Experimental study on quality of PCD tools machined by different electric discharge grinding processes

Guangxian Li*, Mohammad Zulafif Rahim², Songlin Ding¹, Shoujin Sun¹ and John Mo¹

Abstract: Polycrystalline diamond (PCD) is a promising tool material which is utilized to cut difficult-to-machine materials used in aerospace industry. Because of its ultra-hardness, electrical discharge grinding (EDG), a variation of electrical discharge machining, is often adopted to manufacture PCD tools to reduce manufacturing time. This paper investigates the quality of PCD inserts manufactured by two different EDG eroding methods: “2-step machining” and “3-step machining”. Surface roughness and residual stress were investigated after EDG process. An orthogonal cutting experiment was conducted to test the performance of each PCD insert. PCD tools machined with the two methods do not have significant difference in surface roughness. The residual stress status changed from compressive to tensile after EDG process. Also, after being eroded by 3-step EDG process, there was an over 30% declination of residual stress compared with 2-step machining. The results of the orthogonal cutting test showed that the wear amount and the thrust force of PCD inserts machined by 3-step EDG were smaller for the CTB010 insert and the CTX002 insert. In contrast, the CTM302 machined by 3-step EDG did not show obvious improvement in tool wear resistance during the cutting tests.

Keywords: polycrystalline diamond; electrical discharged machining; surface roughness; residual stress; thrust force; wear amount

ABOUT THE AUTHORS
Guangxian Li is a PhD student in school of engineering, RMIT university. He is now majoring in the quality of PCD tools machined by different methods, and their performance in machining titanium alloys. Compared with WC tools, PCD tools have longer tool life but more difficult to machine due to its high hardness. EDG is a grinding method which had higher material removal rate but the thermal defects such as residual stress is inevitable. This paper investigates a “3-step” grinding method which adds a finishing process between the roughing and finishing processes. By using the 3-step grinding method, the residual stress on machined surface was reduced, which improved the tool quality and the performance in cutting process.

PUBLIC INTEREST STATEMENT
High-performance tools are in large demand for the cutting of hard-to-machine materials. Recently, polycrystalline Diamond (PCD) becomes a promising tool material which is utilized to cut materials used in aerospace industry, such as titanium alloys and carbon fiber reinforced plastics. Due its ultra-hardness and high abrasion resistance, electrical discharge grinding (EDG) is often adopted to manufacture PCD tools in order to reduce the time spent on the tool manufacturing process. However, thermal defects generated during the EDG process is inevitable and strongly influences the tool quality and performance, which were influenced by the machining parameters and strategies of EDG. Optimization of the EDG process can improve the quality of PCD tools, which helps to save manufacturing cost and increase machining efficiency.
1. Introduction

Titanium alloys have been widely used in aerospace industry in recent decades because of their outstanding properties including low density and high strength (Park, Beal, Kim, Kwon, & Lantrip, 2011). However, the severe machining conditions reduce the life of conventional cutting tools significantly. For example, the high temperature and the diffusive-abrasive process at tool/workpiece interface and tool/chip interface cause severe crater wear on the tool rake face and flank wear on the tool flank face (Hartung, Kramer, & von Turkovich, 1982). As a result, the cutting speed is limited which affect the machining efficiency adversely when cutting these materials. For many years, tungsten carbide (WC) tools have been used in machining titanium alloys. However, its tool life becomes unacceptably short when applied in high speed cutting processes (larger than 100 m/min) (Su, Liu, Fu, & Xu, 2012). In order to extend the tool life, polycrystalline diamond (PCD) has been applied as a kind of advanced material to manufacture cutting tools. Its outstanding properties including significant hardness (over 8,000 HV), low friction coefficient and excellent thermo-conductivity of up to 500 W/mK at 573 K which is over three time of the WC’s thermal conductivity make it one of the most adoptable tool materials for machining Titanium alloys (Blank et al., 1998; Pan, Kamaruddin, Ding, & Mo, 2014). Experimental results proved that PCD tools have much longer tool life than WC tools in machining Ti-6Al-4 V with the same cutting speed (100, 200 and 300 m/min) (Oosthuizen, Akdogan, & Treurnicht, 2011).

