Research on Electrical Discharge
Machining of Polycrystalline Diamond

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/project 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.

Mohammad Zulafif Rahim

15/06/2015
Abstract

The non-contact process of Electrical Discharge Machining (EDM) eliminates cutting forces, and is regarded as the most effective process to machine polycrystalline diamond (PCD). However, the EDM plasma temperature of up to 12000K in the EDM process will cause damage to the machined surface. With emphasis on the cutting tool product, this study focuses on the analysis of the PCD surface damage caused by the Electrical Discharge Grinding (EDG) process and its optimization strategies. In addition to the graphitization and residual stress, several issues that assumed to be thermal damage indications caused by the process are highlighted. These include the formation of porous surfaces, cutting edge undercuts and some cosmetic aspects at the WC-PCD interface. It was found that the high temperature generated during erosion resulted in the partial conversion of diamond to graphite phase under the surface. Higher finishing in-feed proved to produce better surface quality by means of lower surface graphitization and lower tensile residual stress. The comprehensive discussion undertaken includes the theoretical modelling of the process, together with the validated results. The structural difference and residual stress between PCD manufactured with EDG and conventional grinding have been compared. Performance tests have also been conducted at the end of the methodology to evaluate and validate the models.
Acknowledgements

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Publications

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ISI impact factor:1.458, 5-year impact factor:1.42, H Index:58, Ranking (Order by SJR-Scopus indicator): 34/237 in Manufact. & Industrial Eng., Class of Journal: Q1


ISI impact factor:0.703, 5-year impact factor:0.86, H Index:27, Ranking (Order by SJR-Scopus indicator): 62/237 in Manufact. & Industrial Eng., Class of Journal: Q2

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Google Scholar, ProQuest, Copernicus International Indexed


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<th>Symbol</th>
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<th>Unit</th>
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<tr>
<td>$A$</td>
<td>cross sectional area</td>
<td>(mm$^2$)</td>
</tr>
<tr>
<td>$a$</td>
<td>diamond grain radius</td>
<td>(µm)</td>
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<td>$C$</td>
<td>specific heat of material</td>
<td>(J/kgK)</td>
</tr>
<tr>
<td>$C_m$</td>
<td>erosion resistance index</td>
<td>($10^{12} J^2/ m s kg$)</td>
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<td>$c_c$</td>
<td>heat capacitance for cobalt</td>
<td>(J/kgK)</td>
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<tr>
<td>$d$</td>
<td>lattice spacing</td>
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<td>$E$</td>
<td>modulus of elasticity</td>
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<td>$i$</td>
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</tr>
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<td>$q$</td>
<td>heat flux</td>
<td>(J/s)</td>
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<td>$V$</td>
<td>viscosity</td>
<td>(kg/ms)</td>
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</table>
\( \nu \)  Poisson’s ratio

\( \nu_{ur} \)  unstressed Raman value (cm\(^{-1}\))

\( \nu_{s} \)  Raman shift value (cm\(^{-1}\))

\( \chi \)  coefficient of stress-induced frequency shift (N/m\(^2\))

\( \alpha \)  coefficient of thermal expansion (K\(^{-1}\))

\( \theta \)  temperature difference (K)

\( \theta_c \)  X-ray diffraction angle (degree, \(^{\circ}\))

\( \lambda \)  elastic modulus

\( \lambda_c \)  X-ray wavelength (nm)

\( \mu \)  shear modulus

\( \sigma \)  tensile residual stress (N/m\(^2\))

\( \sigma_t \)  tangential stress (N/m\(^2\))

\( \sigma_r \)  radial stress (N/m\(^2\))

\( \Psi \)  X-ray diffraction tilt angle (degree, \(^{\circ}\))
Chapter 1 Introduction

1.1. Research Background

Known as a hard and brittle material, polycrystalline diamond (PCD) is produced from diamond particles that are sintered together under high temperature and high pressure conditions (at temperatures of 1670K to 1770K and pressures of 5GPa to 6GPa) in the presence of a catalytic metal [1-4]. PCD is becoming popular because of its excellent physical characteristics. It has been applied widely in die and cutting tool applications due to the high hardness, good thermal conductivity, high strength, and chemical resistance to most corrosive environments [5, 6]. Until 1996, applications of PCD tools were monopolized by the automotive sector due to the limitations of the process, which is efficient only in forming simple shapes [1]. Conventionally abrasive grinding processes have been established as the fabricating method for PCD cutting tools. Although better surface roughness can be obtained by conventional grinding, low grinding efficiency and large grinding forces induced during the process are inherent problems that limit the wide application of PCD tools. The non-contact process of Electric Discharge Machining (EDM) eliminates cutting forces, and is regarded as the process that will result in a better application by means of process flexibility with lower production costs [6]. For this reason, nowadays, further investigation on EDM of PCD is becoming extensive, and EDM is expected to be the best strategy in integrating the complicated geometric shape and superior properties of PCD for optimized process characteristics. Figure 1 shows an example of complicated tools shape that demand high process flexibility.
However, the EDM plasma with the temperature of up to 12000K in the EDM process will cause damage to the machined surface [1]. Erasmus et al. [8] reported that the PCD material would be subjected to reduction in compression stress when it was repeatedly annealed to about 1070K. This might due to the graphitization process catalysed by the cobalt (and typically has an onset temperature of around 1020K) [8]. The effect is expected to be more dominant for the EDMed surface, since the temperature is comparatively much higher than the annealing temperature.

The damaged surface or surface integrity associated with the thermal effect include graphitization and residual stress. This surface damage is usually correlated with the zone termed the Heat Affected Zone (HAZ). In order to achieve better performance, surface damage or defects should be controlled. Surface defects will induce stress concentration that is also considered a weak spot for crack propagation. Removing the damaged surface by grinding is not the best solution, especially when the surface geometry is complex.

The available research includes the strategies on how to overcome the major drawback in EDM, which is low production rate, and high surface roughness. However, the PCD industries, especially in cutting tool production, should not only consider the economic aspect, but also need to place emphasis on the quality aspect of the product. The primary concern is that there is insufficient data on the surface quality or surface integrity relating to the application performance of the tools. With
emphasis on the cutting tool product, this study is focused on the analysis of the Polycrystalline Diamond (PCD) surface damage caused in the fabrication process, specifically in the Electrical Discharge Grinding (EDG) process, and its optimization strategies.

1.2. Objectives and Research Questions

Since its development, PCD has been applied in the aerospace, automotive, wood and mining industries as cutting tools due to its outstanding cutting performance. Because of the ultra-hardness and low electric conductivity, PCD tools are very difficult to fabricate. The high costs caused by low machining efficiency have seriously hindered its widespread application in industry.

Although PCD tools are superior in toughness (chipping resistance), a 300% to 500% scatter in tool life has been reported in the automotive industries [9]. Indeed, unexplained breakages of PCD tools used for similar applications are also common [2, 9]. In addition to the direct cost of the tools, indirect costs are caused by the large amount of time needed to replace failed tools and set up new ones on each shift each day, which causes huge losses to the company over the long run. Figure 2 shows an example of weekly tool consumption for the drilling and milling of carbon fibre reinforced plastic (CFRP) components at Boeing Aerostructures Australia (a medium size company at Port Melbourne, Australia). High performance PCD tools with a much longer tool life would have been a perfect solution.

However, there is as yet no theory to explain adequately the relationships between tool life and the modified PCD properties after specific fabrication or machining strategy. Owing to the special structure of PCD, the EDM erosion process is very complex. The machining mechanism is distinctively different from conventional electrical conductive material. Because of the lack of theoretical support on the modified PCD properties after erosion, industry EDG technology has to rely on visible qualities, such as surface finish and geometrical accuracy, in order to define
the quality of the PCD tools. In fact, the author found that the other factors, such as residual stress and graphitization significantly altered the PCD tool life, although similar visible quality is achieved.

![Figure 2: Weekly tool usage in Boeing Aerostructures Australia](image)

As an attempt to resolve the issues, the following research objectives are defined:

- a. To develop a new methodology to identify HAZ.
- b. To find the best method to quantify the residual stress on PCD.
- c. To investigate the effects of plasma temperature generated by electrical sparks on PCD tool life.
- d. To optimize the EDG parameters (electrode polarity, wheel rotation direction, pulse on-time, pulse off-time, sparking voltage, and finishing in-feed) to improve PCD tool performance.

The key research questions are:

- a. How to determine the HAZ in PCD?
- b. What are the structural differences between PCD tools manufactured with different EDG processes?
- c. What are the differences in residual stress between PCD tools manufactured with EDG and conventional grinding processes?
Chapter 1. Introduction

d. What is the relationship between the plasma temperature in the EDG process and PCD tool quality (tool life)?

e. How will the machining parameters (electrode polarity, wheel rotation direction, pulse on-time, pulse off-time, sparking voltage, and finishing in-feed) affect the wear behaviour of PCD tools?

1.3. Scope of the Investigation

The scope of this study is as follows:

a. The research includes both theoretical and experimental knowledge analysis.

b. PCD samples with cobalt binder and different particle sizes will be used in this investigation.

c. Finishing processes are limited to conventional grinding and EDG.

d. CNC cutting tests will be conducted to prove and validate theoretical findings.
1.4. **Challenges in PCD Tools Fabrication**

PCD is commonly produced in a thin layer of 0.5mm to 0.7mm thickness on a supporting layer of tungsten carbide (WC). PCD tools are usually fabricated in three steps:

a. Cut PCD blanks into small inserts;
b. Braze the inserts on a carbide substrate;
c. Machine and sharp the cutting edges into the required dimension and surface finish.

Figure 3 shows an example of PCD tools for the milling process.

![Figure 3: PCD tool.](image)

The research was begun with the observation of the PCD tools’ surface quality after erosion. Several issues that were assumed as thermal damage indications caused by the process were highlighted. This included the formation of cutting edge undercut and some cosmetic aspects at the WC-PCD interface. However, whether the phenomena are the real implications of thermal damage was in question. Figure 4 shows the example of edge undercut mentioned. Initially, it was inferred that the formation of edge undercut happened due to the excessive tensile stress generated on the tip. However, the inference was incorrect and the exact reasons have been
reported in this thesis. Since the issue was reported previously but unexplained, the study was regarded as the first that successfully resolved the issue.

![Figure 4: Edge undercut](image)

From the industrial perspective, a notch that appeared on the WC-PCD interface is also considered a temperature-induced defect. Due to the difficult-to-observe PCD thermal damage, the notch appearance is referred to as gauging the damage level. With the bigger notch that appeared after erosion, a bigger thermal impact is predictably performed on the surface during erosion. With this hypothesis, the notch becomes an industrial concern. However, the emergence of this hypothesis became confusing when inconsistent notch width was achieved with similar repetition of the process. Regarding this issue, two possibilities were drawn as follows:

a. There is an uncontrolled variable that affects the process.
b. The machine system is unstable, and this then caused inconsistency in energy supplied for the plasma development.

The thermal damage issues are as yet not well understood by the research community. In order to gain better understanding of the PCD thermal damage, a series of scientific investigations on process stability is urgently required. Chapters 4 and 5 discuss the importance of some control factors and the findings related to these issues.
1.5. Research Methodology

The flowchart in Figure 5 shows the methodology of the research.

![Flowchart](image)

**Figure 5**: Research methodology

The alteration of residual stress and phase transformation (graphitization) was expected to indicate the HAZ of the PCD due to the erosion process. Metallurgical examination methods, such as optical metallography, Scanning Electron Microscope (SEM), X-ray diffraction (XRD) and Raman spectroscopy, were identified as suitable instruments for the analysis. Through the literature, it was found that the Raman method is the best method for residual analysis determination. The small laser spot size and reasonably small penetration depth were found to provide better measurement accuracy than XRD. This was considered a highly sensible method for being able to detect amorphous carbon structure.

![Diagram](image)

**Figure 6**: Illustration of the process flow
Determination of the control factors is a vital procedure for ensuring good repeatability of the process and avoiding obstruction or interference of external elements with the results obtained. Focusing on the surface quality and the cutting edge sharpness, the effects of tool polarity and wheel rotation direction were determined. The best strategies were then taken as the standard in the succeeding investigation.

As the next step, the PCD-eroded surface quality was evaluated. Specimens that were prepared by EDG with different machining parameters were analysed. With the aid of the morphological findings, different PCD erosion mechanisms were discussed. A comprehensive discussion was undertaken and the theoretical modelling of the process was obtained. The structural differences between PCD manufactured with EDG and conventional grinding were also compared. The performance test was conducted at the end of the methodology as a process evaluation.

Overall, the research seeks to better understand the PCD surface thermal damage caused by the EDG plasma and its influence on tool life. With this fundamental understanding, better process optimization and better PCD tools utilization can be expected.
Chapter 2 Literature Review

2.1. Introduction

The applications of PCD tools include the shaping of various materials, such as aluminium alloy used in the automotive industries, and wood, rock and rubber [1, 3, 10-13]. Due to PCD’s excellent properties, this tool material is also regarded as the best candidate for machining exotic materials for the aerospace industries [14]. The significant hardness and excellent thermal conductivity of PCD, of up to 920 W/mK, makes it the most promising tool material for machining titanium [5]. In addition, several studies demonstrate the use of PCD in micro-machining glass and other micro optical-related devices made from tungsten carbide, electro-less plated nickel and silicon [15, 16]. In Printed Circuit Board (PCB) industries, PCD has also been used in the cutting tools with special blade configurations [2].

However, the outstanding mechanical, electrical and thermal properties of this material have a negative influence in that uneconomical and inefficient manufacturing processes often result [17, 18]. Low G ratios, high cutting force and high wheel cost pose the main challenges to conventional grinding production of PCD parts [17]. Similarly, for lapping processes, low efficiency, low removal rate, high cost and poor consistency are the major problems [17, 19, 20]. Experiments show that the G-ratio of conventional grinding of PCD tools is between 0.015 and 0.025 and MRR is between 0.226mm³/min and 0.886mm³/min, depending on different grind size and structures [21]. Another problem with conventional grinding is the possibility of micro-cracks due to the high cutting force [21].

Brecher et al. [22] and Wang [23] used laser ablation, and achieved equivalent surface quality as abrasive grinding. However, unless ultra-short laser pulses of picoseconds were applied, which would result in unacceptably low MRR, a
conventional abrasive grinding process has to be followed in order to remove the severe heat affected zone [22]. In 2013, Qinjian et al. [24] developed another type of hybrid method by combining electrical discharge machining and ultrasonic-assisted mechanical grinding, but it was found that the hybrid method had limited impact on MRR. Likewise, Iwai et al. [25] developed an abrasive grinding-assisted EDM by using a metal-bounded diamond wheel for machining EC-PCD, but no obvious improvement in the grinding ratio was achieved in grinding conventional PCD material. For these reasons the EDM process is considered a good alternative for machining PCD due to its non-contact nature.

EDM is a non-conventional material removal process that uses thermal energy to melt or vaporize the work piece using high temperature sparks between the work piece and an electrode. EDM can be used for all conductive materials, regardless of their hardness and other mechanical properties, and is particularly good for fragile work pieces [26]. This chapter reviews the current achievements and findings of the EDM process of PCD.

2.2. PCD EDM Process

Early attempts to machine the diamond by EDM began in 1960. Heerschap et al. [27] revealed that non-conductive diamond could be machined using EDM by implementing a graphite coating on the diamond work piece. This is similar to the concept of “assisted electrode” used on EDM of insulated ceramics [28, 29]. To form the conductive coating of graphite, the diamond was heated up by non-oxidising flame to a temperature higher than its graphitization temperature [27, 30]. This was to ensure the conversion of diamond into graphite specifically on the work piece surface in order to provide a conductor path for spark initiation. The conductivity of the graphite enabled initial sparking and the erosion process was caused to the diamond-graphite conversion so that the process is self-sustaining. Hence, newly formed graphite was obtained on the eroded surface, providing connection to the current source [27, 30]. Figure 7 illustrates the aforementioned erosion concept.
The emergence of PCD resolved the issues of non-conductivity of diamond. The presence of up to 15% by weight of metallic cobalt in the PCD composition makes it possible to machine PCD using EDM [6, 31-33]. Research on PCD EDM may be divided into Die/Sink EDM, EDG and Electrical Discharge Wire Machining (EDWM). Although they posit the same concept, EDG and EDWM vary significantly in machining parameters. Instead of static electrodes typically used in Die/Sink EDM, a rotating electrode wheel is used in EDG. This improves the flushing efficiency, since the rotating wheel electrode effectively drags dielectric into the gap. It thus yields better in-material removal rate, tool wear ratio and surface roughness [34-37].

2.2.1. EDM Polarity

Several studies show that a lesser electrode wear ratio was obtained when positive polarity of the tool electrode was used during EDM of PCD [6, 38]. Carbon plating of the positive electrode (which is the electrode in this case) was believed to be the reason for the reduction of electrode wear when this method is used [6, 39]. The
transformation of diamond into other forms of carbon occurs during the EDM sparking process. The result from the conversion process is the formation carbon ions, which are then involved in the positive electrode plating operation. This heat-resolved carbon acts as a shield that protects the electrode from wear [6]. Furthermore, the deposited carbon is also reported to come from the dielectric medium when hydrocarbon dielectric was used [40].

However, the adhesion also had a negative impact on process precision. Wang et al. [6] revealed that the formation of carbon adhesion (graphite and amorphous carbon) on the silver-tungsten alloy electrode rod led to increases in the effective electrode size. It thus produced a hole with a size bigger than the required dimension. Particularly in micro-hole machining, increase in the electrode size due to plating phenomena will significantly affect process precision. The comparison of the shape of electrodes after EDM with different polarity is shown in Figure 8.
Figure 8: Comparison of electrode shape obtained by SEM after different polarity machining. (a) Initial shape of electrode (before machining) (b) Electrode after the positive polarity erosion (positive polarity of the tool electrode) (c) Electrode shape after negative polarity erosion (negative polarity of the tool electrode)[6]
2.2.2. Material Removal Rate

Considering the thermal conductivity, specific heat, and melting point of materials, Wang et al. [6] quantified the degree of difficulty for EDM of several materials. The degree of difficulty for a material to be eroded can be calculated using the following formula:

\[ C_m = KCT_m^2 \]  

(2.1)

where \( C_m \) is the erosion resistance index (ERI) \( (10^{12} \) J/m s kg) and \( K, C \) and \( T_m \) are the thermal conductivity expressed in W/(mK), specific heat is expressed in J/(kg K), and melting point is expressed in K, respectively. As shown in Table 1, in comparison to the ERI of tungsten, copper and steel, the highest ERI was attributed to PCD, indicating that PCD is the hardest material to be eroded by EDM.

<table>
<thead>
<tr>
<th>Material</th>
<th>Erosion resistance index ( (10^{12} ) J/m s kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tungsten</td>
<td>2.99</td>
</tr>
<tr>
<td>Copper</td>
<td>2.79</td>
</tr>
<tr>
<td>Steel</td>
<td>0.230</td>
</tr>
<tr>
<td>PCD</td>
<td>4</td>
</tr>
</tbody>
</table>

It is well understood that the smaller PCD grain size will give better MRR, because it has higher electrical conductivity than PCD with bigger grains. This is due to the fact that PCD with smaller grain size has a higher proportion of cobalt content than is the case with bigger grain size PCD. Since cobalt is a highly conductive material and diamond is non-conductive, the electrical conductivity of smaller grain PCD is higher.
Figure 9 shows several strategies that have been applied to optimize the production rate in EDM machining of ordinary materials [41-45]. But, to the authors’ knowledge, very little research has been reported on the effect of tool electrode material and dielectric in EDM machining of PCD. Current research for the purpose of improving the MRR in EDM of PCD is more focused on the optimization of parameters. PCD is a highly thermally conductive material (a range of 250 to 920 W/mK) [5]. As a result, it suffers high energy losses per unit volume, which slows down the melting operation. Therefore, in a roughing operation, higher voltage and current are required to get the higher sparking energy for better MRR. However, it was reported that there is an interaction between the sparking energy and the charging process of capacitors. After a certain limit, charging capacitors of the EDM machine more than is required also results in lower MRR. Although higher energy is provided, a major amount of time was spent on the charging process [46].

Parameter control is also important for avoiding a short circuit during the operation. Using the current and voltage feedback system integrated to the machine, a specific pulse known as normal, arc and short circuit pulses could be observed. Short circuit pulses occur when the electrode is in contact with the work piece and are believed not to contribute anything to removing material. However, the control activity of PCD EDM parameter is challenging, since the feedback system is not necessarily accurate in representing the real machining behaviour. As was found by Ye et al. [47], in some cases the short circuit pulses did not happen, although the electrode was contacting the PCD surface. This was due to the electrode making contact with a
non-conductive diamond particle that protruded from the PCD surface and the sparking still being between the cobalt and the electrode.

