temperature of plasma was around tens of thousands of Celsius degree, which was far above the melting point of diamond. In the eroding process, the heating time was long enough to melt and vaporize the PCD material due to the longer time-on. However, the energy of plasma was not totally used in eroding the PCD materials. A proportion of the heat was transferred to the areas beneath the machined surface forming the “heat effect zone”, which had large tensile residual stress and high level of graphitization. It has been proved that the depth of the “heat effect zone” was around 20 beneath the machined surface [108]. As a result, the tool surface has to be refined by the finishing process to release the residual stress.
In the finishing process, when using smaller discharging current to erode the surface of workpiece, the energy of plasma is far less than the energy in roughing process and graphitization within a smaller area is the material removing mechanism (Figure 76(b)). Therefore, the finishing process tends to remove the superficial workpiece material without creating obvious residual stress. Therefore, higher finishing in-feed resulted in better surface quality because the material with the higher stress caused in the roughing process was removed. However, tensile residual stress still existed on the machined surface even a 40-μm finishing in-feed was applied which indicated that a certain degree of tensile residual stress exists under the surface even with the highest finishing in-feed. This stress was assumed to be accumulated in the finishing processes of the eroded tools. Also, the difference in residual stresses of CTM302 tools obtained with 30 μm and 40 μm finishing in-feed were not different significantly, it can be regarded that tensile residual stress reached its minimum limitation. In contrast, the decrease of residual stress of the CTB002 tools and CTB010 tools was with the increase of finishing in-feed from 30 μm to 40 μm. It could be assumed that the residual stress could be further reduced by increasing the finishing in-feed.
5.3 Short-distance groove cutting test

5.3.1 Experimental setup

To assess the performance of the tools prepared by different processes, a series of grooving tests, which was similar to the experiment conducted by Liu et al. [109], and Hintze et al. [110], were carried out on a three-axis CNC machine center (HAAS) to examine the toughness of the tool tips. Both ground and eroded tools with best surface quality, cutting edge sharpness and lowest residual stress were selected: the ground tools TA01, TA07, TA13, and the eroded tools TE04, TE08, TE12. Tungsten carbide (WC) was applied as the workpiece material because it could accelerate the wear at tool nose within a short cutting length (Table 22). Other than for precise control of the grooving depth, the simple kinematics process was used to reduce the obstruction of external elements such as the influence of vibration and chattering to the final result. A 25 mm (length) × 100 um (depth) groove was carved on the workpiece surface surface by the tip of the PCD tools at a cutting speed of 15 m/min. The cutting tests were conducted on a three axis CNC milling machine (HAAS). The PCD tool was fixed on a tool holder (10 degree rake angle and six
degree clearance angle) and the workpiece was clamped on the dynamometer which was mounted on the table of milling machine (Figure 77).

Table 22 Mechanical properties of tungsten carbide

<table>
<thead>
<tr>
<th>Mohs hardness</th>
<th>Thermal conductivity</th>
<th>Elastic modulus</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>42 W/mK</td>
<td>90 Mpsi</td>
<td>580 Mpsi</td>
</tr>
</tbody>
</table>

During the cutting process, the cutting forces in X direction and Z direction was recorded and processed via a force measurement system (Figure 78), which includes an 8 channel dynamometer (Kistler 9527B), a signal amplifier (Kistler 5070A), a data acquisition card (National Instrument DAQ 6036E), and the softwares (MatLab and SignalExpress). After the tests, the 3D scanning of grooves (Figure 79(a)) was developed by using IF Edgemaster (Alicona 3D scanner). By plotting the profile of grooves (Figure 79(b)), the wear amount of wear at tool nose was obtained (“wear amount” = “cutting depth” – “groove depth”).

Figure 77 Experiment setup for the grooving tests
5.3.2 Analysis of cutting forces and wear amount

According to the results of measurement and calculation (Figure 80), the wear amounts of ground tools were larger than that of the eroded tools. It is found that the decrease in the depth of cut for TA01, TA07 and TA13 were all above 20 µm (25 µm, 22 µm and 27 µm respectively). The wear amount of TE04, TE08 and TE12 were 18 µm, 13 µm and 15 µm. TE08 and TE12
showed significant improvement of tool wear resistance, the wear amounts were about half of the tools machined by abrasive grinding.