However, due to the ultra-hardness and high abrasive resistance, it is extremely difficult to grind PCD tools to certain shapes. Conventionally, the surface of PCD tools can be ground by using a diamond grinder wheel. This abrasive grinding process provides really good surface roughness and sharp cutting edge although its machining efficiency is extremely low. In order to improve the material removal rate when manufacturing PCD tools, electrical discharge grinding (EDG), a variation of electrical discharge machining (EDM) process but with a rotational electrode, is now gradually be adopted in industry to manufacture PCD tools. Different from conventionally grinding which removes material mostly through physical abrasion, EDG erodes PCD by generating high-energy plasma between the workpiece and the metallic electrode which reduces the machining time significantly. In an EDG process, the thermal effect of plasma changes the distribution and status of residual stress. Similar to conventional grinding, EDG erosion is consisted of both roughing and finishing processes as well (Iwai, Ninomiya, & Suzuki, 2013). For the roughing process, material is removed by plasma with high energy generated by the discharge current. In the finishing process, small-energy plasma was generated to remove the material for refining the workpiece surface. Normally, four main types of discharge states (Liu et al., 2006) could be generated during the EDG process: normal discharge, open circuit, arc and short circuit, as shown in Figure 1. Except the first type which contributes to the removal of workpiece materials, other states are abnormal discharges. Both short and open circuit reduce EDM erosion efficiency because effective plasma channel were not generated during the on-time period. With the characteristic of very short or no ignition delay time, an arc damages the surface finish because it deteriorate the gap status and make the EDM process instability (Ding, Yuan, Li, & Wang, 2006; Jiang, Zhao, Xi, Gu, & Kang, 2012). The discharge states are classified by the following formula (Pey Tee, Hosseinnezhad, Brandt, & Mo, 2013):

\[
\begin{aligned}
  t_0 & = 0 & \text{short circuit} \\
  t_0 & < t_e & \text{arc} \\
  t_e & < t_o & \text{normal discharge} \\
  t_e & = t_o & \text{open circuit}
\end{aligned}
\]

where \( t_d \), \( t_e \), \( t_o \) represents the ignition delay time, pulse duration (time-on), and the threshold time (time-off) for arc identification, respectively. The ignition delay times show a big variation but the pulse on-time and off-time are the same (Hu, Ding, Brandt, & Mo, 2014).

However, because of the high temperature generated in the EDG process, thermal effect, which is inevitable, is detrimental to the quality of machined surface and affects the life and performance of PCD tools (Yadav, Jain, & Dixit, 2002). One of the problem is the thermal residual stress which...
reduces the surface abrasive resistance and weakens the grains boundaries (McNamara, Alveen, Damm, et al., 2015). As a kind of sintered tool, PCD is manufactured by diamond grains and certain metals (cobalt in this paper) as the secondary phase under high pressure and temperature (Tso & Liu, 2002). Due to the mismatch of thermal expansion coefficient between the diamond and the cobalt, residual stress is accumulated during three processes: the original sintering process, the later brazing and grinding process when fabricating the tool (Paggett, Drake, Krawitz, Winholtz, & Griffin, 2002). This thermal stress has significant influence on the fracture of PCD structure during the cutting process. According to Yahiaoui, Gerbaud, Paris, Denape, and Dourfaye (2013), tensile residual stress in the PCD layer could cause inner cracks, weaken the strength of diamond to diamond bonding, and reduce tool wear resistance. Other scholars investigated the effect of residual stress by finite element modelling (Chen, Xu, Ma, & Xu, 2010; McNamara, Alveen, Carolan, Murphy, & Ivankovića, 2015), the results showed that residual stress tended to concentrated at the PCD/cobalt interface, which caused the instability of the PCD structure. From the experiments conducted by Li, Rahim, Ding, and Sun (2015) and Rahim, Li, Ding, Mo, and Brandt (2015), it is found that residual stress is the main factor that influence the wear process of PCD tools, the machined PCD tools which had lower residual stress had better resistance to tool nose fracture and flank wear when cutting hard-to-machine materials. The status and value of residual stress was affected by many factors. It was assumed that the thickness of PCD layer influenced the distribution of residual stress in the entire PCD layer of an insert (Chen et al., 2010). In other words, the distribution of residual stress is depended on the thickness ratio of PCD layer and WC substrate. Moreover, the size of PCD grains affected residual stress on PCD surface as well. Larger compressive residual stress existed within PCD layer made of bigger diamond particles (for example 30 μm) (Jia et al., 2011). Ding and Mo (2015) proposed a detailed mechanism on the change of residual stress caused by the EDG process, it is found that the residual stress was mainly accumulated in the roughing process and mostly removed by finishing process. The value of residual stress was affected by the parameters selected in roughing process time-on, time-off, in-feed and current, and the in-feed in finishing process.