2.2.3. Surface Roughness and Morphology

Surface roughness is an important factor that affects the performance of cutting tools, particularly in high precision machining [5, 48]. Due to the extremely high hardness of PCD, together with high chemical stability, mechanical processing does not appear to be the best machining strategy for producing a very fine surface while considering the production cost [5].

In the roughing operation of PCD EDM, granularity of the surface results when individual diamond grains drop out of the surface, which makes the roughness value proportional to the grain size [1]. Hence, finer grain size is to be preferred when a better surface finish is a priority. However, in some tool applications, specifically in machining metal matrix composite (MMC) materials, bigger grain PCD is preferential. The investigation into the performance of PCD tools in machining of MMCs showed that better tool wear performance was achieved by PCD with bigger grains [49-51]. Although better in surface finish, a high percentage of cobalt in small PCD grain structure is also believed to be involved in weakening the structure, due to its affinity for carbon and its catalytic action in changing diamond to other forms of carbon at high temperatures [52]. For this reason, the investigation of surface roughness obtained by the fabrication process, especially for big PCD grain (10µm grain size and above), is crucial for the development of high performance tools.

Olsen et al. [32] believed that, during the sparking process, some diamond grains were lost as a result of the highly conductive cobalt network being preferentially eroded [31, 32]. For this reason, sparked PCD surfaces were generally of lower quality than conductive Chemical Vaporized Deposition (CVD) diamond film, so-called CVDITE CDE, even when fine diamond is used (2µm) [31]. Unlike PCD, in CVDITE CDE film production, the conductivity of diamond grains is increased by increasing the electrical conductivity of the diamond crystal itself through boron
doping [32]. Therefore, the spark will not only initiate on the grain boundary but can also happen on the grain surface. This led to the EDM of CVDITE CDE process cutting through the diamond crystal and not detaching the grains as a reason for finer surface value. [31]. To better understand the difference in mechanism, PCD and CVDITE CDE film material are compared in Table 2. It was believed that the major factor causing selective erosion of the PCD is the low electrical conductivity of diamond in contrast to the highly conductive cobalt path at the grain boundaries.

**Table 2: Comparison between PCD and CVDITE CDE material**

<table>
<thead>
<tr>
<th></th>
<th>PCD material</th>
<th>Conductive CVD (CVDITE CDE) material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity</td>
<td>Around 459 W/mK (for 10µm grains)[53]</td>
<td>Up to 2200 W/mK[32]</td>
</tr>
<tr>
<td>Compositions</td>
<td>Consists of cobalt binder and diamond grains</td>
<td>Consists of no metallic second phase [32]</td>
</tr>
<tr>
<td>Grains structure</td>
<td>Diamond might comprising both lamellar and fine grains, depends on the production method and starting materials [54].</td>
<td>Comprising only columnar/ lamellar diamond grains [32].</td>
</tr>
<tr>
<td>Specific resistance</td>
<td>1.4×10^{-4}Ωm[53]</td>
<td>0.4~1 x10^{-3} Ωm [55]</td>
</tr>
</tbody>
</table>

This principle has also been proved by Suzuki et al. [53]. A new type of PCD was developed by following the same concept as conductive CVDITE CDE. The boron atoms were incorporated into the diamond lattice in order to increase electrical conductivity [32, 53]. As a result, better surface finish than the standard PCD was achieved after the WEDM process. Interestingly, observation on the new PCD developed showed that the grain was flattened by the electro-discharge process (Figure 10). Better oxidation resistance might also be the other factor contributing to the lower surface roughness of the boron-doped PCD while EDMed in water dielectric. By oxidation analysis of CVD (CVDITE CDE), it was shown that better oxidation resistance is obtained when the diamond is doped with boron [55].
In the EDM process, discharge energy obtained by the spark significantly affects the roughness of the work piece surface. Although high sparking energy is desirable for better MRR, the higher the discharge energy, the higher the surface roughness will be [33]. Zhang et al. [56] claimed that low surface roughness obtained by low sparking energy is due to the chemical effect of molten cobalt. They believed that the temperature of the spark is high enough for diamond to graphite conversion on the surface. The converted diamond or graphite will then be dissolved into the molten cobalt before being removed easily by the blast that forms due to the dielectric oil vaporization [56]. The effect will not be significant when high sparking energy is used, since the cobalt will be vaporized [56].

In other study, even though with a similar sparking energy, Han et al. [57] believed that the surface roughness may not necessarily be similar. They stated that the heat flux generated from the process had a significant effect on the surface roughness as well as on surface morphology [57]. Heat flux, defined as the heat transfer rate per unit area, is related to the magnitude of current used during the EDM process. With the same sparking energy, the heat flux may not be the same. With the same discharge energy, a pulse with short duration and high peak current will give higher heat flux than a pulse with long duration and low peak current [57]. Consider the following basic formula for the temperature gradient calculation:
\[ q = -K \Delta T \]  

(2.2)

where \( \Delta T \), \( q \) and \( K \) are the temperature difference, heat flux and material conductivity, respectively. Rearrange equation 2.2 so that:

\[ T_2 - T_1 = -\frac{q}{K} \]  

(2.3)

Since the heat flux is a vectorial quantity, \( T_2 \) should be defined as the temperature on deeper surface and \( T_1 \) is the temperature of the surface that is exposed to the spark. Higher heat flux, defined as the higher heat rate per unit area, will reduce the chance of heat losses due to the conduction on the surface, thus creating deeper craters.

Little research has been done regarding the effect of dielectric in the machining of PCD materials. WEDM of PCD in oil can result in better surface quality than deionized water [53]. It was also reported that implementing WEDM of PCD in a water bath would increase the selective erosion on the cobalt region, since the cobalt has a much higher electrochemical equivalence than the other elements in PCD [58, 59]. Furthermore, the oxygen content in water also results in the oxidation of the PCD machined surface [55]. Wu et al. have shown the increase in oxygen content toward the edge of the WEDMed surface [59]. Figure 11 shows the voids that occurred due to the selective erosion of cobalt on the PCD surface.
2.2.4. Challenges on Cutting of Laminar Discs

The laminar disc blanks are made from PCD on a carbide substrate. Although the carbide substrate provides the PCD tools with sufficient toughness [60], EDM of this laminar structure is a challenge, since the layers are made of materials with dissimilar properties [58, 61]. Preferential erosion of the carbide occurs at the PCD-carbide interface and this not only causes a notch to form but also increases residual stress in this area [1]. The notch is believed to be more dominant when the bigger grain structure is used [1]. An analysis was conducted by Cao et al. [17] in an attempt to minimize the notch depth that was categorized as the most serious PCD surface defect caused by EDM. Through parameter optimization, they successfully reduced the notch depth on the diamond-WC interface to only 0.03mm [17].

Pisarciuc and Cristian [58] stated that “due to the manufacturing process, the cobalt concentration is higher in the transition zone between the carbide substrate and the diamond matrix. The low resistance of cobalt to thermal erosion compared with the other components, give rise to increased material removal in this area” [58]. This is proved by the element mapping result (Figure 12) obtained by Shin et al. [62] just after the HPHT sintering process of PCD. The result shows that the composition of cobalt is dominant on the PCD-WC interface. However, there is also an unexplained phenomenon which occurred during the roughing operation: formation of another notch that appeared just below the top edge of the PCD was observed [58]. Further study on the behaviour is needed to explain the phenomenon.
2.2.5. Heat Affected Zone (HAZ)

In EDM of metals, the recast layer, also known as the white layer, is a thin layer on the surface of the work piece which is formed by the re-solidification of melted material that has not been swept away by the dielectric during the EDM process. This layer usually presents after the WEDM or Die Sinking EDM due to an inefficient flushing operation [58]. The melted material is quickly chilled, primarily by heat conditions in the bulk of the work piece, resulting in an exceedingly hard surface. For this reason, a smaller grained annealed microstructure is usually formed just beneath the machined surface which also results in better surface hardness [58, 63]. The surface integrity result from the EDM process on ordinary material (metals) is illustrated in Figure 13.
Chapter 2. Literature Review

Figure 13: Heat affected zone of EDMed surface [58]

The heat affected zone (HAZ) when machining a metal is the zone that is subjected to very high temperatures, though not high enough to be melted, but which promotes some microstructure changes [43, 58, 64]. It will generally extend to a depth of a few microns beneath the machined surface. Research has shown that the surface damage due to the heat of plasma appeared up to 0.05mm in depth [31]. The depth is dependent on the temperature gradient profile, which is affected by the electrode materials, dielectric and machining conditions [43]. Although a recast layer may not be generated in the EDG of PCD, there will generally be a HAZ, which is largely unavoidable when dealing with thermal processing. This HAZ is also generally called the modified zone or affected layer by some researchers when dealing with PCD [65, 66].

Metallurgical examination of the surfaces using various techniques such as optical metallography, Scanning Electron Microscope (SEM), X-ray diffraction (XRD) and Raman spectroscopy has been undertaken by many researchers to study the behaviour of material due to thermal stress [65-77]. The affected layer with a thickness more than 70µm has been observed on the PCD surface after EDM with a roughing condition [65] (Figure 14a). The thickness of this layer is also believed to significantly affect PCD tool life. However, detailed explanation of the structural properties of this layer has remained unknown. As shown in Figure 14b, nearly the same layer was also observed by Kalyanasundram et al. on the PCD sample after
LWJ machining. Using the Raman analytical method, a laser that focused on the layer formed strongly indicates the formation of graphite. A high proportion of graphite on this area can be explained by the diamond to graphite conversion to be covered in section 2.2.6.

The failure of material structure usually starts from the surface [69]. Hence, in order to have better performance, the surface damage or defects should be controlled. Surface defects will induce stress concentration, leading to crack propagation [78]. Removing the damaged surface by grinding is not generally feasible, especially when a complex surface is involved. Surface cracking on EDMed PCD is typically associated with the heat generated by the process [1]. Increasing the heat will increase the PCD grain volume that will increase the residual stress especially on the surface. Once residual stress is increased over certain limits, initial cracks a few nanometres will be caused. These nano-scale cracks pose a major concern in making PCD cutting tools, because they are one of the main reasons for tool failure and short tool life. Rapid loading with machining vibration requires the tool to have high fatigue strength. Nano-cracks will tend to be propagated when the tool is under the fatigue loading. The crack will tend to appear on the grain boundary or diamond bridge (Figure 15), which is the weakest part of the microstructure. This causes dislodgement of diamond particles as the mechanism for tool wear [49].

![Figure 14: SEM image of PCD (a) after EDM (b) after LWJ [65, 66]](image-url)
2.2.6. Material Phase Transformation

Extensive studies have been done by many researchers on the effect of diamond tool geometry on machining performance [79, 80]. However, the quality of the surface structure should also be taken into account. In PCD erosion, material phase transformation is another concern. Although PCD is mainly composed of extremely strong diamond, the material is weakened when it is in high-temperature contact with iron group metals (cobalt, iron, nickel) [1, 3, 4, 32, 58]. Diamond will lose its stability and graphitize more easily when in high-temperature contact (onset temperature of 970K) with these carbon-diffusing materials [1, 31, 81, 82]. Without the catalyst metal, the graphitization only occurs at temperatures above 2000K [10, 83]. The temperature of sparks from EDM are much higher (up to 12000K) [1, 64], which guarantees the diamond to graphite conversion. As shown in Figure 16, PCD that is constituted of Catalytic High Pressure High Temperature (HPHT) diamond will transform into several phases under specific conditions.

![Diamond Bridge Diagram](image)
It was found that the oxygen content is greater close to the eroded cutting edge (approximately 60% by atomic weight of oxygen was detected). In fact, the atomic content of carbon (which indicates the percentage of diamond or graphite) decreased steadily toward the edge (Figure 17) [59]. These elucidated the availability of microstructure change of PCD that was subjected to EDM. During the EDM process, the outer PCD surface is exposed to plasma with a high temperature and can be converted to graphite carbon, which will then be dissolved by molten cobalt before being removed by flushing [56]. Meanwhile, the inner surface that has lower energy will tend to be transformed into graphite. It was expected that the graphitization of PCD is easier than that of a single diamond due to the availability of cobalt in its composition. The conversion of diamond while under EDM, however, will cause reduction of bonding strength and increase the probability of surface damage. Furthermore, the elastic and thermal properties between grains are changed when the phase transformation occurs [84].
Diamond converted into another carbon structure will not retain diamond’s superior properties and this leads to lower product quality. Graphite acts as a transition stage in the oxidation process (transformation into CO or CO$_2$) in the structure. The oxidation effect will be more dominant when the structure is used in a high temperature environment, which is particularly pertinent in the application of cutting tools, in which the machining temperature can be up to 1200K. It has been found by Bondarenko et al. [85] that chemical and thermal wear frequently appeared in high speed machining due to high temperatures of more than 970K [85]. The transformation of the diamond to graphite decreases the strength of the structure and increases tool wear; as a result, it has a negative impact on tool life.

To understand the thermal damage development process, removal mechanism information is required. The scarcity of information on this removal mechanism is a challenge to explore. In a study, Olsen et al. [32] reported that the PCD diamond grains are lost from the surface due to the preferential erosion of the highly conductive cobalt network. On the other hand, Kozak [86] believed that the cobalt binders are fractured due to the thermal stress developed by the process caused by the diamond grain dislocation. Zhang et al. [56], however, believed that the effect of
high temperature plasma would not only be to melt the cobalt metal but also graphitize the diamond grain. The graphite consequently dissolves into the molten cobalt before being flushed away by the dielectric. These studies show the variation of information on the mechanism, which thus requires a better explanation.

2.3. Conclusion

Current achievements and findings of the PCD EDM have been discussed. Major discoveries have been made on the surface roughness and material removal rate. It was found that the surface graphitization happened due to EDM. But this is not well explained. As yet there is no research undertaken explicitly to quantify thermal damage caused by the high plasma temperature. Until now, the thermal damage has not been well explained, together with undefined control methods. Theoretical approaches should be developed to estimate the degree of thermal damage on the surface.

Residual stress was reported to have significant effects on surface strength degradation. The residual stress in PCD bulk has been reported as a result of the High Pressure High Temperature (HPHT) process in sintering. However, no discovery was reported on the effect of EDM plasma thermal stress to surface strength alteration. It is well known that residual stress in the machining process promotes cracks, weakens diamond grain boundaries and leads to unpredicted tool failure. Unlike EDM of metallic materials, the theories about residual stress caused by the EDG process are not well-established. The mathematical relationship between thermal damage and controllable machining parameters has been unclear.

This review shows the gaps in current knowledge. Therefore, the research findings obtained in this research can be considered a contribution to current scientific understanding.
Chapter 3 Experiment Procedure and Method of Analysis

3.1. Introduction

Electric discharge grinding (EDG), a variation of electric discharge machining, has proven to be an effective process to manufacture PCD tools in industry. This chapter provides the basic description of the EDG process used. However, details of experimental parameters and setup will be described later in as the investigation proceeds. Comparison between X-ray diffraction (XRD) and Raman spectroscopy capability to analyse the material properties of PCD due to the erosion process is also presented in this chapter.

3.2. Electrical Discharge Grinding Process

A commercially available RX7 EDG machine was used in this study (Figure 18). In this process, PCD with different grades were machined through plasma erosion generated by the sparking process. As illustrated in Figure 19, the sparks are generated by the pulse generator and happen in small sparking gaps of between 15µm to 20µm. During erosion, the dielectric (hydrocarbon oil) was flushed into the gap to provide better disruptive strength. In fact, hydrocarbon oil increases spark frequency through quick deionization. Combined with the rotating electrode process, higher debris removal efficiency can be expected. In addition, the dielectric was supplied as a cooling system to quickly lower the temperature at the erosion surface during the spark interval.
Figure 18: RX7 EDG machine

Figure 19: Schematic of the EDG process

Figure 20 illustrates several phases of electrical discharge in EDM [87]. Although the erosion only occurred during the discharge phase (pulse on-time duration), the other phase will indirectly influence the total energy obtained by the spark. It is known that the duration of pulse off-time (pulse interval) will define the sparking
frequency of the process: the shorter the pulse off-duration, the higher the sparking frequency. However, there is no guarantee of a higher erosion rate of the process. An insufficient pulse interval will result in incomplete ionisation of the dielectric. This will consequently result in premature sparking (referred to as “arcing”). Arcing was categorised as an unused pulse, since it will not contribute to material removal. Indeed, it will increase the energy losses of the process [88]. The pulse interval should also be long enough to provide an efficient flushing condition. Efficient flushing is important, since debris congestion in the gap will cause spark intervention. In fact, it was found that the increase in the PCD erosion residue reduced the number of active pulses [88]. On the other hand, increases in the pulse interval will result in higher sparking energy. During the pulse duration (pulse on-time), the plasma is generated and results in sudden increase in the discharge current. The high pressure plasma will be sustained in this period of time before collapsing as the electricity is cut-off by the generator. It consequently causes violent ejection of the erosion residue [87].

Figure 20: Discharge phases in EDM [87]
In this study, a tungsten-copper wheel that is used commercially to erode PCD was selected. The polarity of the electrodes (wheel and PCD) is interchangeable; different polarities were used at different stages of the investigation.

The pulse generator shown in Figure 21a was used in this research. The generator is able to produce open voltage of up to 150V; the current is programmable with the resolution of 1A; and there is a minimum pulse duration (on-time) and pulse interval (off-time) of 1 µs. Different combination of erosion parameters produces different heat energy. The heat energy that transferred to the PCD surface in certain rate generates high temperature that is responsible for removal process. The current and voltage generated by the erosion were examined by the feedback system that was part of the machine. The data acquisition system Figure 21b was responsible for retracting the current and voltage profile of the spark with a maximum data resolution of 10 MHz, which enables the data measurement of 10 times for every microsecond. The data was stored in the high performance data storage system before transfer into the computer for the analysis. The voltage and current signals obtained were used for heat flux calculation, as will be described in detail in Chapter 6 of this thesis. This was then used to determine the temperature distribution under the eroded surface.
3.3. Raman analysis

Diamond is a structure of carbon atoms arranged in a three-dimensional crystal structure with extremely strong and stable bonding. To analyse the quality of the machined surface of PCD, a suitable method is required that can distinguish between diamond and other carbon allotropes. Raman spectroscopic analysis is a simple and non-destructive method that can be implemented to determine the existence of specific carbon crystal structures [89]. Raman spectroscopy is a device developed to observe the Raman Effect, particularly in solid materials and liquids. The Raman Effect can be defined as the vibration frequency of the chemical bonding as a response to the laser incident.

Different chemical bonding produces different vibration frequency, known as the Raman wave number, as a footprint for the specific bonding structure. Several
studies show that the formation of peak bands on a specific range of wave numbers distinguishes between several carbon allotropes and structures \([6, 83, 90]\). The five main types of the structure are clearly summarized in Table 3. The main carbon structures can be categorized as graphite, amorphous carbon, diamond and hexagonal diamond \([83]\).

**Table 3:** Peak band centre for the Raman analysis as carbon lattice structure identification \([6, 83, 90]\)

<table>
<thead>
<tr>
<th>Crystalline Form</th>
<th>Carbon Structure</th>
<th>Wave number (cm(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{Sp}^2)</td>
<td>Graphite</td>
<td>((1575) to (1597))]([6, 83, 91])</td>
</tr>
<tr>
<td></td>
<td>Polycrystalline Graphite</td>
<td>1355 ([91])</td>
</tr>
<tr>
<td></td>
<td>Hexagonal diamond ([83])</td>
<td>((1311) to (1359))] ([83])</td>
</tr>
<tr>
<td></td>
<td>Amorphous carbon (mixture (\text{sp}^2) and (\text{sp}^3) bonded carbon) ([89])</td>
<td>1334 ([6])</td>
</tr>
<tr>
<td>(\text{Sp}^3)</td>
<td>Diamond (cubic diamond)</td>
<td>1332 ([83, 89, 90, 92])</td>
</tr>
</tbody>
</table>

As an illustration of the method, Figure 22 shows the graphical representation of Raman spectra result obtained by Wang et al. \([6]\) in determining the material composition of adhered material on their electrode before and after it has been used in negative polarity EDM of PCD. The result indicates that the major proportion of plated material comprises both amorphous carbon and graphite. In another investigation, Zhang et al. \([56]\) revealed diamond conversion after micro-EDM of PCD. Although a very low discharge energy was used (a sparking temperature of 5700K), Raman spectroscopic inspection on PCD material after micro-EDM process indicated values of 1580\(\text{cm}^{-1}\) and 1350\(\text{cm}^{-1}\) Raman shift \([56]\), indicating the formation of graphite and hexagonal diamond, respectively.
Implementing Raman analysis will not only give information on the formation of specific crystalline structure, but the spectrum obtained can be used for the residual stress calculation. The following is the basic equation used in the calculation:

\[ \sigma = \frac{(\nu_s - \nu_r)}{\chi} \]  \hspace{1cm} (3.1)

where \( \sigma \) is the compression residual stress (GPa), \( \nu_s \) is Raman shift value for diamond (cm\(^{-1}\)), \( \nu_r \) is the unstressed Raman value (cm\(^{-1}\)), and \( \chi \) is the pressure coefficient. Using the diamond anvil high pressure cell, the \( \chi \) value is determined by previous researchers. Catledge et al. [68] stated that the \( \chi \) value of 1.62 cm\(^{-1}\)GPa\(^{-1}\) should be used for PCD with a high diamond fraction (more than 96%). For PCD with a higher cobalt fraction, the hydrostatic stress approximation is reasonable to apply. This mandates the use of a 2.88 cm\(^{-1}\)GPa\(^{-1}\) \( \chi \) value for the calculation.