By analysing the cutting forces in Z-direction (Figure 81(a)), it was found that the wear mechanism of PCD tools machined by abrasive grinding and EDG were different. Cutting forces of the ground tools were influenced by the grain sizes of the PCD materials. Specifically, larger cutting force in Z-direction was found when cutting with TA01 because higher volume percentage of cobalt and smaller grain-sized diamond made the structure of tool tip less brittle and less abrasive resistant. In contrast, the Z direction force when using TA13 changed irregularly and fluctuated obviously at the end of the cutting process, this was to be the results of fracture of large-size diamond grains based on the proposed wear mechanism in Chapter 3. For eroded PCD inserts, all the three cutting forces in Z direction increased up to around 40 N with the nearly same ratio (Figure 81(b)), which meant that the abrasive wear process developed steady during the cutting process.
To investigate the wear processes of the tools in grooving processes, a Philip 30XL Scanning Electronic Microscope (SEM) was utilized to examine the worn tool surface. Specifically, ground PCD inserts which suffered compressive residual stress was prone to fracture wear at tool nose. According to the SEM images of PCD inserts machined by abrasive grinding (Figure 82), the worn areas were coarse without any adhesion, which meant fracture happened around the tips of ground tools. The simplified wear mechanism of ground tools is shown in Figure 83. The structure of PCD near the tool tip became unstable when the external stress and the residual stress exerted on this area during the cutting process. Then, the breakage of cobalt-diamond bonding and diamond-diamond bonding led to the collapse of PCD structure around tool tips.
The development of fracture has a relationship with the diamond grain size, which was reflected by the cutting force and wear amount. For the tool made of CTB002 which consisted of small-size grains (2 μm), the breaking of D-D bonds and D-Co bonds was more significant, which caused the larger thrust force and wear amount. In contrast, the fracture of the tools made of CTB010 and CTM302 was less serious, because the two types PCD tool materials consist of larger diamond grains and had larger volume fraction of diamond which made them more resistant fracture.

Figure 82 Worn surface of ground PCD tools (a) CTB002 (b) CTB010 (c) CTM302
5.3.4 Analysis of wear process of eroded tools

Compared with the wear development of ground tools, all eroded inserts tended to wear in a steady abrasive process. To be specific, obvious BUL scaled upon the worn surface of eroded inserts (Figure 84(a), Figure 84(c) and Figure 84(d)), and the adhered material was proved to be the tungsten (Figure 84(b)) by the results of EDS, which indicated that the wear mechanism of eroded tools was different from that of ground tools. During the EDG process, a large amount of heat was generated when plasma formed between the anode (electrode) and cathode (workpiece). Although most of the energy within one spark was used to melt and vaporize the facial PCD material, a proportion of the heat could still affect the deeper section beneath the top surface of PCD as the thermal conductivity of PCD is high (5 times of that of WC). This excessive heat weakened the C-C bonding within the diamond structure (Figure 85). According to Kai’s results [69], the breaking of C-C bonding caused the layer dislodgement within the diamond structure microscopically. In the early stage of the cutting process, the material of tungsten adhered on the initial worn area, C and WC carbide were bonded strongly. With the continuing of the cutting process, the BUL was removed by tool/workpiece abrasion, and workpiece material combined...
with C on the fresh worn surface formed new BUL to continue this abrasive wear process. Because the C-C bonding was weakened, the development of abrasive-adhesive wear was steady regardless the size of diamond grains.