As a result, it is meaningful to machine the PCD tools with lower residual stress which have longer tool life and better performance in cutting processes. In this study, a new 3-step EDG machining method which added a sub-finishing step between roughing and finishing process was investigated. It is hypothesized that the added sub-finishing step could remove the material rapidly and to generate less residual stress at the same time. By adopting the 3-step EDG process, the quality of the PCD tools was improved, which including the reduction of residual stress on machined surface without induce
any defects on the tool geometric characters such as the increase of roughness of machined surface. Also, there was a comparison about the performance of PCD inserts machined by 2-step erosion and 3-step erosion respectively, which intended to examine the fracture resistance of PCD structures.

2. Experiment

2.1. EDM process of PCD inserts
In this study, six samples were prepared with three kinds of PCD materials consisted by different-size diamond grains manufactured by “Element Six”: CTX002 (2 μm), CTB010 (10 μm) and CTM302 (mix of 2 and 30 μm). The basic properties of the PCD materials are shown in Table 1. All the samples were cut into small cubes with the dimension of 7.0 × 7.0 mm from the PCD discs using a wire-cut EDM machine. The EDG process was conducted on a commercial EDG machine (Figure 2) which can provide voltage/current ranging from 200 V/20 A to 20 V/1 A. Different EDG strategies were adopted for each sample (Table 2). According to Table 3, larger machining parameters (current, time-on and time-off) were used in the roughing process to remove the superficial workpiece material as fast as possible. The while for both semi-finishing process and finishing process, time-on and time-off were of the same but the currents used were different. Both total in-feed and finishing in-feed for machining all the inserts were the same, which were 190 and 40 μm respectively.

After the grinding process, the roughness of machined surface was measured with “Alicona” optical microscope. PerkinElmer Raman Station 400F was utilized to measure residual stress. According to the Raman spectrum of the finished surface, residual stress is reflected by the shift of the peak which stands for the existence of certain material (Prawer et al., 2000). In this research, the spectrum of each insert was acquired with a 100 μm laser spot to analyze the types of carbon and status of residual stress on the machined surface.

2.2. Cutting test
The performance of machined inserts was investigated through a series of orthogonal cutting tests which were conducted on a three axis CNC milling machine (HAAS). The PCD tool was fixed on a tool holder. The rake angle of the setup is 10° and clearance angle is 6°; the workpiece was clamped on the dynamometer which was mounted on the table of the milling machine (Figure 3).

<table>
<thead>
<tr>
<th>Workpiece material</th>
<th>CTX002</th>
<th>CTB010</th>
<th>CTM302</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall thickness (μm)</td>
<td>3.18</td>
<td>3.18</td>
<td>3.18</td>
</tr>
<tr>
<td>PCD layer thickness (mm)</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Diamond fraction (Vol %)</td>
<td>84.8%</td>
<td>89.7%</td>
<td>91.4%</td>
</tr>
<tr>
<td>Cobalt fraction (Vol %)</td>
<td>15.2%</td>
<td>10.3%</td>
<td>8.6%</td>
</tr>
<tr>
<td>Grain size (μm)</td>
<td>2</td>
<td>10</td>
<td>2 to 30</td>
</tr>
</tbody>
</table>

Figure 2. Erosion process on a commercial EDG machine.
made of WC (Table 4) was used because it could accelerate the wear at tool nose within a short cutting length. A 25 mm (length) × 100 μm (depth) groove was carved on the WC surface by the tip of the PCD insert at a cutting speed of 15 m/min.