Unstressed diamond particles, as shown in Figure 23, have been used to determine the \( \nu_r \) value to be used in the stress calculation. Through the Raman analysis by a
Chapter 3. Experimental Procedure and Method of Analysis

Perkin Elmer Spectrum Raman Station 400 equipped with a 785nm laser wavelength, the value of 1330cm$^{-1}$ has been obtained.

![SEM image of 10µm synthetic diamond particles.](image1)

**Figure 23:** SEM image of 10µm synthetic diamond particles.

![Raman spectra of the unstressed diamond grains](image2)

**Figure 24:** Raman spectra of the unstressed diamond grains.
3.4. XRD Analysis

Different from the laser emission used in Raman analysis, an x-ray beam is applied in XRD analysis. Specific crystalline phase structures were identified based on the degree of beam reflection. Similar to the Raman analysis, the method is non-destructive and no sample preparation is required.

A crystal structure is a combination of unit cells. The unit cell can be a single atom or atoms arranged together in three-dimensional arrangement. The atoms are arranged in regular atomic distance, \( d \), and the value is non-identical for different crystal phases. Due to this special characteristic, the atomic distance was used in XRD to identify specific crystal phases in the measured volume.

In XRD, the atomic distance is measured according to Bragg’s law:

\[ n\lambda_c = 2d \sin \theta_c \]  

(3.2)

where the \( n \), \( \lambda_c \), and \( \theta_c \) are the integer, X-ray wavelength, and the diffracted beam angle, respectively. When the X-ray beam focuses on the solid structure with a certain incidence angle, the beam will penetrate to a certain depth before being diffracted to a certain angle. Using equation 3.2, the diffracted angle will then be used for the atomic distance calculation. The crystal phase is identified by comparing the value of the atomic distance obtained with the available known standard.

In addition to the crystalline phase identification, XRD also provides information on the residual stress under the surface. It was found that the increase in atomic distance results in a corresponding change in the increase of the structure strain. The relationship between the strain and the atomic distance is explained by the following general equation:

\[ \varepsilon = \frac{d_{\text{final}} - d_{\text{initial}}}{d_{\text{initial}}} \]  

(3.3)
where $\varepsilon$, $d_{hkl}$, $d_o$ are the strain, lattice spacing of the measured volume and lattice spacing of unstress or original structure, respectively. Using Hooke’s law, the relationship between strain and stress, $\sigma$ could be defined as follows:

$$\sigma = E \varepsilon$$

(3.4)

where $E$ is the elastic modulus of the material. However, the stress under the surface may not be represented only by this single equation. Using this fundamental understanding, several methods have been developed for average stress evaluation. These include the $\text{Sin}^2 \Psi$ method, single angle, two angles, and the Mi~rion-Cohen methods [93]. Of these techniques, the $\text{Sin}^2 \Psi$ method is the most popular method and is implemented by many researchers for stress analysis of diamond-related material [94]. Using this method, the value of atomic distance must be collected at various tilt angles, $\Psi$. As the next step, the calculated atomic distance is plotted in the $\text{Sin}^2 \Psi$ function. The following relation is then used:

$$\frac{d\Psi - d_o}{d_o} = \frac{1 + \nu}{E \sigma_{\text{total}}} \text{Sin}^2 \Psi$$

(3.5)

where $d\Psi$ is the atomic distance at $\Psi$. Rearranging equation 3.5, the stress can be calculated by the following simplified equation:

$$\sigma_{\text{total}} = \left( \frac{E}{1 + \nu} \right) m$$

(3.6)

where $m$ is the slope of the $d$ vs. the $\text{Sin}^2 \Psi$ plotted graph.
3.5. **XRD vs. Raman analysis in Residual Stress and Graphitization Analysis**

The feasibility of using XRD and Raman analysis for residual stress analysis was studied through the literature. Table 4 shows several studies related to PCD residual stress analysis.

**Table 4: Overview of selected literatures**

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Details</th>
<th>Method of analysis</th>
<th>Finding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erasmus et al. [8]</td>
<td>Studied the stress in PCD caused by lapping and annealing process.</td>
<td>Raman</td>
<td>Full width half maximum (FWHM) of the Raman spectrum can be used for the indication of the “crystal disorder”</td>
</tr>
<tr>
<td>Ferreira et al. [94]</td>
<td>Studied the diamond film surface stress induced by doped boron.</td>
<td>Raman and XRD</td>
<td>A more reasonable stress result was obtained by Raman analysis. High penetration depth (~600µm) is the disadvantage of XRD.</td>
</tr>
<tr>
<td>Yingfei et al. [95]</td>
<td>Analysed the wear pattern and its mechanisms for diamond tools during the ultra-precision turning of composite material.</td>
<td>Raman and XRD</td>
<td>XRD analysis did not detect the availability of graphite on the diffusive abrasive worn surface. Raman analysis was considered a more sensible method to detect graphite on the worn surface of the tool.</td>
</tr>
<tr>
<td>Shane et al. [68]</td>
<td>Studied the stress in three layers of PCD that sintered with different diamond grain size.</td>
<td>Raman</td>
<td>Micro-Raman spectroscopy was believed a method able to measure the stress in PCD with</td>
</tr>
</tbody>
</table>
Both methods use a specific source of light to penetrate into the surface, in order to obtain the structural information. Since the signal collected is the average information collected from its penetration path, the light penetration depth is a major concern. As stated by Ferreira et al. [94], the penetration depth of X-rays through diamond can be up to 600µm, which is far deeper than the depth of interest (HAZ thickness is expected to be about 30µm to 60µm, as theorized in Chapter 6 of this thesis). Deeper penetration depth will cause interference of the information from the unaffected region on the result obtained. The Raman laser has better penetration depth relative to HAZ thickness. Erasmus et al. [8] and Ferreira et al. [97] state that the penetration depth of the Raman laser is less than 10µm, where the value is dependent on the laser wavelength used.

The probe size of the Raman laser is also reported to be smaller than the X-ray beam diameter typically use in XRD. Raman Spectra with a 785nm laser wavelength for the Perkin Elmer Spectrum Raman Station 400 produces a 100µm laser spot diameter. The CuKα X-ray source used in the XRD Bruker GADDS (General Area Detector Diffraction System) produces an approximately 500µm laser beam for surface measurement. Since the interest area is the area across the thickness of approximately 1mm (the thickness the of PCD layer), the smaller probe size is to be preferred.

Furthermore, the Raman laser is known to be highly sensitive to amorphous carbon. Hence, a clear pattern of the amorphous carbon spectrum can be obtained. Since the
amorphous carbon is a non-crystalline structure, clear amorphous diffraction patterns cannot be formed in XRD.

3.6. Conclusion

The basic procedure in the EDG process of PCD was demonstrated and its basic principle understanding was discussed. Several analysis systems, such as the data acquisition equipment, the Raman spectra analyser, and the XRD system were also discussed. Through the literature, it was found that the Raman method was the best method for the HAZ analysis of PCD. The small laser spot size of diameter of 100µm and reasonably small penetration depth of less than 10µm will provide better measurement accuracy than XRD. Raman analysis is also regarded as a very sensible method that is able to detect amorphous carbon structure. For this reason, Raman equipment was selected as the main facility for the carbon structure analysis of PCD.
Chapter 4 Investigation on the Effect of Electrode Polarity

4.1. Introduction

Negative polarity is normally used in EDM of conventional material [40]. The theory behind the application is that, in negative polarity, the electron flows from the negative electrode (EDM tool) to the positive electrode (material being eroded) [64]. The positive ions at the same time move in an inverse direction but with much lower acceleration than electrons, since the electron is much lighter. This makes the erosion on the positive electrode more dominant [40]. However, during the roughing operation with long pulse duration, the effect on ion acceleration becomes significant due to the increase of positive ions proportion [40]. Furthermore, ions that are heavier than electrons are believed to have a higher momentum when they collide with the work piece surface, and hence increase the material removal rate (MRR). For these reasons, positive polarity is known to be a suitable method for EDM roughing of PCD. However, to date information on the effects of polarity at low energy level or in finishing machining by electrical discharge grinding (EDG) process has been inadequate. In this subchapter, the discussion focusses on the surface morphology and elemental distribution of PCD surface, and its material removal rate caused by differences in finishing polarity.

Part of this chapter has been used in the following publications:
4.2. Experimental Procedure

The preliminary experiment was conducted by eroding the PCD tools with 10μm grain size of industrial diamond using the EDG process. The roughing process for every sample was done using positive wheel polarity, as suggested by many researchers. With a very small sparking energy, as shown in Table 5, two batches of PCD tools, identified as batch “A” and “B”, have been eroded with negative and positive polarity, respectively.

<table>
<thead>
<tr>
<th>Batch</th>
<th>Wheel Polarity</th>
<th>Finishing Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Current (A)</td>
</tr>
<tr>
<td>A</td>
<td>Negative</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>Positive</td>
<td></td>
</tr>
</tbody>
</table>

Every sample was prepared with similar machining conditions to ensure the repeatability of the process. Every sample was cleaned by an ultrasonic cleaning machine with ethanol and acetone as the cleaning solution. In this preliminary experiment, a porous surface was produced by the positive polarity of the finishing process, which is believed to be caused by the spark concentration phenomenon, for which the reason has yet to be uncovered.

The author believed that the carbon plating as discussed in several studies would be the best reason to explain the phenomenon. Unlike electrode carbon plating, an additional layer of carbon on the PCD surface will not contribute to better heat
conductivity. Better electrical conductivity of the carbon in comparison with the
diamond grains is expected to give an advantage to the process, as will be discussed
later. Instead, there is a probability of impeding the spark concentration when carbon
plating occurs on the PCD surface; improvement in material removal rate can be
expected. However, the availability of the plating phenomenon to occur in this
efficient flushing process remains in question.

Further investigation was conducted by implementing a series of erosions to further
explore the effect of polarity. In this case, the material removal rate was added as the
additional output in this investigation. PCD insert tools with different grades were
used in this subsequent investigation. Table 6 shows the types of PCD used and their
composition properties. Similar to what was previously used in the preliminary
experiment, two stages of EDG erosion (roughing and finishing) were used as the
machining strategy. The roughing procedure was purposely done to obtain a flat
surface before the finishing process was undertaken sequentially. The machining
parameters are shown in Table 7.

**Table 6: Properties of PCD [98-100]**

<table>
<thead>
<tr>
<th>PCD Types</th>
<th>PCD Grain Size (µm)</th>
<th>Diamond Fraction (Vol %)</th>
<th>Cobalt Fraction (Vol %)</th>
<th>PCD to WC layer thickness ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTX002</td>
<td>2</td>
<td>84.8</td>
<td>15.2</td>
<td>0.13</td>
</tr>
<tr>
<td>CTB010</td>
<td>10</td>
<td>89.7</td>
<td>10.3</td>
<td>0.13</td>
</tr>
<tr>
<td>CTM302</td>
<td>2-30</td>
<td>91.4</td>
<td>8.6</td>
<td>0.18</td>
</tr>
</tbody>
</table>

**Table 7: EDG machining parameters**

<table>
<thead>
<tr>
<th>Operation</th>
<th>Open-Voltage (V)</th>
<th>Wheel rotation speed (rpm)</th>
<th>Current (A)</th>
<th>On-time (µs)</th>
<th>Off-time (µs)</th>
<th>In-feed (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roughing</td>
<td>120</td>
<td>250</td>
<td>12</td>
<td>40</td>
<td>20</td>
<td>0.5</td>
</tr>
<tr>
<td>Finishing</td>
<td></td>
<td></td>
<td>1, 3</td>
<td>1</td>
<td>4</td>
<td>0.04</td>
</tr>
</tbody>
</table>
PCD with a total cross-sectional area of $23\text{mm}^2$ (7.2mm PCD width and 3.18mm total thickness) was divided into four regions, as shown in Figure 25. In this EDG process, a commercially available tungsten-copper wheel with a diameter of 150 mm acted as the tool electrode and hydrocarbon oil was used as the dielectric. The tool positioning information was used to define the erosion level of PCD. With the high-resolution encoder, the EDM gap control system can achieve a precise position of 0.1µm. As shown in Figure 26, the adaptive scheme of the process was implemented to adjust the feed rate of PCD to match the erosion rate. The machining time was taken when the process started to erode the specific region to a 5µm depth. This continuous erosion enabled the precise interpretation of material erosion rate of PCD with respect to erosion depth.
Figure 25: Experimental setup and procedure
Figure 26: Block diagram of the EDM gap control system
By referring to the feeding movement of the PCD, the following equation can be used to calculate the material erosion rate of the process:

\[ \dot{m} = \dot{s}A \]  

(4.1)

where \( \dot{m} \), \( \dot{s} \), and \( A \) are the volume erosion rate (mm\(^3\)/s), feed rate, and work piece cross-sectional area, respectively. By considering the constant cross-section applied, the feed rate is proportional to the material erosion rate of the process, thus justifying the use of the feed rate as the material erosion rate indication.

### 4.3. Result and Discussion

#### 4.3.1. Morphological Analysis

Figure 28 illustrates the secondary electron (SE) image of the PCD surface with different finishing process polarity.

*Figure 27: Surface produced by finishing operation. (a) Negative polarity. (b) Positive polarity.*
Chapter 4. The Effect of Electrode Polarity

Figure 28: Close up view of the surfaces produced. (a) Negative polarity. (b) Positive polarity.

Figure 29: EDX surface mapping

Due to the polarity effect, two different surface structures were produced (Figure 27 and Figure 28). The images show that a porous surface was produced by the positive polarity of the finishing process. EDX surface mapping analysis in Figure 29 indicates that the top structure formed on the positive polarity surface dominated by the carbon element represents diamond, as will be proved later by the Raman analysis.
Although an even surface (non-porous) surface was produced by the EDG with negative polarity, EDX line mapping (Figure 30a) indicates uneven distribution of the carbon element on the surface. The carbon composition reduces at approximately every 10µm scanning length, similar to the size of the PCD grains. The reduction of the carbon elements indicates the location of the diamond grain boundary of the PCD. Obviously, the cobalt percentage increases on the boundary region, compensating for the carbon reduction. Interestingly, this finding shows that selective erosion does not happen during negative polarity erosion. Since the cobalt surface at the grain boundary region is on the same level as the diamond grain surface, there is no evidence that the sparking only happened on the more electrical-conductive cobalt region. In the other case, Figure 30b shows that the percentage of carbon reduces while scanning towards the pores created by the positive polarity. In this region, oxygen, tungsten and cobalt percentages dominate with up to 40% of the total elemental composition. A higher percentage of the oxygen element is believed to be an indication of a higher percentage of recast oxidised material on the surface.

The formation of this oxidised material has been proven by the compound analysis of XRD implemented on the eroded surface, as shown in Figure 31. Cobalt oxide (CoO) compound was detected on PCD eroded by both erosion polarities. As stated by Chen [101], the catalyst metal will oxidise during the oxidation process of carbon. The oxidation reaction of diamond during the erosion that is also known as graphitization will result in the production of carbon monoxide (CO), carbon dioxide (CO₂) and cobalt oxide (CoO), through the following reaction:

\[
\begin{align*}
C + \frac{1}{2}O_2 &= CO \\
C + O_2 &= CO_2 \\
Co + \frac{1}{2}O_2 &= CoO
\end{align*}
\]  

The availability of the WC and W₂C on the surface was believed to be due to the deposition of the metallic debris of the WC backing that was simultaneously eroded.
Figure 30: Elemental composition (a) Negative polarity, (b) Positive polarity
Figure 31: XRD analysis of the surface eroded with different polarities (a) Negative polarity, (b) Positive polarity
Chapter 4. The Effect of Electrode Polarity

Raman analysis with 14-point line mapping was executed across a pore on the positive polarity surface (Figure 29). Formation of Raman peak at around ~1332cm\(^{-1}\) (D peak) and ~1580cm\(^{-1}\) (G peak) were evidence of the availability of diamond and graphite, respectively [102]. Relative comparison of the graphite composition was undertaken between the peaks (Points 1 and 14) and a pore (Points 7 and 8) structure. Since the Raman intensity is a composition-dependent response for a specific functional group, a higher G peak intensity of normalised Raman scanned on the pore indicates a higher percentage of graphite structure. As shown in Figure 32a, there is also a difference in Raman shift for the D peak between the PCD surface eroded by positive and negative polarity which has been observed

Full-width half-maximum (FWHM) can be obtained by measuring the width of the Raman band of half-maximum intensity value (Figure 32b). In this case, the Raman bands at intensity value of 50 have been measured. As stated by Erasmus et al. [8], larger FWHM indicates higher micro defects formed by the process. Broader FWHM while scanning towards the pores also indicates a higher degree of crystal disorder, as well as plastic deformation on that area. Also, the FWHM of the Raman spectrum was observed to be close to the FWHM value of the PCD surface eroded by the negative polarity when the Raman laser is focussed accurately on the centre of a pore (Points 6 and 7). Higher defect density of that region relative to the top surface is believed to be due to the higher energy applied by the concentrated sparks.
The author theorised that the carbon plating happens on the positive electrode during positive polarity erosion. At the same time, sparking is happening in the PCD cobalt region due to better electrical conductivity than with the diamond grains. As a result, only the non-conductive diamond grains are left on the surface. The cobalt will melt and evaporate, while the diamond-to-diamond bonding retains the grains’ position in a skeleton shape, thus leading it to have a porous-look surface.
Conversely, since the PCD electrode is located at the positive electrode during negative polarity, the carbon is deposited on the PCD surface, referred as the “black layer”. The availability of this black layer, as illustrated in Figure 33, will avoid the selective erosion phenomenon and enable the heat to be distributed evenly on the surface, consequently resulting in a smooth eroded surface. During the heating process, the protruded diamond grains underneath the black layer undergo graphitization. Some portion of graphite dissolves into the molten cobalt before being flushed away by the dielectric. The other portion is solidified, thickening the black layer to some extent. The process is repeated until the maximum thickness is achieved. Unlike in positive polarity, up to 15% cobalt was found to be deposited on the diamond top surface after erosion with the negative polarity (as previously illustrated in Figure 30).

![Diagram](https://via.placeholder.com/150)

**Figure 33**: Illustration of the black layer assisted erosion theory

### 4.3.2. Material Removal Rate

PCD undergoes erosion by ions in positive polarity and by electrons in negative polarity EDG. In negative polarity, the electrons that bombard the PCD create thermal erosion energy during collision [64]. This electron bombardment happens at the higher frequency than the ion bombardment that happens in positive polarity EDG with similar finishing parameters. The theory thus explains the reason for a higher erosion rate in negative polarity implemented in this study. Figure 34 and
Figure 35 show the feed rate (representing erosion rate) obtained by different PCD grades used. 

In this study, a 1A current for positive polarity machining was found unable to erode PCD, even for the smallest PCD grade used. The erosion only happened to a few microns depth before the system was stopped from feeding forward the work piece toward the wheel. The phenomenon was repeatable, and was consistent with what was caused by the eroded surface morphology of PCD, as will be discussed later. Nevertheless, using a 3A current, the erosion was successful and that erosion rate is shown in Figure 34. The reduction in erosion rate for positive polarity presumes that it represents the normal erosion behaviour. In particular for the first 10µm erosion (region A), the process should be faster in removing only a smaller volume of rough residue surface left by the roughing operation (Figure 36).

![Figure 34: Material erosion rate of different PCD types (positive polarity)](image-url)
Figure 35: Material erosion rate of different PCD types (negative polarity)
Figure 36: Residue surface left by the roughing surface: (a) SEM image (CTB010), (b) Surface profile (CTX002), (c) Surface profile (CTB010), (d) Surface profile (CTM302)

The graph constructed for negative polarity (Figure 35) represents a surprising inverse trend. Considering the hardest to erode PCD (CTM302), the erosion rate was found to fit well the one phase decay exponential line pattern shown in Figure 37.
Chapter 4. The Effect of Electrode Polarity

Figure 37: Non-linear regression line fitting

The non-linear line trend indicates the increase in the material erosion rate, where up to a 250% improvement was recorded. Increase in the material erosion rate at a higher in-feed location shows the influence of the carbon plating on the surface. In fact, the erosion of the subsequent region was faster than the erosion of the earlier 10\(\mu\)m erosion depth (Region A). As theorized, it was found that the deposition of migrated material so-called black layer (as mentioned in Section 4.3.1) on the PCD surface increased with longer machining time implemented, which is proportional to the machining depth. Figure 38 shows the deposition of the black layer in this continuous erosion process for diamond grain size of 2–30\(\mu\)m. It revealed that that the thicker the black layer formed, the higher the process removal rate. A SEM image of the black layer is shown in Figure 39.