Figure 84 (a) Worn surface of eroded CTB002 (b) EDS analysis of the elements of BUL on the worn tool surface (c) Worn surface of eroded CTB010 (d) Worn surface of eroded CTM302
5.4 Turning test

In this cutting test, the ground tool TA07 and the eroded tools TE08, which had the smallest cutting forces and lowest wear amount of the tools machined by abrasive grinding and EDG respectively in grooving tests, were selected to test their performance in practical cutting processes. To investigate the influence of residual stress on the performance of the eroded tools, an eroded PCD tool made of CTB010 which had a lower residual stress (1.96 GPa) was pre-set as the contrast sample. The flank faces of this tool were processed by a “3-step” EDG method included a sub-finishing process in addition to the roughing and the finishing process. The surface roughness and sharpness of the 3-step eroded tool was similar to that of TE08 which could eliminate the influence of these two factors on the development of tool wear. The whole test was conducted on the HAAS CNC machining center using the same cutting parameters used in Chapter 3 (the 160 m/min cutting speed, the 0.15 mm/rev feed rate and the cutting depth 0.2
Cutting forces and profile of the worn areas were recorded after four continuous turning processes which lasting for 1 min, 2 min, 3 min and 4 min respectively. Morphological characters of wear on flank faces and rake faces were observed through SEM to investigate the development of tool wear.

5.4.1 Flank wear analysis

The acquired images (Figure 86) show the development of flank wear of three types of PCD tools. Compare with flank wear condition of eroded tools, wear on the flank face of the ground tool was more severe. As for TA07 and TE08, flank wear developed from a narrow area around cutting edge into a large triangular area. Also, it can be seen that the maximum width of flank wear of TE08 was just a half of that of TA07 in the following three turning processes (2-minute, 3-minute and 4-minute), which means that tool wear rate at this area was smaller during machining. In contrast, the PCD tools machined with the 3-step EDG process was more resistant to flank wear compared with the tools machined with other two methods. Morphologically, the initial flank wear area was strip-like, and the worn surface was limited to the area around the cutting edge after 10-minute turning instead of developing into a triangular area, not much PCD material near the tool nose was removed in the entire cutting process.

Measured by the Alicona IF EdgeMaster, the change of flank wear width (VB) reflects the evolution of flank wear of different PCD inserts (Figure 87). Specifically, the values of VB of all three tools start within 55 µm. The VBs of TA07 after the following three turning processes are the largest, and the VB was 392 µm after 10-minute which reaches the rejection criterion of the cutting tools according to ISO3685. In contrast, the VBs of TE08 are much smaller 71 µm (after 3min), 140 µm (after 6 min) and 250 µm (after 10 min), which presents better flank wear resistance. The tool machined with the 3-step EDG process showed the best wear resistance, the trend of wear development was steady and it was only 87 µm after 10-minute turning.

The thrust force and main cutting force (force in radial and tangential direction) reflect the difference in the development of flank wear as well (Figure 88). Generally, the change of main cutting force has the similar trend as that of VB values for each PCD insert. As flank wear is
caused by the tool/workpiece abrasion, the increase of friction area leads to the raising of cutting force in tangential direction. Main cutting forces of the three tools initiate around 100 N and increase to different values after 10-minute turning processes. Similar to the development of VB, largest cutting force is found when turning Ti6Al4V with TA07 (293 N after 10-minute turning), and the force in turning the alloy with the TE08 tool was smaller (215 N after 10-minute turning) but had a similar trend. In contrast, the variation of cutting force in tangential direction with the 3-step eroded insert was not obvious, which were 120 N, 136 N, 146 N, and 162 N respectively in each step of the experiment, there conformed to the change of VB values on the flank face of the 3-step eroded insert.

Figure 86 Development of flank wear after different cutting processes
The gradual blunting of tool tip led to the change of cutting force in radial direction and affected the profile of machined surface. As the tips of the tools in this research were sharp, peaks and grooves were generated by the successive movements of tool tips at intervals of feeds [111]. The wear of tool tip during turning causes changes in the depth of grooves on the finished surface.
According to Figure 89, the cutting force in radial direction increased significantly when turning workpiece with both TA07 and TE08. This is accordance to the decreasing of the groove depth after 10-minute machining (Figure 90(b) and Figure 90(c)). Compared with the groove depth achieved in the 1-minute machining, there was a decrease of around 20 µm after 10-minute machining (Figure 91(b) and Figure 91(c)), which was caused by the material lose on the tips of TA07 and TE08. However, for the grooves machined by the 3-step eroded tool, it decreased less than that of machined by TA07: the depth was kept around 100 µm (Figure 90(a) and Figure 91(a)), which meant a relatively intact tool tip was retained. The change of its thrust force proved this assumption as well. The force after 1-minute cutting was around 12 N and increased only 5 N during the following 9-minute cutting, which meant its tool tip was still relatively sharp after the 10-minute cutting process.