As reported by a study [103], there are two kinds of residue generally obtained by the EDM process of PCD (diamond particle and deposited metallic film, particularly on the positive electrode). In die sinking EDM without flushing, Pisarcius [88] found that these residues congested in the gap, and thus the number of inactive pulses (short circuit and arcing) increased towards deeper surface removal. The energy losses increased due to the intervention spark phenomenon. Thus, the productivity of the process was reduced. However, since the dielectric flushing and rotating wheel were
implemented in this study, more efficient flushing ability can be expected. This consequently lowered the probability of crystal congestion in the sparking gap.

**Figure 38:** The images of deposited material on the eroded surface of CTM302 PCD (obtained by the optical microscope with 100x magnification lens): (a) After 10µm finishing in-feed; (b) After 20µm finishing in-feed; (c) After 30µm finishing in-feed; (d) After 40µm finishing in-feed

**Figure 39:** SEM image of the black layer
For large diamond particle size in particular, an increase in machining efficiency can be explained by the increase in electrical conductivity of PCD through covering the surface of the work piece, including the exposed large diamond particles with conductive material. This enables the sparking to occur on the diamond surface, because it is covered by the conductive layer. In this case, the thermal energy would supplied to the diamond grain underneath and this facilitates the erosion process through the graphitization mechanism, as stated in another study [104].

As shown in Figure 40, the black layer comprises all PCD elements (cobalt (Co), carbon (C)) and other additional wheel elements (copper (Cu), tungsten (W) and calcium (Ca)). The electrode material that is electrically conductive was migrated to the work piece in the small discharge gap, and thus increased the electrical conductivity of the PCD. It was believed that the adhered carbon element came from the decomposed hydrocarbon dielectric and graphitization process of diamond particles.

![Figure 40: Elemental composition of the black layer](image)

(The image taken is perpendicular from the eroded surface)
This morphological finding also explains the phenomena of obstructed feeding while eroding with a small current in positive polarity. A few microns’ depth erosion that happens at the early finishing stage indicates the removal process of the highly graphitized residue surface that was left by the roughing process. After the completion of the residue structure removal, the skeleton porous structure is developed. At this point, a small current supplied is insufficient to provide enough energy for a spark to reach the high electrical-conductive cobalt region and thus it inhibits further erosion. At the same time, the electrode wheel is obstructed by the protruded grains from achieving a smaller enough gap for sparking.

4.4. Conclusion

In this study the following conclusions were reached:

a. Negative polarity produced better surface finish than positive polarity erosion, although similar parameters were used. Selective erosion occurred in positive polarity and caused the formation of a porous structure. It was believed that, due to the high momentum of the ion bombardment, together with the spark concentration, on cobalt, large holes were produced. This was supported by the higher percentage of graphite in the pores, together with the higher defect density structure. This indicates that higher energy was focused on that region and converted more diamond into graphite. In fact, Raman Analysis on the pore structure also shows that a higher degree of plastic deformation occurred in that region and was approximately the same as FWHM of the negative polarity eroded surface.

b. The morphological difference of PCD machined with positive and negative polarity was regarded as due to the electrical conductive film deposition phenomenon. In negative polarity, the availability of the conductive layer on the PCD surface eliminated the spark concentration in specific highly conductive regions, specifically for cobalt. The layer facilitated the graphitization process of the diamond grains underneath by a thorough and
even heating process of the surface and thus resulted in the formation of the smooth surface finish.

c. It was found that the black layer is constituted by the wheel elements and migration carbon collected by the degeneration of the dielectric fluid and graphitization during the sparking process. Because of the high conductivity of the dominated elements, this layer is electrically conductive. The formation of a thicker conductive black layer resulted in a significant increase in machining efficiency: an increase of erosion rate of 250% was achieved with the increase of black layer thickness.
Chapter 5 Investigation on the Effect of Wheel Rotation Direction

5.1. Introduction

This chapter discusses the investigation of the effect of wheel rotation direction on the sharpness, geometrical accuracy and quality of the cutting tools produced. It proved that the debris that flowed toward the cutting edge could significantly affect the edge sharpness and symmetry of the tool, which were critical for the smaller edge apex angle. Interestingly, the investigation answered the unexplained phenomenon associated with the undercut that normally formed beneath the PCD cutting edge after erosion, as mentioned in Chapter 1.

In the EDM process, it is well known that the quality of the work piece is affected by many factors such as pulse on/off-time, voltage, current and the quality of pulses. However, in the Electrical Discharge Grinding (EDG) process, in addition to these factors, the quality of the work piece is also affected by the status of the wheel: surface roughness, rotating speed, rotating direction and the polarity of the wheel. These factors play important roles in determining the roughness of the eroded surfaces. Thoe et al. [1] studied the effect of EDG sparking strategies (periphery and face sparking) to the edge and surface finish of the machined PCD blanks. They believed that the worse surface finish of the PCD eroded by the face sparking was due to the poor finish condition of the wheel after dressing. Pei et al. [105] studied the surface finish of the PCD eroded by the periphery sparking. They further explored the effect of wheel speed on the surface roughness of the eroded PCD and found that the roughness decreased with the increase of wheel speed.
Chapter 5. Investigation on the Effect of Wheel Rotation Direction

A research on diamond grinding assisted by EDM was reported by Koshy et al. [106, 107]. Although different in the work piece removal mechanism, they applied a similar working principle of the rotating electrode. In their study, they found that the grinding role decreases and the machined surfaces were more influenced by the EDM, when the applied current exceeded the specific threshold. They also investigated the influence of current, pulse on-time and wheel speed on the material removal rate (MRR) and grinding force. However, the rotating directions of the wheel in EDG machining of PCD material has not as yet been discussed in detail by any researcher. The effects of the rotating direction on the edge sharpness and the surface quality of PCD tools remain unknown.

Since the rotating electrode generates centrifugal forces [35, 36], the flow direction of debris can therefore change with the change of wheel rotation direction. The flow direction, accumulation and clearance of debris in the dielectric can affect the efficiency and stability of the EDG process. This chapter discusses the effect of moving debris on the PCD surface quality, in addition to the edge quality produced by the process. A series of experiments were conducted to analyse the effects of wheel rotation on the quality of PCD tools; these included the symmetry and edge sharpness. Results of the effect of wheel rotation direction, as well as the moving debris direction, are presented. By examining PCD samples with a Scanning Electron Microscope (SEM) and Raman spectroscopy, the formation of the heat-affected layer caused by the high temperature erosion process in the EDG was analysed. It proved that the wheel rotation direction was an important factor to be controlled during the PCD tools fabrication process using EDG. Moreover, this investigation revealed the unexplained phenomenon associated with the undercut that usually formed beneath the PCD cutting edge, which was found by Pisarciuc [103].

Many studies have been conducted in the PCD EDM field in past decades. However, the issues of PCD thermal damage and its quantification technique are as yet not well understood. Industries are now seeking the most economical method to measure the quality of PCD tools. Since the WC backing surface and PCD surface are eroded simultaneously, in some perspectives, poor surface finish of the WC would indicate a
high level of thermal damage of PCD. Because of this issue, the surface finish of the WC is an industrial concern and thus also becomes a subject of interest in this investigation.

**Part of this chapter has been used in the following publication:**
M. Zulafif Rahim, Songlin Ding, and John Mo, Electrical Discharge Grinding of Polycrystalline Diamond – Effect of Wheel Rotation. *Machining Science and Technology an International Journal*, 2014 – Accepted for publication

### 5.2. Equipment and Methodology

PCD (CTB 010) strips with widths of 4.6 mm made by Element Six with the average grain size of 10 µm were used in this research. The two-stage machining process, which included roughing and finishing with 0.25 and 0.03mm in-feed distance respectively, was implemented. The roughing process was done as a standard procedure to achieve the desired edge shape with a high removal rate. The 0.03 mm finishing in-feed is enough to guarantee the smoothness of the surface and to achieve the desired tool sharpness. Table 8 shows the erosion parameters used in the process. Results obtained were mainly associated with the wheel rotation speed of 250 rpm (about 2 m/s), selected based on the optimum speed for the highest material removal rate found by a pilot study, as shown in Figure 41

**Table 8: EDG parameters for specimen preparation**

<table>
<thead>
<tr>
<th>Operation</th>
<th>Voltage (V)</th>
<th>Current (A)</th>
<th>Off-time (µs)</th>
<th>On-time (µs)</th>
<th>In-feed (mm)</th>
<th>Wheel rotation speed (rpm)</th>
<th>Polarity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roughing</td>
<td>120</td>
<td>12</td>
<td>20</td>
<td>40</td>
<td>0.25</td>
<td>250</td>
<td>Positive</td>
</tr>
<tr>
<td>Finishing</td>
<td>120</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.03</td>
<td>250</td>
<td>Negative</td>
</tr>
</tbody>
</table>
In this EDG process, a tungsten-copper wheel with a diameter of 150mm acted as the anode for the roughing operation but was changed to the cathode in the finishing stage. In negative polarity, the electron flows from the negative electrode (wheel electrode) to the positive electrode (material being eroded) [64]. The positive ions at the same time move in the inverse direction but with much lower acceleration than electrons, since the electron is much lighter [106]. Due to the higher kinetic energy of the electron, they collide earlier with the anode and convert their kinetic energy into heat before the ions reach the other electrode [106]. This makes the erosion on the positive electrode more dominant. However, during the roughing operation with long pulse duration, the effect on ion acceleration becomes significant due to the increase of its kinetic energy and proportion [40, 108]. As was found by Koshy et al. [106], who implemented the same concept as EDM with a rotating electrode, the longer the pulse duration used, the higher the erosion rate of the cathode electrode. For these reasons, positive polarity is known as a suitable method for EDG roughing of PCD, as reported by Ding et al. [109]. Hydrocarbon oil was the dielectric used in the process to be flushed into the gaps while the wheel was rotating. In the analysis, the position of dielectric pipes is fixed in all experiments to ensure the repeatability of the process. Two different wheel rotation directions were implemented, as shown in Figure 42. Figure 42a, Figure 42b and Figure 42c show the implementation of
counter-clockwise (ccw) wheel direction, clockwise (cw) wheel direction and the actual EDG process, respectively.

Figure 42: Experimental methodology (wheel direction): (a) Counter-clockwise (ccw), (b) Clockwise (cw), (c) Actual EDG process

Three different edge apex angles $\theta$, of 50°, 70° and 90°, as illustrated in Figure 43a, were eroded using an EDG machine. These three different apex angles were purposely designed to facilitate the observation of the effects of changing edge geometries. Figure 43b and Figure 43c show the samples of the PCD strip before and after the erosion process, respectively. Before the measurement, the prepared samples were ultrasonically cleaned using ethanol and then acetone to remove any contamination on the surface.
The Alicona (IF-EdgeMaster) optical measuring device (microscope) with a 50x magnifications lens was used (Figure 44a). 3D measurement data (Figure 44b) is obtained by this microscope, and IF-EdgeMaster software was used to automatically quantify the sharpness and roughness of the edge produced. For the tool sharpness analysis, several profile paths are extracted by the software from the 3D data, as illustrated in Figure 44c.

The degree of tool sharpness was defined by the sharpness parameter obtained from the path, as shown in Figure 45. Two straight lines are created by the software following the profile path with the most perfect direction. The intersection of these two lines is known as the apex point, which is the ideal geometry of the sharp tool. $Sa$ and $Sy$ are the distance between the apex and the point where the profile leaves the straight line: the smaller the value of these parameters, the better the tool sharpness. For the measurement of radius $r$, a circle is created, where the radius starts from the point where the profile leaves the straight line until a straight profile is obtained.

Additionally, the edge quality was also assessed in terms of its symmetry, $K$. The $K$ value can be calculated by dividing $Sy$ by $Sa$. SEM (FEI Quanta 200) was used as the analysis instrument to check the microstructure. Also, Raman spectra with a 785nm laser wavelength (Perkin Elmer Spectrum Raman Station 400) was used to analyse
different types of carbon formed on the surface. Additional analysis on the surface finish of the tools has also been undertaken to further explore the influence of wheel rotation direction.

Figure 44: Measurement method: (a) Alicona optical measuring device used in the experiment; (b) 3D image of the PCD edge obtained by Alicona; (c) Position of extracted profile paths for tool sharpness measurement

Figure 45: Definition of sharpness parameter.

5.3. Results and Discussion

Figure 46 shows the values of $Sa$ and $Sy$ obtained by the Alicona optical device. The error bars indicate the 95% confident interval of the results obtained. It is clear that, for both parameters, a higher value was obtained by a ccw wheel direction. Furthermore, it can be seen that there was a trend in values of $Sa$ and $Sy$ with the increase of the apex angle of edges. Additional analysis was done by measuring the
radius and degree of symmetry of the edges produced (Figure 47). It can be inferred that, rather than better sharpness, cw wheel rotation produces better edge symmetry and a smaller edge radius.

**Figure 46:** Comparison between Sa and Sy obtained by two different methods, which are WC to PCD (ccw wheel rotation) and PCD to WC (cw wheel rotation)
Better tool sharpness and a more symmetrical edge produced by cw wheel rotation were caused by the movement of the debris in a very small gap between electrodes (copper wheel and PCD work piece). The rotating wheel electrode would effectively drag dielectric into the gap. The debris formed by the erosion would move in the same direction as the wheel rotation. For ccw wheel rotation, the debris accumulated towards the edge while eroding from carbide to PCD. Furthermore, the carbide and graphite debris, which are electrically conductive, created a high conductivity bridge across the gap, thus facilitating the dielectric breakdown process. This caused the concentration of sparks or plasma in that region and thus generated the significant effect on the tool sharpness and symmetry.

The phenomenon can also be theoretically explained by the fluid flow under the moving electrode. As shown in Figure 48, the direction of the main flow is $x$, the direction normal to the moving plate is $y$, and $h$ is the gap between electrodes. Considering the non-slip condition, the fluid that is in contact with the electrode wheel experiences centrifugal force, and moves at the same velocity as the linear velocity of the wheel $V$. In this case, the following boundary condition applies:

**Figure 47:** Effect of wheel rotation on the edge radius and symmetry (1=symmetry)
\( v(x) = 0; \ y = 0 \)
\( v(x) = V; \ y = h \)

\[ (5.1) \]

The operating shear stress is linearly related to the velocity gradient, \( \tau \) and can be determined as:

\[ \tau = \kappa \left( \frac{dv}{dy} \right) \]

\[ (5.2) \]

where \( \kappa \) is the proportional coefficient which depends on the fluid viscosity. The fresh dielectric supplied to the WC surface ensures the unavailability of debris. Thus, the \( \kappa \) value can be defined as the dielectric viscosity constant of Newtonian fluids. Moreover, the fluid velocity, \( v(x) \) can be considered as varying linearly according to the \( h \) distance. However, the dielectric viscosity increases at a higher position of \( x \) due to the larger debris proportion. Thus, the fluid velocity reduces with respect to the viscosity value, \( V_1 > V_2 > V_3 \), which in result in increase in the probability of spark concentration.

![Figure 48: Schematic of fluid flow under a moving plate](image)

Moreover, as shown in Figure 49, a smooth surface was obtained by the PCD machined with the dielectric flowing away from the PCD edge. A porous surface caused by the uneven sparking on the eroded surface was observed. It proved that the
phenomenon of spark concentration occurred when the wheel rotated in a ccw direction.

![Figure 49: SEM image of the eroded surface using different wheel rotation direction: (a) ccw wheel rotation direction (300x magnification); (b) cw wheel direction (300x magnification); (c) ccw wheel direction (2000x magnifications); (d) cw wheel direction (2000x magnification); (e) Illustration of the spark concentration phenomenon.](image)

At areas of higher debris density, more severe damage to the edge occurred and resulted in the formation of undercut, as shown in Figure 50. This has been observed on most specimens machined by the ccw direction, but none was found with cw wheel direction. A similar undercut was also found previously by another study [103], but the mechanism of the formation of the undercut has not been investigated by any researcher to date.
The debris accumulation was one of the factors that contributed to the edge roughness of the PCD. Measurement of the arithmetic edge roughness (Ra) was done on all the samples. As results, Figure 51 and Figure 52 show the profile of roughness of one of the samples and the edge roughness, respectively. As expected, a ccw wheel direction produced worse edge roughness at approximately twice that of the cw wheel direction for 70 degrees and 90 degrees edge apex angles.
Figure 52: The roughness (Ra) of PCD edges measured by Alicona device

The results were also supported by the SEM images of the edges taken from the polished surface, as shown in Figure 53. Together in these images, a thin layer of up to a few microns was observed to appear beneath the eroded surface, with the thickest layer from the PCD sample of 50 degrees apex angle with 100µm thickness. The layer was found to be the same as the affected layer reported by Jia et al. [65]. The Raman Analysis (Figure 54) implemented on these two distinct regions revealed that the percentage of graphite was higher on the affected region. During the EDM process, the outer PCD surface that exposed to plasma will be eroded and flushed away. The inner surface with the lower energy than that required for erosion will remain in place. However, some portion of the diamond on the remaining surface is partially transformed into graphite due to the high temperature, and the affected layer is created. As was found by Chen et al. [83], PCD that is also categorised as Catalytic High Pressure High Temperature (HPHT) diamond transforms into several phases when the temperature reaches 2,000K. There will be a significant transformation in the EDG process, since the high temperature caused by sparks between the electrode and work piece, known as the plasma temperature, rises to 12,000K, even when the pulse durations are very short [64].
Chapter 5. Investigation on the Effect of Wheel Rotation Direction

Figure 53: SEM image of the cutting edge produced (images taken from the polished surface): (a) 90 degree apex angle with cw wheel direction; (b) 70 degree apex angle with cw wheel direction; (c) 50 degree apex angle with cw wheel direction; (d) 90 degree apex angle with ccw wheel direction; (e) 70 degree apex angle with ccw wheel direction; (e) 50 degree apex angle with ccw wheel direction

The effect of higher wheel speed on PCD edge quality for ccw wheel rotation has also been analysed. Through the microscopic analysis (microscopic observation from the polished surface), it was found that increasing the wheel speed does not improve it further, and rough PCD edges as previously described were observed. The result (Figure 55) thus clearly shows that the debris flow direction will significantly influence the edge quality, even at higher wheel rotation speed. In this study, 2000 rpm (about 16 m/s) is the highest tested wheel speed.
Chapter 5. Investigation on the Effect of Wheel Rotation Direction

Figure 54: Results of Raman analysis

![Raman analysis graph](image)

Figure 55: Effect of higher wheel speed

![Effect of higher wheel speed](image)

Figure 56 and Figure 57 show the 3D images of the eroded surface and the profile of the cross-sectional surface, respectively. The 3D image of the eroded surface clearly shows that the rotating direction towards the WC backing sacrificed the WC surface but ensured the smoothness of the PCD eroded surface. Clear offset between the WC and PCD eroded surface was observed, with the WC offset 2µm lower than the PCD surface. Lower melting temperature and lower heat conductivity of the WC than PCD made the erosion process easier and thus created the offset. Furthermore, better
electrical conductivity than PCD also made it possible for the sparking process of WC to occur at the larger gap. Moreover, observation on the cross-section profile of the surface shows the formation of the gap or notch at the intersection between WC and PCD.

![3D images of the eroded surface](image1)

**Figure 56:** 3D images of the eroded surface: (a) cw wheel direction; (b) ccw wheel direction

![Cross-section profile of the surface](image2)

**Figure 57:** Cross-section profile of the surface: (a) cw wheel direction; (b) ccw wheel direction

The mechanism of the formation of the notch has been analyzed by Pisarcic [58]. It was found that the concentration of cobalt was higher in the transition zone between the carbide substrate and the diamond matrix due to the sintering process of PCD.
Chapter 5. Investigation on the Effect of Wheel Rotation Direction

The low resistance of cobalt to thermal erosion compared with the other components gave rise to increased material removal rate in the transition region. However, the inconsistency in notch width is confusing, especially when the wheel rotation direction is uncontrolled. Initially, it was regarded that the notch width inconsistency was caused by the instability of the machine system. When unpredicted high energy sparks were supplied by the undesirable pulses, the bigger notch was formed. However, in this study, it was found that the inconsistency of the notch width was not contributed by the machine system. Instead, in a similar rotation direction, width consistency was achieved. This was illustrated by the reasonably good confident interval shown in Figure 58.