Figure 89 Forces in radial direction in each process of turning experiment
Figure 90 Depth of workpiece surface after 1-minute turning by: (a) 3-step eroded tool (b) TE08 (c) TA07

Figure 91 Depth of workpiece surface after 10-minute turning by: (a) 3-step eroded tool (b) TE08 (c) TA07
SEM images show more detailed morphology on worn areas near the tool tips. It is known that adhesion happened frequently when the temperature was high [112], and it can be seen that a layer of material scaled on the worn flank faces of all three tools, and some of them was removed by tool/workpiece abrasion exposing fresh PCD surface. Results of EDS analysis show that workpiece material adhered on the flank face. This suggests that adhesive-abrasive process was the main factor that contributed to flank wear regardless the grinding methods. Compared with eroded tools, abrasion between the flank face and workpiece surface was more severe because more adhered titanium within worn area of TA07 was removed.

**Figure 92** SEM images (1000×) of rake flank face after 10-minute turning: (a) TA07 (b) TE08 (c) 3-step eroded tool
Based on the results of grooving tests, it was found that residual stress influenced the stability of PCD structure at the tip area. Similarly, the results of turning tests indicated that thermal defects during different grinding processes affected the development of flank wear of PCD tools. The Raman spectrums of TA07, TE08, 3-Step eroded tool and the raw PCD material were presented in Figure 94, and it was found that different carbon phases including graphite (around 1600/cm), poly-crystalline diamond (1330/cm) and nano-crystalline diamond (around 1250/cm) were found on machined PCD surfaces. Nano-sized diamond was found in the layer of conventionally ground PCD while this structure did not exist in the PCD manufactured with EDG process. In abrasive grinding, exerted shear stress and compression did not affect the existence of the nano diamond particles. However, in the EDG process, due to the thermal effect generated by plasma, nano diamond particles were converted to graphite and were removed in the machining. Yingfei et al. [113] found that diamond-graphite conversion was one of the reasons causing diffusive tool wear on flank face. Correspondingly, graphite was detected exist on the machined surfaces of all three tools. The peak of graphite was higher on the flank faces of TE08 and the tool machined by 3-step EDG in comparison to that of on the flank face of TA07.
Figure 94 Results of Raman spectrum on flank surface of three PCD inserts after filtering

Figure 95 shows the Raman shift value obtained from the PCD inserts and the residual stress calculated by using Eq 5.5. It is shown that compressive residual stress existed within the PCD structure of raw material, and both abrasive grinding and EDG were able to ease the compressive condition of residual stress on the PCD layer. Tensile residual stress of 2.57 GPa and 1.71GPa were found on TE08 and 3-step eroded PCD tool respectively. On the other hand, compressive residual stress of 0.04 GPa was found dominating the surface of ground PCD tools which indicated that the compressive residual stress significantly affected tool performance even though its value was much smaller than the values of compressive residual stress. By comparing the performance of TE08 and 3-step eroded PCD tools, the lower compressive residual stress, the better wear resistance. The PCD tool machined with 3-step EDG process had lower residual stress and had achieved 1.5 times better wear resistance (considering the flank wear) than the 2-stped PCD after 10-minute turning process. Residual stress with big values favoured crack propagation at grain boundaries and cobalt diamond interface, which leads to diamond grain decohesion. This weakened structure reduces the abrasion resistance of machined surface. Under the impact of extrinsic constant loading, material near cobalt/diamond interface worn away first and some inter-granular cracks are produced [89]. As a result, bigger value of residual stress caused more unstable structure within the PCD layer.
5.4.2 Crater wear analysis

According to Minton et al. [114], the temperature at tool/chip interface could reach to over 1000K in dry cutting, therefore, applying coolant is necessary when PCD tool is used because the high temperature can accelerate diffusive-adhesive process and deteriorate the strength of PCD tools [53]. However, as presented in Figure 96, the tool wear on rake surface and cutting edge of each PCD insert was still severe. Thick BULs were formed after 3-minute turning, and this layer became even larger when the experiment was finished. It is clear that the level of cutting edge blunt and crater wear on the rake face are different among the three types of PCD tools. The cutting edge becomes blunt owing to the loss of tool material on the rake face near the cutting edge. It can been seen in the SEM images that severe crater wear occurred in the 10-minute turning process: there was titanium adhesion near cutting edge and a “hollow area” near the worn cutting edge of the ground tool. Because the rate of chemical diffusion and adhesion depends on the temperature at tool/chip interface [115], it is reasonable to assume that the temperature at the worn area was higher and the adhesive-abrasive process was severe in turning titanium alloy with TA07. However, different from the ground tool, crater wear of eroded tools was less serious in the 10-minute machining.
Figure 96 Development of crater wear after different cutting processes

Figure 97 shows the condition of tool nose after 20-second turning which indicated the initiation of crater wear. It was found that there was obvious material loss at the tip of TA07, which was similar to the wear morphology of ground tools after grooving tests. The appearance of this significant fracture mode at the early machining step is a good indication of the occurrence of internal cracks that typically associated with the grinding process. The micro-cracks caused by the compressive stress and shear stress initiated the wear on rake face and tool tip, and these
defects accelerated the development of fracture, which led to the development of tool wear. Whilst the tool tips of the eroded inserts were relatively intact, and workpiece material was adhered around tool tips.

Figure 97 SEM images (2000×) of tool nose after 20-second turning: (a) TA07 (b) TE08 (c) 3-step eroded tool

SEM images showed that, after 10-minute turning, BUL was removed on the rake face of TA07 (Figure 98(a)), and this indicates a higher cutting temperature at tool/chip interface during the cutting processes. Also, the edge of TA07 was abraded seriously, a blunt edge was found after the entire turning process was completed. In comparison, exposed PCD material was found on the rake face of TE08 which meant that only a part of BUL was softened and removed. A part of workpiece materials were adhered on rake surface because the cutting temperature was lower compared with TA07 (Figure 98(b)). The adhesion on the rake face of the tool machined by 3-
step eroded tool was thick, and this BUL left on the rake face stopped the further development of crater wear, preserving an intact rake surface on the inserts machined by EDG [57]. Proved by the wear condition of the tool tip and its cutting edge, it can be seen that, on the eroded PCD inserts, the cutting edge near tool tip was well kept, and abraded titanium alloy could be found on nearby surfaces (Figure 98(c)).

Figure 98 SEM images of rake face after 10-minute turning: (a) TA07 (b) TE08 (c) 3-step eroded tool

As aforementioned, the development of crater wear was reflected by the shapes of chips. During the turning process, the thermal effect caused by the deformation of workpiece materials and friction at tool/chip interface was small for the 3-step eroded tool, and this could be proven by the shape of chips (Figure 99). Compared to the chips generated by TA07 which were twisted together, the chips created by eroded PCD tools were regular and the radius of curves were smaller. Especially for the 3-step eroded PCD tools, the chips were segmented during 10-minute
machining. The curvature of chips represents the tool-chip contact length, and a shorter tool-chip contact led to better coolant penetration.

**Figure 99 Chips after 10-minute turning: (a) TA07 (b) TE08 (c) 3-step eroded tool**

Furthermore, relative temperature of each tool can be indirectly predicted based on the profile of tool tips and grooves. The shape of grooves machined by TA07 (Figure 100(c)) was non-uniform after 10-minute machining: titanium alloy was “squeezed” along the direction of feed. In contrast, the profile of the groove machined by the 3-step eroded tool (Figure 100(b)) and TE08 (Figure 100(a)) were still symmetric. Although coolant was applied, the temperature around tool tip was high enough to soften the workpiece material. The asymmetric profiles of surfaces machined by ground tools proved that the temperature was higher than those of tools refined by EDG. This phenomenon was because the material at tool/chip interface and tool/workpiece interface which
was softened at high temperature at tool/workpiece interface was moved along with cutting tools under the force in the feed direction. From the profiles of eroded tools, it can be predicted that the temperature around tool tip areas of TE08 and 3-step eroded tool were not as high as that of TA07. Moreover, a thicker layer of workpiece material adhered to the tool surfaces of the eroded tools, and this prevented the direct contact between PCD and high temperature workpiece material.