![Figure 58: Notch size](image)

The debris flow direction towards the WC backing contributed to the formation of the wider notch. However, conversely, a narrower notch was obtained when implementing ccw wheel rotation direction. As illustrated in Figure 59, for ccw wheel rotation, the dielectric flowing towards the smaller gap area tended to sweep away the accumulated debris on the intersection. Although the rotating wheel
electrode in this process generated centrifugal force for better flushing capability, the surface offset would act as the 'shield' for debris removal, especially when the wheel rotated in a cw direction. This would then result in an inefficient flushing operation. The availability of trapped debris on that location would increase the probability of spark concentration and thus lead to the formation of a wider notch.

**Figure 59:** Illustration of the electrolyte flow and debris accumulation: (a) cw wheel direction; (b) ccw wheel direction; (c) Actual image of the notch

### 5.4. Conclusion

In this study, the wheel rotation direction was found to significantly influence the edge quality, even at the highest wheel rotation speed (approximately 16 m/s is the highest tested speed) when 1A current, 1µs pulse duration, and 1µs pulse interval were used as the finishing parameters. Centrifugal force generated by the rotating wheel would drag the dielectric as well as the accumulating debris in the same direction as it moved. When the wheel rotated in a ccw direction (from WC to PCD), the dielectric that flowed toward the edge would bring together the debris, thus increasing the probability of spark concentration. This concentrated spark, which was unevenly distributed on the surface, then resulted in significant sharpness reduction, formation of edge undercut, a worse surface finish and rougher edge.
Chapter 5. Investigation on the Effect of Wheel Rotation Direction

The trapped debris at the interface region contributed to the formation of a wider notch. The offset that appeared after the erosion acted as the buffer, which resulted in inefficient flushing when the tool was rotating in a cw direction (from PCD to WC).

Although a re-cast layer might not be generated in the EDG of PCD, there will be an affected layer or modified zone caused by the high thermal processing. In this study, changing the apex angle to the smallest value resulted in a significant increase in the layer thickness. Further exploration on the affected layer is crucial, since the conversion of diamond is expected to cause a reduction of surface strength and increase the probability of surface damage. The surface defect induces the stress concentration that is also considered a weak spot for the propagation of cracks.

While the industries are concerned about the surface finish of WC and notch width aspects of tools, it was found that this is not a good index to measure PCD tool quality. The poor surface finish on the WC backing eroded surface and wider notch are more likely caused by flowing debris and cannot be used for the level of PCD tools’ thermal damage prediction. This research found that, although the roughness quality of the WC backing surface was sacrificed, and a wider notch was formed at the WC/PCD interface region when the wheel rotation was in a cw direction, better geometrical accuracy of PCD edges was obtained. This conclusion about behaviour is expected to change the industrial perspective regarding the parameters used to judge the quality of PCD tools.
Chapter 6 Investigation on the Effect of Machining Parameters and Its Theoretical Modelling

6.1. Introduction

In fabricating PCD tools, a PCD chip is cut from larger PCD blanks (produced by the sintering process) and this chip is brazed on the tool/carrier substrate [32] before being machined to the desired shape. The residual stress in the PCD tools is the result of three different phases of manufacture. These are the sintering process, the brazing process that mounts the PCD chip on the tool holder, and the final machining processes. It is believed that the overall residual stress which accumulates on the finished tool surface is related to the combination of these three phases of manufacture, as summarized in Figure 60. The residual stress should be managed properly, so that the toughness properties of the tools can be sustained [61, 110]. Indeed, Yahiaoui et al. [111] stated that the tensile residual stress in diamond promotes cracks, weakens the grain boundaries and contributes to lowering abrasion resistance. In rock drilling applications, it was found that residual stress contributed to the formation of gross fracture wear of diamond tools [112].

![Figure 60: Three stages of the residual stress formation in tool production](image)

The coefficient of thermal expansion (CTE) mismatch between PCD and tungsten carbide (WC), which constitutes the substrate, results in stress and strain development during the cooling process [61, 113]. Chen et al. [114] discovered that the thickness ratio of the diamond layer to the tungsten carbide backing significantly
affects the value and the distribution of residual stress. Jia et al. [115] proved that the PCD of bigger grain size has higher compression residual stress [115]. The compression stress is also reported to be higher at regions closer to the diamond-WC interface due to the significant difference in coefficient of thermal expansion between PCD and WC [113, 116]. Significant thermally-induced stress on the intersection tends to cause delamination failure during the application of PCD tools. Special design of irregular surface topography on the intersection between the PCD and carbide layers has been proposed in order to reduce the probability of delamination-crack propagation [117].

The magnitude and direction of residual stress for the third phase is different with different production strategies [118]. In the machining of steel, for example, the thermal effect produces a different residual stress with respect to the surface depth, due to the non-uniform temperature distribution [119]. Electrical discharge machining (EDM) of ordinary materials usually induces the highest tensile stress just below the machined surface [64, 67], and the value is reported to be directly proportional to the pulse energy used [120, 121]. However, no discovery has been reported on the effect of EDM plasma thermal stress on the surface strength alteration of PCD. It has been reported that surface graphitization occurred due to the EDM of PCD but this has not yet been thoroughly researched. To date, the relationship of the thermal damage to the controllable machining parameters has not been well defined in the literature. Theoretical approaches should be developed in order to predict and estimate the degree of thermally damage to the surface.

Understanding of the material removal mechanism is required in order to fully understand the thermal damage development process, but the scarcity of relevant information on the removal mechanism creates a challenge for further exploration. Olsen et al. [32] reported that the PCD diamond grains are detached from the surface due to the preferential erosion of the highly conductive cobalt network. On the other hand, Kozak et al. [122] believed that the cobalt binder is fractured due to the thermal stress generated by the process which causes diamond grains to separate from the structure. Zhang et al. [56] thought that the high temperature plasma not
only melts the cobalt but also graphitizes the diamond grains. The graphite consequently dissolves into the molten cobalt before being flushed away by the dielectric. This demonstrates disagreement on the fundamental mechanism of material removal and a better explanation is demanded.

This chapter reports on the surface graphitization and residual stress developed under the surface of PCD machined by the Electrical Discharge Grinding (EDG) process. The mechanism of removal and its theoretical model are discussed in detail and found to be in good agreement with the experimental findings.

**Part of this chapter has been used in the following publications:**


**6.2. Equipment and Methodology**

Although PCD is a strong and hard material it is sensitive to high temperatures [123, 124]. It has been reported that the graphitization of diamond occurs at temperatures above 973K when in the presence of cobalt. In addition, up to 36 percent of diamond hardness reduction was reported when the temperature increases from 300K to 550K [124]. Since EDG of PCD tools generally involves a high energy roughing process, the author theorized that graphitization would be present on the PCD surface. The research was begun with the roughing process investigation of CTB010 (PCD with 10µm grain size). The samples were machined with three different roughing parameters as, shown in Table 9. Secondary Electron images from a Scanning
Electron Microscope (SEM) indicated the formation of an affected layer up to 20 µm depth. In this layer microstructure changes due to heat from the roughing process were observed.

**Table 9: EDG parameters for the roughing experiment**

<table>
<thead>
<tr>
<th>Specimen no.</th>
<th>Polarity</th>
<th>Open Voltage (V)</th>
<th>Current (A)</th>
<th>On-Time (µs)</th>
<th>Off-time (µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Positive</td>
<td>120</td>
<td>12</td>
<td>40</td>
<td>20</td>
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<tr>
<td>2</td>
<td></td>
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<td></td>
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</tbody>
</table>

Further investigation was done using three different PCD types of 4.6 mm width. Table 10 shows the properties of these three PCD types [98, 100]. Due to the depth of the observed modified zone, it was hypothesized that the finishing in-feed could make a significant difference to the final surface quality. Two stages of machining, roughing and finishing, were performed for every sample. For each test the same roughing process was used to remove material to a depth of 0.5mm. This was followed by different finishing processes. Table 11 shows the erosion parameters used in this series of experiments.

**Table 10: Properties of PCD [98-100]**

<table>
<thead>
<tr>
<th>PCD Types</th>
<th>Grain Size (µm)</th>
<th>Diamond Fraction (Vol %)</th>
<th>Cobalt Fraction (Vol %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTX002</td>
<td>2</td>
<td>84.8</td>
<td>15.2</td>
</tr>
<tr>
<td>CTB010</td>
<td>10</td>
<td>89.7</td>
<td>10.3</td>
</tr>
<tr>
<td>CTM302</td>
<td>30 to 2</td>
<td>91.4</td>
<td>8.6</td>
</tr>
</tbody>
</table>

A tungsten-copper wheel acted as the anode for the roughing operation and the cathode during the finishing stage. Before every surface analysis, the samples were ultrasonically cleaned using ethanol and acetone to remove any contamination on the surface. For structural quality assessment, Raman spectra with a 785nm (near
infrared) laser wavelength (Perkin Elmer Spectrum Raman Station 400) was used to analyse several types of carbon formed on the surface. With 100μm laser spot size, good averaging of the Raman values of the inspected surface was obtained.

Table 11: EDG parameters for the finishing experiment

<table>
<thead>
<tr>
<th>Operation</th>
<th>Annotation</th>
<th>Polarity of the wheel</th>
<th>Open-Voltage (V)</th>
<th>Wheel rotation speed (rpm)</th>
<th>Current (A)</th>
<th>On-time (µs)</th>
<th>Off-time (µs)</th>
<th>In-feed (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roughing</td>
<td>-</td>
<td>Positive</td>
<td>12</td>
<td>40</td>
<td>20</td>
<td>0.01</td>
<td>0.02</td>
<td>0.5</td>
</tr>
<tr>
<td>A</td>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td></td>
<td></td>
<td>120</td>
<td>250</td>
<td>4</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Finishing</td>
<td>Negative</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>F</td>
<td></td>
<td></td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>G</td>
<td></td>
<td></td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td></td>
<td></td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6.3. Results and Discussion

6.3.1. Effect of Roughing Process

As stated in Chapter 3, Raman spectroscopy has been successfully used in the research relating to diamond material. Several studies show that the formation of peak bands on a particular range of wave number is an indicator which differentiates between several types of carbon lattice structures formed [83, 125]. The formation of the band that is centralized on a specific number is the indication of the presence of carbon lattice structure and the deviation of peak can be used for the surface stress measurement [68, 77].
SEM study of roughly eroded PCD found that the modified region had a thickness of approximately 10μm to 30μm from the eroded surface, as shown in Figure 61 and Figure 62. The formation of this modified zone was believed to be due to the microstructure changes resulting from heat produced in the roughing operation. In the case of a single crystal diamond, simultaneous or explosive disintegration and graphitization of diamond with the activation energy (E_ac) of 42±8 kJ/mol were reported when the temperature reached 2273K [126]. Below this explosive disintegration level, graphitization occurred at an activation energy (E_ac) of 336 ± 21 kJ/mol and this graphitization is known as the diffusive mechanism [126]. At this stage, a significant reduction of the graphitization rate is achieved. The preceding theories provide the best explanation for the appearance of the modified layer up to a certain depth until the level where the graphitization transition of explosive to diffusive mechanism is reached. In the case of machining PCD, the availability of residual cobalt catalyzes graphitization and this reduces the onset temperature for explosive graphitization. Therefore explosive graphitization at temperatures lower than 2273K should be expected.

![SEM images of the PCD after roughing](image)

**Figure 61**: SEM images of the PCD after roughing (modified zone was clearly observed on the 12A PCD sample)
The Raman spectrum obtained from the eroded surface after a roughing operation was compared with the spectrum of the unmodified PCD surface (as received from the material supplier). It was also compared with the spectrum from a single crystal diamond and the results are presented in Figure 63. The spectra obtained from the unmodified PCD demonstrate the three different Raman peaks at $1332 \text{ cm}^{-1}$, $1250 \text{ cm}^{-1}$ and $1600 \text{ cm}^{-1}$. These peaks indicate the presence of cubic diamond, nanocrystalline diamond, and graphite peaks, respectively [83, 127-130].
Sumiya et al. [54] stated that the graphite produces nanocrystalline diamond when subjected to high pressure and high temperature in the manufacturing process. The same conditions were applied to synthetic diamond during the sintering process to make our PCD sample. Graphite, formed by the graphitization of diamond particles at high temperature, would have been converted to nanocrystalline diamond under the high-pressure high-temperature conditions and this caused the appearance of the nanocrystalline diamond 1250 cm\(^{-1}\) peak, similar to that found by Ali et al. [128]. In contrast to the spectra obtained for the unmodified PCD, the spectra obtained from the eroded PCD section demonstrated only the presence of graphite and wide cubic diamond, defined by the Raman peaks at positions of 1306 cm\(^{-1}\) and 1599 cm\(^{-1}\), respectively. This means that, during the erosion process, nanocrystalline diamond is fully graphitized. This phenomenon is due to the higher surface-area-to-volume ratio of nanocrystalline diamond that is in contact with cobalt. Since as an object gets smaller the surface-area-to-volume ratio goes up, a nanosized diamond in PCD will have a very large surface area in contact with cobalt relative to its volume when compared to the larger crystals which constitute the main form of diamond in PCD. This means that the graphitization encouraged by the catalytic action of cobalt would be expected to quickly eliminate all diamond nano particles. Since the intensity ratio between the graphite and diamond peaks relates to the graphitization degree [131, 132], the lower diamond-to-graphite intensity ratio of the eroded PCD when compared to the unmodified PCD is an indication of partial conversion of diamond into graphite under the surface. The conversion not only weakens the structure but also causes significant irreversible expansion, due to the difference between diamond and graphite density [133].

The diamond peak value far from the unstressed cubic diamond value was identified as damaged diamond, similar to that discussed in an earlier manuscript [96]. According to the previous research, the higher the diamond peak position shifted further away from the stress-free diamond peak position (pure diamond grains), the higher the stress [134]. With the position shifted to a lower value, it was concluded that the roughing operation stressed the surface in a tensile direction. The stresses in this study were calculated using the following formula [68].
\[
\sigma = \frac{(\nu_s - \nu_r)}{\chi}
\] (6.1)

where \(\sigma\) is the tensile residual stress (GPa), and \(\nu_s\) is the measured Raman shift value of the diamond (1306 cm\(^{-1}\)), \(\nu_r\) is the unstressed Raman value (1330 cm\(^{-1}\)) and \(\chi\) is the coefficient of stress-induced frequency shift. Instead of using 1.98 cm\(^{-1}\)/GPa for the value of \(\chi\) as used in [135], 2.88 cm\(^{-1}\)/GPa was chosen as the more reasonable value, due to the usage of high volume of cobalt as referred to elsewhere [68]. From the equation, 8.33 GPa tensile residual stress was obtained from the surface eroded by the 12A roughing current. At high erosion powers such as this, the removal mechanism was believed to be due to mechanical failure, caused by thermal expansion of PCD and cobalt metal [122]. CTE mismatch between these two materials generates thermal stress during high-temperature erosion, which causes dislocation, and this promotes the breaking of diamond-to-diamond bonds. SEM investigation of the eroded surface found an average crater size of 10\(\mu\)m, similar to that of the PCD grain size. This constitutes evidence for the hypothesized mechanical failure mechanism (Figure 64). Grain detachment occurred, leaving cobalt as residue in the crater, as shown by the backscatter images. Since cobalt is a heavier element, it appears brighter in color. The appearance of diamond peak intensity of the Raman spectrum of debris collected after the EDG process is also the evidence for the availability of fractured diamond (Figure 65).
**Figure 64:** SEM images (left) and backscatter images (right) of the eroded PCD by roughing

**Figure 65:** Inspection location (the collected debris was deposited on the carbon tape)
6.3.2. Theoretical Model

For the roughing process a physical model of the thermal stress from cobalt-diamond interaction was obtained. It is similar to that used by the authors for the crater size prediction of PCD when undergoing EDM \[136\]. The model emphasizes diamond-to-cobalt interaction during the heating process. The stress components and annotations are indicated in Figure 66.

![Diagram showing thermal stress components](image)

**Figure 66:** Thermal stress components considered in the model ($r =$ position where the stress is estimated, $a =$ diamond grain radius, $\sigma =$ stress component for tangential, $t$ and radial, $r$ direction) \[86\]

In this model the thermal displacement, $u$, and the thermal stress, $\sigma$, in radial and tangential directions was calculated using the following basic formula used by Kozak et al. \[122\]:

\[
\frac{d}{dr} \left[ \frac{1}{r^2} \frac{d}{dr} \left( r^2 u \right) \right] = \frac{\alpha (1 + \nu)}{1 - \nu} \frac{d\theta}{dr}
\]

(6.2)

\[
\sigma_r = \lambda \left( \frac{du}{dr} + \frac{2u}{r} \right) + 2\mu \frac{du}{dr} - (3\lambda + 2\mu) \alpha \theta
\]

(6.3)

\[
\sigma_t = \lambda \left( \frac{du}{dr} + \frac{2u}{r} \right) + 2\mu \frac{u}{r} - (3\lambda + 2\mu) \alpha \theta
\]

(6.4)
where \( r \) is the position at which the stress is determined, \( a \) is the diamond grain radius, \( u \) is the thermal displacement, \( \alpha \) is the coefficient of thermal expansion, \( \theta \) is the temperature difference and \( \sigma \) is the stress component, which is annotated by \( t \) for tangential direction and \( r \) for radial direction. The elastic modulus, \( \lambda \), in terms of Lamé’s first parameter, is a function of Poisson’s ratio, \( v \), and modulus of elasticity, \( E \), given by:

\[
\lambda = \frac{v \cdot E}{(1 + v)(1 - 2v)}
\]

(Lamé’s first parameter (shear modulus), \( \mu \), can be calculated as:

\[
\mu = \frac{E}{2(1 + v)}
\]

The equation was then simplified, and the general equations shown below were obtained:

\[
u = \frac{A}{r^2} \int \theta^2 r \, dr + r C_1 + \frac{C_2}{r}
\]

(Lamé’s second parameter (shear modulus), \( \mu \), can be calculated as:

\[
\mu = \frac{E}{2(1 + v)}
\]

The equation was then simplified, and the general equations shown below were obtained:

\[
\frac{\sigma_r}{r} = \frac{4 \mu A}{r^3} \int \theta^2 r^2 + B C_1 - \frac{C_2}{r^3}
\]

\[
\frac{\sigma_t}{r^3} = \frac{2 \mu A}{r^3} \int \theta^2 r^2 + B C_1 - \frac{2 \mu C_2}{r^3} - 2 A \theta
\]

where the constants \( A \) and \( B \) are:

\[
A = \frac{\alpha (1 + v)}{1 - v}
\]

(6. 10)
The following boundary condition was applied to the physical model derived:

\[ r = 0 \quad u = 0 \]
\[ r = a \quad u^{(1)} = u^{(2)}; \sigma_r^{(1)} = \sigma_r^{(2)} \]
\[ r \to \infty \quad \sigma_r^{(2)} = 0 \]

Similar radial stress is gained when \( r \) is equal to \( a \), where the subscripts 1 and 2 represented the component for diamond and cobalt, respectively. By solving equations 6.7, 6.8 and 6.9 using the above boundary condition, \( C_1 \), and \( C_2 \) were determined:

\[ r = 0 \quad C_2^{(1)} = 0 \]  \hspace{1cm} (6.12)

\[ r = a \quad \frac{1}{3} A_1 T a + a C_1^{(1)} = a C_1^{(2)} + a^{-2} C_2^{(2)} \]  \hspace{1cm} (6.13)

\[ -\frac{4}{3} \mu_1 A_1 T + B_1 C_1^{(1)} = B_2 C_1^{(2)} - 4\mu_2 a^{-3} C_2^{(2)} \]  \hspace{1cm} (6.14)

\[ r \to \infty \quad -\frac{4}{3} \mu_2 A_2 T + B_2 C_1^{(2)} = 0 \]  \hspace{1cm} (6.15)

Substituting \( C_1 \), and \( C_2 \) into equations 6.8 and 6.9, the thermal stress components satisfied the following equations:

\[ \sigma_r^{(1)} = \frac{4}{3} \frac{1}{B_2 \left( B_1 + 4\mu_2 \right)} \left( A_2 B_1 \left( B_2 + 4\mu_2 \right) \mu_2 + A_1 B_1 B_2 \left( \mu_1 - \mu_2 \right) - A_1 B_2 \left( B_1 + 4\mu_2 \right) \mu_1 \right) \theta \]  \hspace{1cm} (6.16)

\[ \sigma_t^{(1)} = \sigma_r^{(1)} \]  \hspace{1cm} (6.17)
The final equation for the thermal stress components was obtained by substituting diamond and cobalt properties found in other studies [122, 137, 138] (Table 12) into the equation. Unlike Kozak et al. [122], temperature-dependent properties of diamond were taken into consideration in developing the final equation. The coefficient of thermal expansion for diamond relative to temperature was obtained by Thewlis et al. [137]. The value follows three different line trends, segregated by three different temperature stages, which are 175K to 275 K for the first stage, 275K to 400K for the second stage, and 400K to 1175K as the final stage. The stages mentioned above are satisfied by the piecewise linear equations shown in Figure 67.

\[
\sigma_r^{(2)} = \frac{d^3}{\rho^3} \sigma_r^{(1)}
\]

(6.18)

\[
\sigma_t^{(2)} = -\frac{1}{2} \sigma_r^{(2)} = -\frac{1}{2} \frac{d^3}{\rho^3} \sigma_r^{(1)}
\]

(6.19)

The final equation for the thermal stress components was obtained by substituting diamond and cobalt properties found in other studies [122, 137, 138] (Table 12) into the equation. Unlike Kozak et al. [122], temperature-dependent properties of diamond were taken into consideration in developing the final equation. The coefficient of thermal expansion for diamond relative to temperature was obtained by Thewlis et al. [137]. The value follows three different line trends, segregated by three different temperature stages, which are 175K to 275 K for the first stage, 275K to 400K for the second stage, and 400K to 1175K as the final stage. The stages mentioned above are satisfied by the piecewise linear equations shown in Figure 67.