![Profiles of cutting edges and machined grooves after 10-minute turning](image)

**Figure 100** Profiles of cutting edges and machined grooves after 10-minute turning: (a) tool and groove profiles of TE08 (b) tool and groove profiles of 3-step eroded tool (c) tool and groove profiles of TA07

### 5.5 Summary

The quality and performance of tools machined by abrasive grinding and EDG were investigated through experimental study, and the results were summarized in Table 23. Tool quality of both eroded and ground tools was examined. It was found, for ground tools, roughness of machined surface and the sharpness of cutting edge was affected by the grinding parameters. While for eroded tools, the influence of machining parameters was insignificant. Difference in residual stress was found on both ground tools and eroded tools. Larger compressive residual stress was
found on the ground tools machined with larger cutting parameters. For eroded tools, increasing
the finishing in-feed was able to produce better surface with lower residual stress. Performance
of the ground and eroded PCD tools was investigated by conducting a series of cutting tests. The
wear resistance of eroded and ground tools were found to be different. Eroded tools were more
resistant to flank wear and crater wear, and the eroded tool with less residual stress had the better
wear resistance compared with the eroded tool with larger residual stress.

Table 23 Results of comparison on quality and performance of different PCD tools

<table>
<thead>
<tr>
<th>Cutting tools</th>
<th>Ground tools</th>
<th>Eroded tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sharpness</td>
<td>Sharpness is better when smaller feed rate was adopted</td>
<td>Finishing in-feed did not influence sharpness significantly</td>
</tr>
<tr>
<td>Roughness</td>
<td>Roughness is higher when larger feed rate was adopted</td>
<td>Finishing in-feed did not influence roughness significantly</td>
</tr>
<tr>
<td>Residual stress</td>
<td>Residual stress was higher when larger cutting parameters were adopted</td>
<td>Residual stress reduced with the increment of finishing in-feed</td>
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<table>
<thead>
<tr>
<th>Performance in cutting tests</th>
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<tr>
<td>Short-distance grooving test</td>
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<td>Long-distance turning test</td>
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Chapter 6 Conclusions and Future works

6.1 Conclusions

PCD is a promising material in cutting titanium alloys due to its outstanding physical and mechanical properties. The comprehensive understanding of the manufacturing process of PCD tools and their wear mechanisms is critical for the wide application of PCD tools in industry. The research investigated the PCD tools in two main areas: the wear mechanism of PCD tools which were analyzed experimentally and theoretically; the manufacturing and application of PCD tools which compared the tool quality and performance of PCD tools refined by different grinding processes.

6.1.1 Experimental study on Wear Mechanism

Three types of PCD tools consisting of different-sized diamond grains were fabricated by conventional abrasive grinding, and the performance of these tools was tested by turning titanium alloy in a series of experiments. After the cutting process, the wear mechanism of PCD tools was investigated by analysing cutting force, flank wear, crater wear and the elements on tool surface.

The flank wear of T002N and T010N developed steadily as reflected by the linearly increased tangential force and VBs. Rectangular worn areas with the exposure of PCD were found near the tool tip, and the scratches on the residual adhesion proved the tool material was removed due to the spalling mechanism. The large-scale fracture happened at the beginning of the cutting when using T302, and the fracture at the tip restricted the development of flank wear. On rake faces, adhesive-abrasive wear as well as the chemical diffusion were more severe due to the high cutting temperature. Scattered BULs were found on the rake faces of T002N and T010N. A thick BUL was preserved on the rake face of the tool CTM302.
More severe wear were found on the surface of T002H, T010H and T302H. The VBs of the three tools developed steadily but much larger after 6 cutting process. The adhesive wear was serious and extended from plastic contact region into elastic contact region. Cracks were found at the boundary of flank wear area, and chipping was found near the tool tips. Three distinctive worn regions were found on the rake faces of the tools under high cutting speeds. Abrasion in sliding zones of tools made of CTB002 and CTB010 was more severe, intensive cracks were found reflecting the higher stress and temperature at the tool/workpiece interfaces. Scratches instead of cracks were found on the sliding zone of T302H. Adhesion in Region III was more significant because of the higher temperature and speed of the chip flow.

In addition to the elements of PCD and workpiece material, oxygen was found on the tool rake faces due to the oxidation of the adhered titanium alloy. The oxidation level was relevant to the cutting temperature at tool/chip interface. The change of morphological and geometric characters of the chips reflected the development of tool wear. Continuous chips were generated when using tool CTB002 and CTB010. Chips generated by the tools made of CTM302 were always smaller due to the large-scale diamond fracture of the tool tip. This fracture changed the speed of chip flow as well as the friction characteristics at the tool/chip interface. When the cutting edge was sharp, periodical dimples were easily found on the surface of chips generated by all three tools. At the end of cutting, plastic deformation dimples become less significant because of the reduction of the sharpness.

6.1.2 Theoretical study on Wear Mechanism

To investigate the wear process of PCD tools theoretically, analytical models describing flank wear process and crater wear process were developed in metallic cutting processes. The material loss in flank wear processes was caused by the combined influence of adhesive wear and 3-body abrasive wear. Besides the effect of adhesive-abrasive wear, chemical diffusion was taken into consideration when developing the model of crater wear. Differential equations which describing the rate of flank wear and crater wear were developed by adopting the tool geometry, cutting parameters and physical properties of workpiece and tool materials. The wear amounts of flank
wear and crater wear after time periods were obtained by solving the differential equations. Width of flank wear (VB) and depth of crater wear (VC) were used as the indicator for the development of flank wear and crater wear respectively.

The model was validated by the results of turning experiments in Chapter 3. The deviation between the predicted and experimental values was used to investigate the difference in wear development of tools made of different PCD materials. The comparison between the calculated results and experimental data showed that the model-based VBs were basically satisfied with the actual values when tools made of CTB002 and CTB010 were used. The calculated VC of the tools made of CTB002 and CTB010 are smaller compared with the depth measured after each cutting process. Both calculated VB and VC of the tool made of CTM302 fluctuated because of the fracture of tool tip during the cutting processes.

6.1.3 The quality and performance of ground tools and eroded tools

Two kinds of grinding strategies, abrasive grinding and EDG, were investigated in this research. A variety of cutting parameters were selected to investigate their influence on quality and cutting performance of both eroded and ground PCD tools. Measurement after machining showed that there was no distinct difference on both surface roughness and cutting edge sharpness among the inserts made of CTB002 and CTB010 machined by abrasive grinding and EDG. Except for the tools made of CTM302, ground tools have higher surface roughness compared with eroded tools due to the larger size of the diamond grains. It was found that the increment of wheel speed and feed rate in abrasive grinding process produced worse results including higher roughness and large cutting edge radius. For eroded tools, similar roughness and sharpness were achieved regardless of the finishing in-feed implemented.

Difference in residual stress was found on both ground tools and eroded tools. Larger compressive residual stress was found on the ground tools machined with larger cutting parameters. The reason was that larger compressive stress was exerted on the machined surface when higher cutting speeds and feed rates were adopted. On the other hand, increasing the
finishing in-feed was able to produce better surface quality by means of lower residual stress and graphitization level. PCD consisting of larger grain size had smaller residual stress after EDG because of the higher volume fraction of diamond. Smaller residual stress was found on the eroded tools with 40 µm finishing in-feed because the HAZ formed in roughing process was removed when larger finishing in-feed was adopted.

Performance of the ground and eroded PCD tools was investigated by conducting a series of grooving tests on the surface of WC carbide workpiece. By analyzing the morphology of worn surface, wear amount and the change of cutting force in vertical direction, the mechanism of wear of eroded and ground tools were found different. During the cutting process, the compressive stress combined with the stress at tool/workpiece interface caused the fracture of tool tip which was the wear mechanism of Ground PCD tools. The level of tool tip fracture depends on the grain size of PCD. During the EDG process, the excessive heat generated by plasma caused tensile residual stress within PCD structure and weakened the C-C bonding as well. Workpiece material adhered on the worn surface initially, and was removed by the abrasion between PCD and WC. This adhesive-abrasive wear process was steady irrelevant with in PCD grain size.