**Table 12: Properties of diamond and cobalt**

<table>
<thead>
<tr>
<th></th>
<th>Diamond</th>
<th>Cobalt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elasticity Modulus, E (GPa)</td>
<td>900</td>
<td>211</td>
</tr>
<tr>
<td>Coefficient of thermal expansion, ( \alpha ) (10-6K(^{-1}))</td>
<td>Temperature dependent</td>
<td>14.2</td>
</tr>
<tr>
<td>Poisson ratio, ( \nu )</td>
<td>0.07</td>
<td>0.32</td>
</tr>
<tr>
<td>Shear Modulus, ( \mu ) (GPa)</td>
<td>420</td>
<td>80</td>
</tr>
</tbody>
</table>
Diamond-to-diamond is the primary bonding mechanism in PCD, as reported previously [62, 139, 140]. Thus, grain dislodgement only occurs when the stress is more than the tensile limit of diamond. This is referred to as the removal mechanism through diamond fracture. The authors’ assumption seemed to contradict Kozak et al., who believed dislodgement happens when the tensile limits for cobalt are reached [122]. For this reason, only the stress for diamond is investigated further. By incorporating the piecewise linear equation with the thermal stress components, equations 6.16 and 6.17, the stress in MPa can be estimated using the following modified equations:

\[
\sigma_t = \sigma_f \begin{cases} 
7.43 \theta + 2.4 \left(10^{-5}\right) \theta T & T \geq 400 \\
7.44 \theta + 4 \left(10^{-6}\right) \theta T & 273.15 \leq T < 400 
\end{cases}
\]  

(6.20)
where $T$ is the temperature of the material. A thermal analysis model was created via ANSYS software to predict the temperature profile so that the stress could be determined. The energy supply for every spark was calculated by the following equation [57, 141]:

$$E_d = \int_0^t i(t) U(t) \, dt$$  \hspace{1cm} (6.21)

where $E_d$, $t$, $i$, and $U$, are the energy, pulse duration, peak current and voltage, respectively. Hence, the heat flux $q$, which is the energy supplied per unit area, can be calculated using the following equation [57] and by assuming that the plasma generated is symmetrical in shape:

$$q(t) = \frac{kE_d}{\pi r_p^2}$$  \hspace{1cm} (6.22)

where $r_p$ is the heat flux radius and $k$ is the energy fraction obtained by the cathode. DiBibonto et al. [142, 143] used the constant energy partition of 8% and 18% for the anode and cathode erosion model of EDM of steel, using a copper electrode. Shankar et al. [108], in their investigation, found that the current, pulse of time, and the electrode gap do not significantly affect the energy partition, but lower thermal diffusivity will cause lower share of input power. Their finding demonstrates that around 40% of the total energy is transferred to the electrode while using water as the dielectric and with steel and copper as the electrodes. There is no comprehensive method that has been proposed thus far to determine the exact energy partition of the EDM process. In this analysis, the $k$ value is assumed to be 15% of the total energy supplied.

The electrode materials may well influence the spark radius. However, it is extremely difficult to prove this, due to extremely short pulse durations [144]. Compared with the steel, the lower electrical conductivity of PCD directly results in
a lower value of current in the gap than the input current set by the operator, and this consequently lowers the plasma radius and heat flux on the gap. The following equation from reference [57], the heat flux radius, \( r_p \), can be calculated by:

\[
\frac{2.4 \times 10^{-3} \times i^{0.4} \times U^{0.4}}{2} = r(t) \tag{6.23}
\]

By applying this equation, it is assumed that the plasma radius grows with time. The value of voltage and current are obtained from the feedback system with which the machine is equipped. Calculated results obtained from equations 6.21 and 6.22 are shown in Figure 68.

The following assumptions are applied to the thermal model:

a. The initial temperature of the process was set as 20°C, which is close to room temperature.
b. Heat flux is considered as originating in the heat source from the plasma created by the process.

c. Thermal convection is applied to the contact surface between PCD and dielectric.

d. The material is assumed to be an isotropic and homogeneous material.

e. The plasma radius was assumed to be symmetrical.

Figure 69 shows the scheme for the boundary conditions applied.

For boundary A,

\[
k \frac{\partial T}{\partial y} = \begin{cases} 
  h_c(T - T_0) & \text{when } r_p > r_{p_{\text{max}}} \\
  q & \text{when } r_p \leq r_{p_{\text{max}}} \\
  0 & \text{off - time}
\end{cases}
\]  

(6.24)
where $h_c$ is the heat transfer coefficient between the material surface and dielectric. In the case of single sparks, a semi-infinite body was considered. Thus, the effect of the surroundings could be neglected. In order to obtain this condition, the radius of the body is assumed to be at least 6 times that of the maximum spark radius calculated [108]. The following boundary condition was applied for boundary B, and C:

$$k \frac{\partial T}{\partial \eta} = 0$$  \hspace{1cm} (6. 25)

where $\eta$ is the direction normal to the surface.

For defining the material characteristic, the temperature-dependent properties of PCD of different grades are calculated based on a number of theoretical formulations developed for ceramic materials with granular grain shapes, assumed to have similar physical morphology as the structure of PCD used. The thermal conductivity, $K$ of PCD, was calculated using a Maxwell equation as follows (similar to that used in reference [145]):

$$K = k_d \frac{2k_d + k_c - 2f_c(k_d - k_c)}{2k_d + k_c + f_c(k_d - k_c)}$$  \hspace{1cm} (6. 26)

where $k_d$, $k_c$, and $f_c$ are the thermal conductivity of diamond, thermal conductivity of cobalt, and cobalt fraction, respectively. The heat capacitance, $C$, also known as the specific heat of material, was calculated using the Neumann-Kopp’s law:

$$C = c_c f_c + c_d f_d$$  \hspace{1cm} (6. 27)

$c_c =$ heat capacitance for cobalt
$c_d =$ heat capacitance for diamond
$f_d = \text{diamond fraction}$

Figure 70 shows the calculated results for the temperature-dependent properties of different PCD grades. The temperature profile obtained from the ANSYS analysis is shown in Figure 71. Integrating the stress equation with the temperature profile obtained enables the residual stress to be predicted. The tensile residual stress measured earlier indicates a value of 8.33GPa, which is in agreement with the highest residual stress reported by Ferreira et al. in their research regarding the residual stress of boron-doped diamond films [94]. Since the roughing process removes diamond by the fracture mechanism, it is reasonably accurate to assume that the maximum thermal stress for diamond is close to that value (in this case, the thermal stress limit for diamond was assumed to be 8.5GPa by taking into account the stress relaxation on the exposed surface). This value is reasonable, since the strength of diamond was reported as being close to that value at the temperature of 1573K [146].

![Figure 70: Temperature-dependent properties calculated](image)

In Figure 71, a straight horizontal line is used to indicate the thermal stress limit of synthetic diamond. The intersection of this line with the diamond grade profile will
give an estimate of the fracture level of the PCD after roughing. The next vertical lines are the offset lines for 10µm and 20µm surface depth representing the finishing in-feed. It was found that the higher the finishing in-feed, the lower the tensile stress on the surface. The finding thus supports the hypothesis that the finishing in-feed will result in a significant surface stress reduction. Figure 72 illustrates the diamond breakage mechanism. At a temperature of about 1400K, the thermal stress is higher than the thermal stress limit for diamond. Therefore, the grains fracture and dislodgement occurs. The grains are separated by the pressure wave generated by the process and flushed away by the dielectric.
Figure 71: Temperature-stress relationship for different PCD
6.3.3. Effect of Finishing Operation

Good surface quality is the precondition for achieving long tool life. Surface quality is usually described by surface roughness, geometrical accuracy, graphitisation and the level of residual stress. However, in current industry, surface quality of PCD tools is mainly judged by the surface roughness which can be as low as 0.1 µm to 0.2 µm in Ra for CTB010 PCD grade size [2, 149]. Due to lacking of theoretical support on the modified PCD properties after erosion, residual stress and graphitisation are not measured after the machining process.

As stated in the previous section, after roughing, a 20µm deep modified zone is observed together with high surface graphitization and tensile surface residual stress. As partial graphitization was predicted to occur at only a few microns depth toward the diamond bulk, deeper finishing removal is expected to produce a better surface quality (lower graphitization and tensile residual stress). The surface roughness was unchanged with different finishing in-feed when similar finishing parameter was implemented (as will be proved in Chapter 7).

As shown in Figure 73, there is no evidence for diamond breakage occurring on the surface eroded by the finishing stage. As only a small erosion energy is used for
finishing, graphitization becomes the main removal mechanism. As stated by Zhang et al. [56], by this mechanism the diamond grains on the top surface will graphitize. The graphite would then dissolve into the molten cobalt before being flushed away by the dielectric. Due to the small energy used in finishing, multiple sequential sparks are required to achieve the graphitization temperature.

![Eroded surface by the finishing operation](image)

**Figure 73:** Eroded surface by the finishing operation

Figure 74 shows the D-value obtained by the Raman spectra. It is clear that, for every sample, a higher diamond peak value was obtained when using a 20μm finishing in-feed. As expected, with higher finishing in-feed, a higher diamond peak value was obtained, which indicates better surface stress (reduction of tensile residual stress). Additionally, the diamond peak location was found to be significantly affected by the machining parameters. The significant difference in diamond peak locations is primarily due to the difference in sparking energy used in the finishing operation. Higher energy caused a higher heat flux to be produced by the plasma, thus increasing the heat penetration depth. As discussed before, the roughing operation produced high residual stress on the surface and the stress relaxation occurred deeper
into the material. As with the roughing process, thermal stress was also generated by the finishing process but with a lower value.

The smaller sparking energy with smaller pulse duration and longer sparking interval was found to minimize the cumulative stress generated by the finishing process. Longer inter-pulse delays allow the heat generated by a single spark to be dissipated into the bulk material before the next spark is generated. In the case of smaller inter-pulse delays (off-time), higher sparking frequency happened, which resulted in lower heat removal by flushing. Thus, the ratio of those parameters (on-time to off-time) considerably affects the level of surface stress (Figure 74). The unclear trend observed on the CTM302 PCD grain was caused by the inconsistency of the machining process. A combination of grain size of between 2µm to 30µm for this grade makes sparking inconsistent. At certain stages, where the distribution of 30 microns grains is high, the erosion process is slower due to the difficulty of big grain erosion. At the same time, the heat was continually supplied to the deeper PCD bulk and the tensile stress was continually generated due to rapid heating up and cooling down. Due to this effect, the stochastic distribution of PCD grains size is regarded as a major factor influencing the residual stress value, especially during low energy erosion.

The stress obtained by the developed model was compared with the actual stress measured by the Raman analysis (Table 13). In this comparison, the actual values were taken only from the surface that was eroded by the smallest current with the lowest pulse-on-to-pulse-off ratio. With these parameters, surface stress modification was minimized, leaving only the stress originating from the roughing process. The results show that the model is reasonably accurate for the thermal stress prediction, since it is closely matched by the actual value measured, except in the case of CTM 302, in which the sparking inconsistency (as discussed) possibly caused the high percentage error obtained (more than 20%).
Figure 74: Raman D-value (a) CTX002 (b) CTB010 (c) CTM302
Table 13: Comparative study between the theoretical values obtained from the physical model and the real value

<table>
<thead>
<tr>
<th>PCD Types</th>
<th>10µm finishing infeed</th>
<th>20µm finishing infeed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Theoretical value</td>
<td>Actual value</td>
</tr>
<tr>
<td>CTX002</td>
<td>5.0</td>
<td>5.4</td>
</tr>
<tr>
<td>CTB010</td>
<td>5.0</td>
<td>5.2</td>
</tr>
<tr>
<td>CTM302</td>
<td>5.0</td>
<td>5.2</td>
</tr>
</tbody>
</table>

The diamond peak to graphite peak intensity ratio was again examined after finishing erosion. As shown in (Figure 75), the graphitization degree reduces with higher finishing in-feed (refer to the result variance between low and high finishing in-feed). This is evidence of a partial graphitization phenomenon caused by the roughing process.
Figure 75: D/G ratio (a) CTX002 (b) CTB010 (c) CTM302
The comparison of the graphitization degree of three different PCD types used shows that the lowest graphitization is for the CTM302, followed by CTB010, and CTX002 (Figure 76). This could be explained as being due to the thermal properties of the material. The PCD with the higher diamond fraction has better thermal conductivity, thus reducing the probability of heat accumulation within the material. In addition, the lower the cobalt catalyst composition, the lesser the diamond-to-cobalt contact area, and this consequently reduces graphitization at lower activation energies.

![Figure 76: A comparison of graphitization degree of three different PCD](image)

6.3.4. Single Discharge Test

Single crater modeling is a useful method for justification of the removal mechanism involved. The model was established, and the size of the simulated crater was confirmed to be in agreement with the craters generated by the single discharge test. In this study, modeling of the crater geometry refers solely to the thermal stress analysis of the PCD system, as discussed in previous sub-chapter.
Clearer crater formation can be expected with smaller PCD grains. For this reason, CMX850 PCD, made by Element Six Ltd. with polished surface, was used in the single discharge test to ensure that small craters could be observed on the original PCD surface. The machining parameters were set up as follows: the open voltage was 120V, the on-time was 100µs, the peak current was 12A, the rotation speed was 2m/s and the electrode wheel was at positive polarity. The Alicona (IF-EdgeMaster) optical measuring device was used to provide 3D measurement data of each crater and the stereo-lithography format of 3D images was exported to a host computer for the morphological analysis.

Figure 77 shows the current and voltage feedback obtained, and the calculation results of equation 6.21 and equation 6.22.

As the results from the single discharge test, Figure 78 shows the profile of two craters produced. The dimensions of those marks are identical: approximately 25 to 30µm and 16 to 19µm crater radius and depth were observed, respectively.
Figure 78: The profile of two craters (a) and (b) on the PCD surface

The crater model shown in Figure 79 was obtained by utilizing the element death to the simulation result, where the elements with the temperature greater than the limit were diminished. As previously, the temperature limit for the fracture mechanism to occur was predicted as 1100K. The model estimated that a 28µm radius and 13µm depth of PCD single crater could be attributed to the process, which is in reasonable agreement with the experimental finding.
6.4. Conclusion

The grain fracture mechanism was the PCD removal mechanism for roughing with high energy erosion and graphitization mode for the finishing stage. The appearance of the modified layer is due to surface graphitization. Simultaneous graphitization on the surface occurred, resulting in the formation of a “modified zone” until some limit where the graphitization rate reduced significantly. The author believed that the high residual stress and surface graphitization could be defined as the thermal damage of PCD. The thermal stress generated by the roughing process is believed to be the main contributor to the final residual stress on the surface. Higher finishing in-feed results in higher graphitized and stressed structure removal, thus resulting in better surface quality. A model for the residual stress prediction was developed by integrating the physical model with the thermal profile obtained by the ANSYS software. The results demonstrated that the developed model is reasonably accurate for the thermal residual stress prediction of EDM of PCD.
The crater size for individual sparks was also determined experimentally and found to be in good agreement with the simulation predicted value. This study clearly shows the feasibility of using the thermal stress theoretical approach for modeling of a single crater in PCD EDM. This result thus supports the argument that the breakage mechanism happened during high energy PCD erosion.
Chapter 7 Tool Quality Investigation and Performance Analysis

7.1. Introduction

In recent years the use of advanced materials such as Carbon Fibre Reinforced Plastic (CFRP) and titanium alloys is becoming more and more popular in the aerospace and automotive industries, owing to their excellent performances caused by high strength and low mass. To reduce defects in the final products, the machining of CFRP requires the cutting tools to retain edge sharpness in machining. PCD offers a range of advantages over conventional carbide tools, and is regarded as the most suitable material for this application, because of its long tool life in high speed machining of tough or abrasive materials such as CFRP, ceramics and titanium alloys. Not only does it reduce production time, but it also reduces the manufacturing cost due to its ultra-hardness and long durability. These properties have led to a huge demand amongst various industries for PCD cutting tools for not just manufacturing but also for maintenance, repair and overhaul (MRO) operations.

Conventional abrasive grinding and EDG are two different processes, with different removal mechanisms to machine PCD. In 2002, Tso et al. [2] discovered that PCD tools fabricated with conventional grinding have better tool life as compared to eroded PCD tools. Higher thermal damage and the rougher surface of eroded PCD are the reasons that lead to their early failure. Several groups of grinding parameters were tested on CTB010 PCD and the electrode rotation speed was found to be the most significant factor influencing surface roughness. In another paper, Liu et al. [21] determined the effect of the diamond grinding wheel (type of bonding and grit size) on the Material Removal Rate, G-ratio (volumetric material removal divided by the volumetric diamond wheel loss) and surface roughness. Considering the value of G-ratio, surface roughness, surface crack and material removal rate, they found that
Chapter 7. Tool Quality Investigation and Performance Analysis

the vitrified bond of the diamond wheel was the most suitable grinding wheel to machine PCD, and a mesh number of 1000 was the optimum wheel grade. The increase in mesh number has not remarkably increased tool quality but has significantly reduced material removal rate.

Dold et al. [147] investigated the edge quality of ground PCD tools. They found that smaller grains of ground PCD commonly exhibited large chipping on the cutting edge and resulted in the formation of torn-out grains on the ground region, together with holes particularly in the binder material. A secondary laser treatment method for ground PCD tools was introduced to get a homogenous surface specifically on the cutting edge geometry. In their research, edge radii of 4.3µm to 6.5µm were achieved by their laser-treated PCD. Ishimarua et al. [148] reported that sharp PCD tools with sub-micro meter radii could be produced after treatment using an ultraviolet ray irradiation assisted polishing method. However, it suffered from a low polishing rate. With the rapid advance of drilling technology, various new cutting tools have been designed with complex geometry and profile to increase drilling efficiency. Therefore, there is a pressing need for a highly flexible process to machine the intricate shape of PCD tools. In comparison to conventional die sinking EDM, the rotating wheel of EDG increases the flushing efficiency of the process, thus reducing the probability of debris interaction and accumulation. Debris interaction causes the formation of concentrated plasma and this affects process efficiency. Efficient flushing is critical to reduce the chance of re-welded diamond debris to the eroded surface, which increases spark inconsistency [88].

It is known that the sharpness of the cutting edge has a significant influence on the production of good quality holes in composites, as it reduces delamination [148]. The current state of the art for PCD erosion is able to produce sharp cutting edges. However, up till now, the EDG erosion of PCD material in comparison to the well-established conventional grinding method, especially in producing sharp cutting edges, has not been investigated in detail by any researcher. This chapter investigates the effects of the PCD manufacturing process on the quality of PCD tools. Two different processes of EDG and abrasive grinding are compared. The comparison
includes the surface morphology, structural quality (residual stress and graphitization), and performance analysis of the PCD tools produced.

**Part of this chapter has been used in the following publications:**

**M. Zulafif Rahim**, Guangxian Li, Songlin Ding, and John Mo, Milan Brandt, Electrical Discharge Grinding versus Abrasive Grinding in Polycrystalline Diamond Machining. *Jurnal Teknologi*. 2015. – Accepted for publication


### 7.2. Methodology

PCD with different grades was used in this investigation. Table 14 shows the types of PCD used and their composition.