After the grooving tests, two tools (TA07 and TE08) were selected to test their wear resistance in turning process. An inserts machined by 3-step EDG was selected as a comparison to discuss the influence of residual stress and graphitization on tool wear process. Different types of tool wear including flank wear, crater wear and edge chipping were found. TA07 suffered the most serious flank wear among the three PCD tools indicating that the tool/workpiece abrasion was most severe. In contrast, the least worn condition was found on surface of the tool machined by 3-step EDG process. Residual stress is one of the factors that accelerated the flank wear of the three PCD tools. The stress at cobalt/diamond interface made the structure unstable and reduced the wear resistance of PCD tools. Eroded tools with bigger residual stress have larger worn area on the flank face after machining. Nano-sized diamond particles found in conventionally ground PCD tools weakened the strength of diamond structure. While, for tools machined by EDG, this structure did not exist because of the thermal effects of EDG. The size of worn areas on rake surface proved that higher tool temperature led to more severe crater wear. By analyzing surface
profile of the grooves cut by the three types of PCD tools, it was found that there was an obvious decrease in the depth of grooves cut with ground PCD tool and the tool refined the 2-step EDG method. This phenomenon proved that the wear at tips of these two tools was more serious than at the tips of tools machined by the 3-step EDG. The temperature at tool/workpiece interface of conventionally ground and 2-step eroded inserts was highest as proved by the asymmetric profile of the grooves.

6.2. Future Work

6.2.1 Micro-structure of mix-size diamond grains

In this research, it has been found that the size of diamond grains and the volume percentage of the binder material affect the structure of the sintered PCD materials, which causes the difference in wear mechanism of the tools made of these PCD materials. Tools made of CTB010 which consisted of larger-size diamond grains and higher volume fraction was more resistant to flank wear than the tools made of CTB002. The wear mechanisms of the tools made of CTB010 and CTM302 were different although the volume fractions of diamond of these two materials are similar. As for CTM302, it is sintered with diamond grains ranging from 2 micron sized grains to 30 micron sized grains, however the proportion of diamond grains of a certain size is not clear (CTM302 is a commercial PCD material). The wear resistance and mechanism of tools made of different PCD materials consist of mix-sized diamond grains is a new aspect that can be investigated. The influence from the size of diamond grains, the proportion of amount of each kind of diamond grains, and how these two factors will affect the properties of PCD material could be find out.
6.2.2 Performance of eroded tools and ground tools in other cutting processes

In this research, the performance of eroded tools and ground tools were compared by conducting a series of cutting tests. The results of both short-distance grooving tests and continuous turning tests showed that tools machined by EDG had better wear resistance than the ground tool. Two invisible quality factors, residual stress and graphitization, were proved to be contributed to the phenomenon. Besides turning, milling and drilling are two dominant manufacturing sequences in industry, and the wear mechanism of mills and drills are different from turning due to their unique material removal mechanism. Tools suffered high-frequently dynamic cutting force in milling process. Under this cutting condition, cutting edges are prone to suffering chipping and other damage caused by fracture. On the part of drilling, it is a kind of internal operation which causes high cutting temperature, which will stimulate the development of adhesive wear and diffusive wear. Limited to the cost and time consumption of the manufacturing of PCD drills and PCD mills, the performance tests of milling and drilling were not conducted. For PCD tools machined by different grinding processes, their performance on resistance of fracture and high temperature in these two cutting methods is worthy to be investigated.

6.2.3 Influence of residual stress mathematically

Residual stress was found to be an important factor affecting the quality and performance of PCD tools. The results of grooving test showed that the eroded tools with tensile residual stress had better wear resistance compared with ground tools with compressive residual stress even though the value of compressive residual stress was smaller. In the turning test, 3-step eroded PCD tools performed better than TE08 which was machined by 2-step EDG method because of the less residual stress on the surface of 3-step eroded tools. However, how residual stress affected the development of tool wear quantitatively is not clear. Residual stress was a kind of inner stress, which was caused by the mismatch of the coefficient of thermal expansion of diamond and binder material. A compressive analytical model on cutting force can be further developed based on the combined effort of external stress and inner residual stress.
Reference


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