<table>
<thead>
<tr>
<th>PCD Types</th>
<th>PCD Grain Size (µm)</th>
<th>Diamond Fraction (Vol %)</th>
<th>Cobalt Fraction (Vol %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTX002</td>
<td>2</td>
<td>84.8</td>
<td>15.2</td>
</tr>
<tr>
<td>CTB010</td>
<td>10</td>
<td>89.7</td>
<td>10.3</td>
</tr>
<tr>
<td>CTM302</td>
<td>30 to 2</td>
<td>91.4</td>
<td>8.6</td>
</tr>
</tbody>
</table>

7.2.1. Conventional Grinding Parameter Selection

For conventional grinding, a COBORN RG6 computer numerical control (CNC) automatic grinding machine equipped with vitrified bond D16 diamond grinding wheel (Trochilics Ltd, UK) was used (Figure 80). The machine was specifically selected due to its capability to precisely control the machining parameters to enable
the high precision grinding depth control. The chattering and vibration during grinding that commonly associated with the non-uniform wear of the wheel should be control for better grinding depth consistency. The vitrified bond wheel was selected, because it was the most suitable wheel type for effective and efficient PCD grinding due to its appropriate capacity to hold the diamond grit during the process [21]. Since the dull wheel can initiate work piece vibration, the wheel grinder was frequently dressing to maintain its sharpness. Perpendicular grinding was used, as it produces a better surface finish than the parallel method [2]. Suitable machining parameters were selected so that the actual grinding depth was smaller than the onset depth for brittle to ductile transition of PCD, which was in the range of 0.0013µm to 0.0085µm [149].

![Grinding process of PCD](image)

**Figure 80:** Grinding process of PCD: (a) Machine setup; (b) PCD insert holder

As the baseline, most of the parameters used in this study are closely similar to those reported in literature that have successfully produced good surface finish [2, 21]. A lower oscillation rate was applied and this is expected to produce better surface quality, according to Tso and Liu [2]. A relatively large range of wheel velocities and grinding in-feed were implemented to further explore their effect on cutting edge sharpness and roughness. The following machining parameters were used: cutting feed rate of 0.2mm/min and 0.5mm/min, wheel velocity of 10 m/s, 20m/s, and 30 m/s. The contact load was 10kg, and fixed oscillation rate of 15mm/sec was used. To control the grinding temperature, general water-based coolant was used in this
tool insert preparation method. The feed rates used were sufficiently small to comply with the ductile removal mechanism (actual grinding depth \( g_m \) of 0.0004 to 0.0015\( \mu \text{m} \)), as calculated using the following formula [149]:

\[
g_m = \left( 2a \frac{V_{osc}}{V} \sqrt{\frac{\Delta}{D}} \right) \quad (7.1)
\]

where \( 2a \) is the distance between the successive grains (\(~150\mu \text{m})\), \( V_{osc} \) is the wheel oscillation speed, \( V \) is the wheel velocity, and \( D \) is the wheel diameter (150mm). The maximum grinding in-feed \( \Delta \), was calculated by [149]:

\[
\Delta = \frac{d}{V_{osc}} \times V_f \quad (7.2)
\]

Where \( d \) is the oscillation travel distance (21mm) and \( V_f \) is the feed rate used.

7.2.2. EDG Machining Parameters Selection

A tungsten-copper wheel electrode with a rotational speed of 2 m/s was used in this study (Figure 81). According to Rahim et al. [104], a short pulse duration with long pulse interval was most suitable for the finishing operation in order to reduce the heat damage (residual stress, graphitized structure) of the eroded surface. Table 15 shows the EDG parameters used in this study.

**Figure 81:** EDG process of PCD: (a) Machine setup; (b) PCD insert holder
## Table 15: EDG machining parameters

<table>
<thead>
<tr>
<th>Operation</th>
<th>Polarity of the wheel electrode</th>
<th>Open-Voltage (V)</th>
<th>Wheel rotation speed (rpm)</th>
<th>Current (A)</th>
<th>On-time (µs)</th>
<th>Off-time (µs)</th>
<th>In-feed (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roughing</td>
<td>Positive</td>
<td>120</td>
<td>250</td>
<td>12</td>
<td>40</td>
<td>20</td>
<td>0.5</td>
</tr>
<tr>
<td>Finishing</td>
<td>Negative</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>0.01-0.04</td>
<td></td>
</tr>
</tbody>
</table>

A two-stage machining strategy involving roughing and finishing was implemented. It is expected that higher in-feed increases machining depth caused by the small energy pulses, thus reducing the total residual stress generated by the roughing process. To further investigate the in-feed effect on the quality of PCD tools, an in-feed higher than that applied in another study [104] (0.02 mm) was implemented. As shown by the crater depth generated in the roughing operation (Figure 36), an in-feed of 0.01 mm was found to be the minimum in-feed (lowest finishing depth) that was needed to clean-up the rough surface generated by the preceding roughing process.

### 7.2.3. Morphological, Structural Quality, and Residual Stress Analysis

An Alicona (IF-EdgeMaster) 3D microscope fitted with a 50x magnification lens was used for the analysis of tool sharpness and surface roughness. The non-contact measurement enables more accurate measurement result. The edge radius was obtained by analyzing the extracted 3D images using the robust Gaussian fitting circle method, which is similar to that described by Wyen et al. [150].

For structural quality and residual stress assessment, Raman Spectra produced with a 785nm laser wavelength (Perkin Elmer Spectrum Raman Station 400) was used to analyze the types of carbon formed on the machined PCD surface. With 100µm laser spot size, good averaging of the Raman values of the inspected surface were obtained. The tensile residual stress value were calculated by the following equation [104]:

\[
\sigma = -\frac{(\nu R - \nu r)}{\chi}
\]  

(7.3)
where $\sigma$ is the tensile residual stress (GPa), $v_s$ is the measured Raman shift value of the diamond, $v_r$ is the unstressed Raman value (1330 cm$^{-1}$) and $\chi$ is the coefficient of stress-induced frequency shift (2.88 cm$^{-1}$/GPa).

7.2.4. Performance Analysis

To assess the performance of the tools prepared by different processes, continuous grooving was carried out on a 3-axis CNC machine center (HAAS). Similar to that applied by Liu et al. [151] and Hintze et al. [152], a grooving test of tungsten carbide (WC) was implemented because of its simple kinematics. A WC blank was used as the cutting work piece to speed up the tool wear process. The grooving was implemented in a dry condition, and the spindle was locked to prevent any rotation. A cutting speed of 14 m/min, together with gradually increased grooving depth of up to 100µm was applied (Figure 82). The tips of the insert and the WC work piece surface were probed in each experiment to ensure high measuring accuracy. At the end of the process, the surface of the tool was inspected with a microscope to determine the level of failure referred as the “cutting tip shortening”, which was also defined as dwindling height of tip, similar to that used by Nakamoto et al. [153, 154].

The signal of the cutting force was collected through a six-channel dynamometer (Kistler 9257B) installed underneath the work piece. The model of coupler was the Kistler Multiple Charge Amplifier 5070. The force signal was recorded via a data acquisition (DAQ) card (National Instrument model 6036E). The setup of the experimental system is illustrated in Figure 82: Experimental setup.
Chapter 7. Tool Quality Investigation and Performance Analysis

7.3. Results and Discussion

7.3.1. Morphological Analysis

Figure 83 shows the surface roughness (Ra) of the three types of PCD samples machined with the two machining approaches. The surface roughness of these samples was compared with the results obtained by Tso and Liu [2] and
Kuppuswamy et al. [149], as shown in Figure 83b. It can be seen that the roughness decreases with slower wheel velocity and lower feed rate.

Figure 83: Surface roughness: (a) CTX002 ground surface; (b) CTB010 ground surface; (c) CTX302 ground surface; (d) Eroded surface

With the selected machining parameters, most of the surfaces machined by the conventional grinding process exhibit excellent surface finish in the range of 0.1µm to 0.2µm. Except for CTM302, the surface roughness was relatively high due to the difficulty of cutting PCD made of bigger grains. The greater hardness of CTM302 PCD is due to the lower cobalt content than other types of PCD. On the other hand, different finishing in-feed did not produce any change in the surface roughness of eroded PCD (Figure 83d). Ra of approximately 140 nm was obtained for CTX002 and CTB010. This is closely similar to the PCD that was ground with the slowest wheel velocity and lowest feed rate.
Although they are closely similar in terms of surface roughness, microscopic observation revealed that they are different in morphological appearance. Figure 84 shows the Scanning Electron Microscope (SEM) images of the machined surface obtained by the two different processes. As was found in our previous research [104], graphitization occurred during the finishing erosion. In the machining process, diamond grains on the top surface would graphitize and dissolve into the molten cobalt before being flushed away by the dielectric. Since the energy applied in each spark is relatively low, and is below the energy required to shatter the diamond particles, the machined surface appears smooth and without craters (as shown in Figure 84a). It can be seen that the grain intersection disappeared due to filling up by the re-cast molten material, mainly cobalt and the wheel elements (tungsten (W), copper (Cu), and calcium (Ca)), as shown in the energy dispersive spectrometry (EDS), as discussed in Chapter 4 of this thesis (Figure 30). Since the finishing process was conducted with negative polarity of the wheel electrode, the surface plating phenomenon occurred on the anode electrode (in this case PCD) during erosion, and thus such elements accumulated on the surface of the PCD [6].

As shown in Figure 84b, as the ductile mode grinding occurred in ground PCD, tiny grooves without cracks were observed on the surface. This indicates that the grinding process implemented was successful in cutting through the grains of PCD. Flat grains with clear boundaries were observed. The discontinuous grain boundary indicates the presence of diamond-to-diamond bonding, as discussed by Rahim et al. [104]. This type of diamond bonding was the dominant PCD bonding mechanism which holds
diamond particles together, as found by Shin et al. [62, 139]. This bonding was created during the sintering process, which was assisted by the graphitization of diamond in the presence of catalytic cobalt.

The results of quantitative analysis of tool sharpness are shown in Figure 85. Considering the standard deviation of the mean results, the in-feed was not found to contribute significantly to the edge radius, especially for the PCD with smallest grains. The obvious difference could only be observed on the PCD machined with high wheel velocities. The reason for such a phenomenon is not clear and further experiments are needed to elucidate the mechanism. However, there is a relatively proportional relationship between the surface roughness and the tool sharpness. In general, the edge morphology of eroded and ground PCD (with lowest wheel velocity and feed rate) was found to be identical, as shown by the SEM images in Figure 86.

**Figure 85**: Cutting edge radius: (a) CTX002 ground surface; (b) CTB010 ground surface; (c) CTX302 ground surface; (d) Eroded surface
Chapter 7. Tool Quality Investigation and Performance Analysis

7.3.2. Residual Stress and Graphitization Analysis

Figure 86: SEM image of the cutting edge CTB010 prepared by different methods: (a) EDG erosion; (b) Conventionally ground with 10m/s wheel velocity 5µm in-feed

Figure 87a to Figure 86c show the Raman value of diamond peak (D-peak between 1310 and 1335 cm⁻¹) obtained from the ground surface. According to Equation 7.3, the results indicate that most of the ground PCD exhibits compression residual stress, because the values were greater than the unstressed D-peak value of 1330cm⁻¹. This result matched the values achieved by Erasmus et al. [8]. To analyse the effect of PCD grain size on the value of residual stress generated, the deviation in Raman value for every PCD grade were compared. The phenomenon that PCD with smaller grain size has larger deviation indicates that a significant change in residual stress occurred with the change of grinding parameters. The smallest PCD grain (CTX002) produced the maximum Raman value of 1334cm⁻¹, which corresponds to residual stress of 1.4 GPa. Due to the higher strength of a coarser PCD grade [155], CTM302 exhibited a smaller shift in D-value, and the maximum compression residual stress is only 0.7 GPa.

In the case of EDG, the erosion process stressed the surface in a tensile direction. It should be noted that, even though no morphological changes were observed with different finishing in-feed, there was a noticeable difference in the residual stress values, where values in the range of 1316.4cm⁻¹ to 1328.7cm⁻¹ were recorded, which
indicates the values of residual stress were 4.7GPa and 0.7GPa, respectively. Also, as shown in Figure 87d, it is clear that the highest D-peak value was obtained in samples prepared with the highest finishing in-feed; this indicates that lower surface stress was due to the reduction of tensile residual stress. 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 [104].

However, although a 40µm finishing in-feed was applied, the highest D-peak values obtained by EDG were found to be approximately 2cm⁻¹ lower than the unstressed diamond (refer to the D-peak value of CTM302). This indicates a certain degree of tensile residual stress exists under the surface even with the highest finishing in-feed implemented. Since the Raman D-peak values were obtained with 30µm and 40µm in-feed, which are not different significantly, it can be regarded that tensile residual stress of CTM302 reached its minimum limit. Due to the higher thermal conductivity of the coarser PCD, a shallower heat-affected depth could be expected. In fact, the lowest percentage of cobalt (as described in Table 14) among the other PCD grades contributed to the lowest expansion difference between diamond and cobalt matrix.
Chapter 7. Tool Quality Investigation and Performance Analysis

Figure 87: Raman value of the Ground PCD: (a) CTX002 ground surface; (b) CTB010 ground surface; (c) CTX302 ground surface; (d) Eroded surface

Raman analysis of the machined surface provides the necessary evidence to prove the existence of graphite material. However, it is not stringent to directly conclude that the graphitization happened in the grinding process, since graphite material is a part of PCD elements formed during the sintering process [104]. Different levels of graphitization exist in different PCD grades after sintering due to different proportions of cobalt content. The smaller diamond-to-cobalt contact area will consequently reduce graphitization. The graphitization caused by the grinding can only be confirmed by the relative comparison of the graphite level before and after the process. In this study, the relative comparison of the graphitization level of ground and eroded PCD was conducted by comparing the Raman intensity ratio between the graphite peak, G-peak (1580- 1800 cm\(^{-1}\)) and D-peak. It is known that the higher the G/D ratio, the higher the graphitization level [131, 132]. Figure 88 and Figure 89 show the D-peak and G-peak values obtained by the Raman spectra of ground and eroded surfaces, respectively. The higher graphite peak associated with the erosion process is due to the higher processing temperature. Also, changing the
finishing in-feed from 10µm to 40µm resulted in a significant difference in graphitization level in the EDG process. The graphitization reduces the hardness of PCD and causes abrasive wear during the application [95]. As reported by Yingfei et al. [95], diamond-graphite conversion can also result in severe diffusive wear that will affect the consistency of the tool quality. This highlights the necessity of the finishing process, which will not only ensure achieving the desired surface topography, but also the removal of the highly stressed and graphitized structure. The high graphitization level of machined PCD tools may be the cause of diffusive wear in ultra-precision machining reported by Yingfei [95], where the machining temperature was expected to be lower than the diamond-graphite conversion temperature.

Several peaks were observed on the Raman spectrum of ground PCD. In addition to the D-peak and G-peak, as discussed before, an additional peak at ~1250 was observed, indicating the presence of nanocrystalline diamond [128]. Similar to graphite material, nanocrystalline diamond is also a part of unmodified (as sintered) PCD. In contrast, the spectra obtained from the eroded PCD section demonstrate only the presence of graphite and diamond. As the nanocrystalline diamond normally accumulates at the grain boundary, the graphitization caused by the catalytic action of cobalt in contact would be expected to quickly eliminate all diamond nanoparticles during high-temperature erosion.
Figure 88: Raman spectra of ground polycrystalline diamond
Figure 89: Raman spectra of eroded polycrystalline diamond
7.3.3. Performance Test

It is observed that graphitization and residual stress are the significant factors affecting tool life. 3D images in Figure 90 demonstrate that the greatest wear resistance occurred on the PCD that has been eroded with highest finishing in-feed. A groove of 80 µm in depth, closely similar to the one produced by the ground PCD, was created by the eroded cutting tool that had been prepared with the highest finishing in-feed. As mentioned in Section 7.3.2, the high quality of PCD tools was attributed to having the lowest graphitization and tensile residual stress. For eroded PCD tools prepared with the smallest in-feed value, the tool failed at the earlier stage, and thus the shallow groove was produced.

After the grooving test, fine grooves and chipping or breakage were observed on the PCD tools. The generation of the fine grooves indicates it was an abrasive wear mechanism and it happened as a result of the surface softening of the PCD. It was reported that abrasive wear happened due to graphitization as a result of the chemical interaction between PCD tool and the work piece [95]. In this study, it was noticeable that the level of abrasive wear was influenced by the graphitization level generated by the tool preparation process. Higher graphitization level of eroded PCD machined with smaller in-feed led to a wider abrasive wear. In fact, the abrasive wear did not appear on the ground tools that were more prone to fractured wear. Similar wear behaviours were found on all PCD types used in this investigation, as shown in Figure 91, Figure 92 and Figure 93.
Figure 90: 3D images of the worn cutting tools, grooves prepared by specific PCD tools insert and their cross-sectional profile: (a) Eroded CTB010 (10µm finishing in-feed); (b) Eroded CTB010 (40µm finishing in-feed); (c) Ground CTB010 (10m/s machining velocity, 0.2mm/min feed rate)
Figure 91: Wear mode of the cutting tools (CTX002): (a) Eroded (10µm finishing in-feed); (b) Eroded (40µm finishing in-feed); (c) Ground
Figure 92: Wear mode of the cutting tools (CTB010): (a) Eroded (10µm finishing in-feed); (b) Eroded (40µm finishing in-feed); (c) Ground
Figure 93: Wear mode of the cutting tools: (CTM302) (a) Eroded (10µm finishing in-feed); (b) Eroded (40µm finishing in-feed); (c) Ground

The EDS spectrum obtained from point A in Figure 92a indicates the existence of adhesive tungsten in the abrasive wear region. As shown in Figure 94, the dominant tungsten material consists of 64.04% of the total composition of the material in that particular area. The adhered material remained in that place after the machining process due to the better fracture resistance. The surface was abraded slowly and the adhesion process was continuously happening. Although minor breakage mode could
be observed, adhesive material remained in the major portion of the wear region. Ground PCD exhibited a different diamond grain loosening mode. A high proportion of PCD grains fractured during the grooving, thereby exposing the fresh breakage PCD without the appearance of adhesive material on the surface.

As tool dimension is important to maintain machining accuracy, the dimension of the PCD tool was inspected at the end of the process. Since the grooving test tends to flatten the nose of the inserts, the “cutting tip shortening” (the wear out distance) was defined as the most suitable performance indicator (Figure 95a). The analysis on the cutting force, particularly the normal force in z-direction of the grooving process, shows that there was a good relationship between cutting force and the tip shortening (Figure 95b). Normal cutting force was higher at the higher wear value due to the reduction in its surface shearing ability, caused by the blunted cutting edge.
As discussed in Section 7.3.1, all eroded PCD with similar grade are closely similar in roughness and sharpness. Hence, it can be concluded that the difference in their performance (tool life) was caused by the difference in residual stress and graphitization. From Figure 96 it can be observed that the increase in finishing in-feed or depth produced better tool quality, which was caused by the lower
graphitization and residual stress. Conversely, although being better in surface residual stress, ground PCD exhibited higher wear level than the PCD that was eroded with 40 micron finishing in-feed. Internal cracking of the diamond-to-diamond bonding underneath the surface due to the mechanical stress might cause lower PCD toughness, and result in the fracture mode even though lower residual stress was obtained. As in most cases, micro-cracking often occurred in the mechanical machining of PCD, including polishing [156-158].

In addition, it was found that the difference in radius and surface finish produced by different grinding parameters did not cause significant difference to the cutting force, as shown in Figure 97. This finding indicates that invisible factors (residual stress and graphitization) could be regarded as the main reason that contributes more significantly to tool failure. However, the influence of each invisible factor could not be distinguished, since they were found to be directly proportional to each other. Since both factors are directly influenced by temperature, they concurrently decrease or increase, depending on the regional temperature. In fact, the diamond to graphite phase transformation also causes permanent volume expansion of the phase, thus contributing to the evolution of residual stress in that region.

![Figure 97: Cutting force produced by ground PCD](image-url)
7.4. Conclusion

Both abrasive grinding and erosion processes are capable of producing similar surface roughness (Ra) and edge sharpness. In this study, a grinding speed of 10 m/s with a feed rate of 0.2 mm/min produced identical morphology to that of the eroded PCD. Except for the largest PCD grade size, higher roughness was obtained by the conventional grinding process due to its higher bulk hardness value.

Increasing wheel speed in the conventional grinding process produced worse surface finish as well as reducing cutting edge sharpness. In EDG, similar roughness and sharpness were achieved regardless of the finishing in-feed implemented. This proved that the minimum finishing depth was sufficient to clean the residue surface left by the preceding roughing process. Although the indexes of visible quality (surface roughness and sharpness) are closely similar in both processes, this does not guarantee that similar tool qualities were achieved due to the difference in residual stress and graphitization level. Overall, ground PCD produced lower graphite than the eroded process due to the lower processing temperature. Machining force introduced in grinding caused the generation of compression residual stress on the PCD surface. On the other hand, the high-temperature in the EDG erosion stressed the surface toward tensile direction. Increasing the finishing in-feed was able to produce better surface quality by means of lower residual stress and graphitization level.

For many years industry-acceptable PCD tools have been judged by both fabricators and end users alike on visible surface quality only: surface roughness and edge sharpness. Residual stress and graphitization level inside the PCD tool is currently an open factor that is not measured after the machining process. These factors were found to be significantly affected by the selected machining parameters, and process selection thus highlights the importance of the evaluation of these invisible quality indexes.
Higher tensile residual stress and graphitization lead to lower strength of PCD. Thus, this results in more severe tool wear after the grooving tests. A highly graphitized structure was found to be the reason for abrasive wear of the tools. This paper highlighted the essential requirements for understanding the degree of thermal damage based on machining parameters. It is important to ensure that the residual stress is in the acceptable range. The finishing process is required not only to achieve the desired surface topography, but also to remove the highly stressed and graphitized structure to achieve better tool performance. The invisible quality factors have a more significant effect on PCD tool life.
Chapter 8 Tool Quality Assessment and Validation

8.1. Introduction

It was shown in Chapter 7 that higher finishing in-feed of the finishing process resulted to the better tools performance due to the higher removal of the damaged structure. The grooving test revealed that different wear modes occurred in the tools that were prepared with different processes: fracture mode for the ground PCD and abrasive mode for the eroded PCD. However, the analysis was done using a simple kinematic test. In order to further investigate tool performance, as well as to mimic the real machining situation, longer machining duration was implemented. In this case, the PCD prepared with different machining method and strategies were used in the turning process of titanium alloy. Instead of the 2-stage eroded (roughing and finishing erosion) and ground PCD, an additional tool was prepared with 3-stage erosion of roughing, semi-finishing and finishing. Since higher in-feed of the low energy erosion was applied, 3-stage erosion was expected to produce better tool quality.

Part of this chapter has been used in the following publication:
8.2. Methodology

The turning experiment was conducted on a CNC lathe (Okuma Genos L200E-M), as illustrated in Figure 98. A titanium alloy bar of Ti-6Al-4V (Grade 5) was used as the work piece in this process. Table 16 and Table 17 show the properties and chemical composition of the work piece, respectively.

**Table 16: Properties of Ti-6Al-4V used**

<table>
<thead>
<tr>
<th>Material</th>
<th>Density, kg/m³</th>
<th>Hardness, Vickers</th>
<th>Elastic Modulus, GPa</th>
<th>Poisson’s Ratio</th>
<th>Thermal Conductivity, W/m.K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-6Al-4V</td>
<td>4430</td>
<td>349</td>
<td>113.8</td>
<td>0.342</td>
<td>6.7</td>
</tr>
</tbody>
</table>

**Table 17: Chemical composition of the work piece**

<table>
<thead>
<tr>
<th>Element</th>
<th>Ti</th>
<th>Al</th>
<th>V</th>
<th>Fe</th>
<th>C</th>
<th>O</th>
<th>N</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight percentage (Wt%)</td>
<td>88.3</td>
<td>6.5</td>
<td>4.3</td>
<td>0.3</td>
<td>0.1</td>
<td>0.3</td>
<td>0.05</td>
<td>0.02</td>
</tr>
</tbody>
</table>

The cutting speed of 160m/min, feed rate of 0.15mm/rev, cutting depth of 0.2mm, and negative rake angle of 3° were used. Synthetic coolant was flushed onto the turning point during the operation to overcome the generation of excessive temperatures. Differing from the preceding grooving experiment, only CTB010 PCD grade size was used in this investigation. The inserts were prepared with different machining strategies as follows:

a. Conventional grinding by using a grinding speed of 10m/s, feed rate of 0.2mm/min, grinding load of 10kg and oscillation rate of 15mm/sec. (similar erosion parameters as used in Chapter 7);

b. EDG by using 2-stage erosion of roughing and 40 µm finishing in-feed (similar erosion parameters as used in Chapter 7);

c. EDG by using 3-stage erosion (roughening, semi-finishing, and finishing).
Similar machining procedures as previously discussed in Chapter 7 were implemented. Except for the 3-stage eroded PCD, erosion parameters as shown in Table 18 were applied.

![Figure 98: Experimental setup for the turning test](image)

**Table 18: 3-stage erosion parameters**

<table>
<thead>
<tr>
<th>Operation</th>
<th>Wheel electrode polarity</th>
<th>Open-Voltage (V)</th>
<th>Wheel rotation speed (rpm)</th>
<th>Current (A)</th>
<th>On-time (µs)</th>
<th>Off-time (µs)</th>
<th>In-feed (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roughing</td>
<td>Positive</td>
<td>120</td>
<td>250</td>
<td>12</td>
<td>40</td>
<td>20</td>
<td>0.5</td>
</tr>
<tr>
<td>Semi-finishing</td>
<td>Negative</td>
<td></td>
<td></td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>0.04</td>
</tr>
<tr>
<td>Finishing</td>
<td>Negative</td>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>0.03</td>
</tr>
</tbody>
</table>

In this study, tool wear and titanium-machined surface were examined and quantified at every 1, 3, 6 and 10 minutes of the turning process using the Alicona microscope.
The high resolution images of the worn PCDs were collected using the Scanning Electron Microscope (SEM) to enable the tool wear mode analysis.

**8.3. Result and Discussion**

Since higher in-feed was implemented for the 3-stage eroded PCD, lower tensile residual stress was generated under the surface. As shown in Figure 99, in comparison with 2-stage eroded PCD, a higher Raman value was obtained by the 3-stage eroded PCD, indicating lower tensile residual stress. From Chapter 7, it was also known that the ground PCD exhibited compression residual stress, since higher a Raman value than the unstressed D-peak value of 1330 cm\(^{-1}\) was obtained.

![Image](image.png)

**Figure 99:** Raman analysis of the PCD surface

It was stated in Chapter 6 and Chapter 7 that the graphitization level could be determined by comparing the Raman intensity ratio between graphite peak, G-peak (1580-1800 cm\(^{-1}\)), and Diamond peak, D-peak (1330-1335 cm\(^{-1}\)). However, since the finishing in-feed implemented in this investigation was more than the thickness of the observed simultaneous graphitization layer (approximately 10\(\mu\)m to 30\(\mu\)m, as shown in Figure 64 of Chapter 6), insignificant D/G peak intensity ratio was
observed. However, it is not stringent to conclude that all PCD samples exhibited similar graphitization level. Closely similar intensity ratios observed might due to the limited sensitivity of the Raman equipment used. Nanocrystalline diamond peaks that only exist on the Raman spectrum obtained from the ground PCD showed that it exhibited the lowest graphitization level. Conversely, the nanocrystalline that disappeared in eroded samples was due to higher graphitization, as elaborated in Section 6.3.1 and Section 7.3.2.

In the performance investigation, the tool life was defined based on the tool flank wear ($V_c$). Figure 100 shows the propagation trend of the wear for PCD tools prepared with different machining strategies. The results show that the ground PCD exhibited the highest flank wear rate in comparison with the other PCD specimen. This was followed by the 2-stage eroded PCD and 3-stage eroded PCD, respectively. Differing from the other PCD tools, 3-stage eroded PCD underwent a fairly uniform wear rate, indicating a better wear resistance. It thus validated the author’s previous finding in Chapter 7 that better performance of PCD tools was obtained when higher finishing in-feed was implemented in the erosion process. Deeper surface removal by low energy erosion resulted in better tool durability. In this study, 3-stage eroded PCD was machined with a total of 70µm low energy erosion where 30µm finishing process was used in addition to 40µm semi-finishing operation. The higher depth of low energy erosion caused the higher removal of the damaged surface generated by the preceding roughing process.

![Figure 100: Flank wear after each stage of turning experiment](image-url)
Figure 101 and Figure 102 show the tool failure modes after 30 seconds and 10 minutes of the machining process, respectively. The results indicate that, after 30 seconds of the turning process, the tools undergo similar wear mode, as previously discussed in the grooving test section (Chapter 7). The fracture mode was obviously observed on the ground cutting tools edge, while abrasiveness was the predominant wear mode for both eroded PCDs. From the figure, it can be observed that after 10 minutes of the turning process, the fracture-look surface for ground PCD has disappeared. At this stage, 50µm nose width vanished, and a smooth worn surface was produced. Although surface morphology was approximately similar to the eroded PCD after 10 minutes of the turning process, it suffered largest flank wear.

As reported by Bordin et al. [159], the rake face wear development rate increased the chip contact length (length of contact between chip and tool rake face). The chip contact length can be determined by measuring the length of the sliding zone or wear traces that is parallel with the chip moving direction as shown in Figure 103. Bigger chip contact length led to progressive increase of the machining temperature, caused by the higher friction energy that was generated during the chip-tool abrasion process. In fact, the intimate contact between the rake face and the chip reduced coolant penetration, increased the friction, and shortened tool life [159]. Hence, significant fracture wear mode or significant abrasive mode that developed at the early machining stage should be avoided, since it will cause increases in chip contact length and consequently accelerate the wear process.

Instead of the rake face analysis, the chip morphology will also represent the length of the chip contact. Bigger curvature of the chip indicates the longer contact of the chip with the rake surface. Smaller curvature indicates that the chips were lifted upward earlier and separated earlier from the tool surface [159]. Significant difference in the type of chip produced was observed as early as 30 seconds of the turning process. It was found that the continuous chip with bigger curvature was developed by the ground and 2-stage eroded PCD caused by the bigger rake face wear (see Figure 101b and Figure 101c). Nevertheless, the 3-stage eroded PCD persistently produced smaller curvature of segmented chips due to its ability to
maintain the edge sharpness up until 10 minutes of the machining process. Figure 103 shows the type of chips produced by different PCD and their relationship with cutting edge morphology. It can also be observed that longer chip contact was generated as a result of the bigger rake face wear.

Figure 104 and Figure 105 show the groove-like profile of the work piece surface obtained by the Alicona microscope. In the images, the depth is encoded in colour. The observation of the tungsten machined indicates that the grooves produced by the 3-stage eroded PCD after 1 minute’s machining is deeper than the grooves produced by the other tools. The groove depth is also consistent up to 10 minutes of the turning process. For the surface machined by 2-steps eroded and ground PCD, approximately 20µm and 25 µm reductions in the groove depth, respectively, were observed.
Figure 101: PCD tools after 30 seconds of the turning process: (a) 3-stage PCD; (b) 2-stage PCD; (c) Ground PCD
Figure 102: PCD tools after 10 minutes of the turning process: (a) 3-stage PCD; (b) 2-stage PCD; (c) Ground PCD
Figure 103: PCD nose wear and their effect to the chip formation after 10 minutes of the turning process: (a) 3-stage eroded PCD; (b) 2-stage eroded PCD; (c) Ground PCD
Figure 104: Work piece surface after 1 minute machining: (a) 3-stage eroded PCD; (b) 2-stage eroded PCD; (c) Ground PCD

Figure 105: Work piece surface after 10 minute’s machining: (a) 3-stage eroded PCD; (b) 2-stage eroded PCD; (c) Ground PCD
8.4. Conclusion

Through the turning process of the titanium alloy, the result obtained in Chapter 7 was successfully validated. In line with the previous finding, the results show that the invisible quality factors are substantially important for determining final tool quality. Comparing the tool performance of 2-stage and 3-stage eroded PCD, the quality factors (residual stress and graphitization) significantly affect the tool performance. In this study, 3-stage eroded PCD successfully achieved 1.5 times better wear resistance (considering flank wear) than 2-stage eroded PCD after 10 minutes of the turning process. Similar to the author’s finding in the grooving test, although the ground PCD exhibited the lowest tensile residual stress and graphitization level, the tool quality was the lowest among the tool candidates. The significant appearance of fracture mode at the early machining stage is a good indication of the availability of internal cracks that are typically associated with the grinding process due to the mechanical force used in the removal process. The early failure mode was considered to be the reason for the higher wear rate at the later stage of the machining. Larger flank wear on ground and 2-stage eroded PCD at the early machining stage contributed to the longer chip contact. The intimate contact of the chips isolated the PCD surface from the coolant contact and thereby caused the higher machining temperature. Thus the wear process was accelerated.
Chapter 9 Summary

9.1. Summary

The effects of plasma temperature on the eroded PCD surface were discussed in detail in this thesis. Raman analyses are the methodologies implemented for the residual stress and graphitization measurement. With reasonable penetration depth closer to HAZ thickness, together with small laser spot size, Raman analysis is regarded as the best measurement strategy. Through novel approaches, it was found that the roughing process is the main contributor to the residual stress on the surface. HAZ that consisted of oxidised metal and graphitised PCD appeared for several micrometres depth, with the value varied with different machine parameters setup.

At the beginning of the research, several issues assumed as thermal damage indications cause by the process were highlighted. These include the formation of a porous surface, cutting edge undercut and some cosmetic aspects at the WC-PCD interface. It was concluded that the negative polarity of the wheel was the best finishing strategy to obtain the optimum surface finish and removal rate. A porous surface was produced by the positive wheel polarity erosion method due to the selective erosion of cobalt metal. Conversely, a smooth surface was produced by the negative wheel polarity erosion method. The availability of a deposited conductive “black layer” on the eroded surface hindered selective erosion, and thus the smooth surface was produced. In fact, the machining efficiency increased with the thicker black layer formed; an increase in erosion rate of 250% was recorded.

In the wheel rotation direction investigation, author found that best edge quality was produced by PCD-to-WC wheel direction. It was proved that the moving direction of the debris was significantly influenced by the centrifugal force generated by the
rotating electrode. PCD-to-WC wheel rotation direction ensured that fresh dielectric was supplied to the cutting edge. However, when the wheel rotated in WC-to-PCD direction, the centrifugal force generated would bring the debris toward the cutting edge, thus increasing the probability of spark concentration. This resulted in sharpness reduction, worse surface finish, a rougher edge and edge undercut. Moreover, the study is regarded as the first that successfully resolved the unexplained issue of the PCD edge undercut. The study also answered industrial doubts as to whether or not notch width and WC backing appearance indicate the level of thermal damage. It was found that these two indications have no relation with thermal damage. A wider notch appeared due to spark concentration on the WC-PCD interface.

There was comprehensive discussion of the removal mechanism involved in PCD erosion. With the aid of the morphological findings, it was proved that removal through fracture occurred in the roughing operation. A model for the thermal stress prediction was developed and found to have good agreement with the findings. Kozak et al. [122] concluded that dislodgement of diamond particles happened when tensile stress reaches the limits of cobalt. However, based on extensive experiments, it was found that their conclusion was incorrect. Rather, diamond-to-diamond bonding is the primary bonding mechanism in PCD, where grain dislodgement occurred in the roughing operation when the stress was larger than the tensile limit of diamond.

High temperature used for the roughing erosion also resulted in the partial conversion of diamond to graphite phase under the surface. A modified zone with a thickness up to 20µm appeared, resulting from the simultaneous or explosive graphitization of diamond under the surface. Through the Raman method, it was found that the surface eroded by the roughing operation suffered from a very high tensile residual stress (approximately 8GPa tensile residual stress was generated under the eroded surface). This signified the need for a finishing process, not only to achieve the desired surface topography, but also to get rid of the high stressed PCD structure. In finishing, the sparking energy produced was insufficient for the
breakage phenomenon to occur. It was discovered that graphitization was a dominant removal mechanism. Similar to the roughing process, residual stress was also generated by the finishing process, but with a smaller value. A combination of smaller sparking energy, smaller pulse duration (on-time) and longer inter-pulse delays (off-time) minimised the cumulative residual stress generated by the finishing operation. With higher finishing in-feed (finishing depth), better surface quality by means of lower surface graphitization and lower tensile residual stress were produced. In addition, the residual stress obtained after the finishing process was found to be in agreement with the calculated theoretical value.

In this research, the graphitized PCD and residual stress were considered as the heat damage induced by the EDG. The grooving test was implemented for assessing the significance of this thermally induced defect for performance quality of the tool. In this investigation, the PCD tool performance produced by the two processes (EDG and abrasive grinding) was compared. Closely similar visible surface quality (surface roughness and tool sharpness) was obtained by both processes. However, it was found that there was a significant difference in residual stress and graphitization level. In this study, residual stress and graphitization induced by both processes were analysed quantitatively with the Raman method. Maximum compression residual stress of 1.4GPa was recorded in the ground PCD of the smallest grade size. Minimum compression residual stress of 0.7GPa was found in the PCD of the biggest grade. Conversely, in the EDG-eroded PCDs, the dominant residual stress was tensile stress, with values in the range from 4.7GPa to 0.4GPa. Through cutting tests, it was revealed that the residual stress and graphitization influenced the wear mechanism of the tool. It was also observed that abrasive wear dominated the wear pattern of the highly graphitized PCD tools, while breakage through fracture was the main wear mechanism for abrasively ground PCD, which has a structure of lower level graphitization. It was proved that, with the implemented parameters, best tool life was obtained by the PCD that was eroded with the highest finishing in-feed.

For many years industry-acceptable PCD tools have been judged by both fabricators and end users alike on visible surface quality only: surface roughness and edge...
sharpness. Residual stress and graphitization level inside the PCD tool is currently an open factor that is not measured after the machining process. In this study, these factors were found to be significantly affected by the selected machining parameters and process selection, thus highlighting the importance of the evaluation of these invisible quality indexes. Therefore, this research has contributed to new scientific understanding of the factors that affect PCD tool life.

Based on the previous theoretical model developed, increasing finishing in-feed will result in better tool quality, but consequently the machining time increases. For this reason, 3-stage EDG (roughing, semi-finishing, and finishing) with total in-feed of 70µm was proposed. The result from the Raman analysis proved that 3-stage machining minimized the final residual stress and graphitization on the surface. Through the titanium alloy turning experiment, it was found that the three-stage process exhibited the best wear resistance. In addition, the results obtained from the grooving test were also validated through this turning experiment. Although showing lower wear resistance than the 3-stage eroded PCD, a 40µm finish eroded PCD again demonstrated better wear resistance than ground PCD. Observation on the tool wear development indicated that the ground PCD undergoes fracture mode wear at the early wear stage (machining duration of 30sec) similar to that found in the grooving test.

Overall, the following four main innovation were achieved:

a. A new thermal residual stress model was developed.
b. A new PCD erosion mechanism was found.
c. A new approach for PCD thermal damage evaluation was developed.
d. A novel theory of PCD tool failure was discovered.
9.2. Future Work

9.2.1. Investigation on Material Removal Rate

The root cause that results in the low machining efficiency of PCD is its poor electrical conductivity caused by the special physical structure, particularly for PCD sintered with large-size diamond particles. This problem has not been addressed by any research and it is likely to be the reason why no significant increase in EDG efficiency had been achieved. In this study, it was proved that the electrical conductivity of PCD would be increase through covering the work piece surface, including the exposed large diamond particles with non-conductive cobalt covering it, with conductive material (Chapter 4). The increase in MRR was caused by the continuous accumulation of conductive particles, which consist of carbon and wheel elements. These particles migrated to PCD surface in the similar way to those used for modifying the work piece surface using EDM [160] and EDM machining of nonconductive material with assisting electrodes [161]. The formation of the conductive layer, or the “black layer”, increased the conductivity of PCD and thereby resulted in a significant increase in effective normal discharging pulses.

Further exploration on the effect of several conductive materials on the PCD surface might be undertaken and it would be beneficial for a more effective erosion process. The conductive material will come from four sources: suspended micro-particles added in the dielectric, carbon particles decomposed from the dielectric fluid, material migrated from the electrode, and micro debris. Significant increase in machining efficiency will be achieved through the increased electrical conductivity of PCD. Any conclusions drawn from this study will be applicable to the machining of other low-conductivity or non-conductive materials.

9.2.2. Mathematical modelling of thermal residual stress

Residual stress inside the PCD tool is currently an open factor which is not measured after the EDM process; its determination in industry is more reliant on empirical models. The mathematical model developed in this thesis will be fundamental to the
development of an accurate erosion model. Unlike this residual stress model, which uses only idealized thermal models by assuming a smooth EDG process without any abnormal pulses, it is recommended that a new thermal model be developed to integrate the factors such as abnormal discharging pulses, graphitization and catalyst debris. Since these will affect the energy distributions, a more accurate thermal model could be expected.

9.2.3. An extensive investigation on PCD tool invisible quality

Two invisible quality factors of PCD were introduced in this study. As stated in Chapter 6, residual stress and graphitization were influenced by EDG sparking parameters of the finishing process. A lower on-time (pulse duration) to off-time (pulse interval) ratio was highlighted as a factor that will reduce the tensile residual stress and graphitization level of PCD. However, due to the limitation ability of the pulse generator used, 1µs was the minimum pulse on-time that could be generated. Increasing the pulse interval is not the interest, since this will reduce the spark frequency and consequently reduce the material removal rate.

Because of this, a nanosecond pulse of current developing pulse generator was expected to produce better quality of PCD. However, to maintain or probably increase the erosion rate, the sparking current should be increased to compensate for the energy reduction caused by reduction in pulse duration. Yet, due to immature needle pulse generator technology, the effect of nanosecond pulse duration on PCD quality remains in question and this thus requires further investigation.
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