During the cutting process, the cutting forces in X direction and Z direction were recorded and processed via a force measurement system (Figure 4), which includes an 8 channel dynamometer (Kistler 9527B), a signal amplifier (Kistler 5070A), a data acquisition card (National Instrument DAQ 6036E), and software programs (MatLab and SignalExpress). 3D models of grooves (Figure 5(a)) were developed by using IF Edgemaster (Alicona 3D scanner) after the tests. By plotting the profile of grooves (Figure 5(b)), the wear amount of wear at tool nose, which was the difference between

Table 1. Machining parameters and PCD materials for different samples

<table>
<thead>
<tr>
<th>No. of sample</th>
<th>Machining method</th>
<th>PCD material</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2-step</td>
<td>CTX002</td>
</tr>
<tr>
<td>2</td>
<td>3-step</td>
<td>CTX002</td>
</tr>
<tr>
<td>3</td>
<td>2-step</td>
<td>CTB010</td>
</tr>
<tr>
<td>4</td>
<td>3-step</td>
<td>CTB010</td>
</tr>
<tr>
<td>5</td>
<td>2-step</td>
<td>CTM302</td>
</tr>
<tr>
<td>6</td>
<td>3-step</td>
<td>CTM302</td>
</tr>
</tbody>
</table>

Table 2. Machining parameters for two-step EDG and three-step EDG processes

<table>
<thead>
<tr>
<th>Stage</th>
<th>Two-step machining</th>
<th>Three-step machining</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time-on (μs)</td>
<td>Time-off (μs)</td>
</tr>
<tr>
<td>Roughing</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>Semi-fin</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Finishing</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 3. Machining parameters and PCD materials for different samples

<table>
<thead>
<tr>
<th>No. of sample</th>
<th>Machining method</th>
<th>PCD material</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2-step</td>
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</tr>
<tr>
<td>2</td>
<td>3-step</td>
<td>CTX002</td>
</tr>
<tr>
<td>3</td>
<td>2-step</td>
<td>CTB010</td>
</tr>
<tr>
<td>4</td>
<td>3-step</td>
<td>CTB010</td>
</tr>
<tr>
<td>5</td>
<td>2-step</td>
<td>CTM302</td>
</tr>
<tr>
<td>6</td>
<td>3-step</td>
<td>CTM302</td>
</tr>
</tbody>
</table>

Table 4. Mechanical properties of tungsten carbide

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mohs hardness</td>
<td>7.5</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>42 W/mK</td>
</tr>
<tr>
<td>Elastic modulus</td>
<td>90 Mpsi</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>580 Mpsi</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.24</td>
</tr>
</tbody>
</table>
cutting depth and groove depth, was obtained. A Philip 30XL Scanning Electronic Microscope was utilized to examine the worn tool surface. Morphology and adhered materials on the worn surface were checked to investigate wear mechanism of different PCD tools.

3. Result and discussion

Tool quality was investigated after the EDG processes and cutting tests which include the roughness and residual stress of machined surface, and the wear resistance of each inserts. Roughness of machined surface was measured by “Alicona” optical microscope with a magnitude of 50 times. For each surface of one sample, five different positions on each machined surface were sampled and the roughness was the average value of them. According to the measured results (Table 5), there was no obvious difference in the roughness of machined surface regardless the methods of EDG process. Generally, the measured values are all around 100 nm which indicates that both EDG processes got fine surface profile after machining. To be specific, the surface of inserts consisting of larger size grains is rougher, the roughness of CTX002 is generally smaller than that of CTB010 and the roughness of CTX302 is the biggest. The difference in volume fractions of cobalt in CTX002, CTB010 and CTM302 leads to the difference in conductivity of these PCD inserts. For CTX002, the better electrical conductivity and evenly distributed diamond grains ensured the generation of normal sparks which made the surface roughness smaller after erosion. In contrast, CTM302 was consisted of 2 and 30 μm diamond grains, and its electrical conductivity was relatively poor due to its smaller volume fraction of cobalt. This made the status of plasma less stable than that of CTX002 and caused large surface roughness. Furthermore, the surface roughness of eroded surfaces after 3-step eroding did not present an ascending or descending trend compared with the roughness after 2-step eroding. Only the roughness of CTB010 was reduced from 100 to 98.3 nm after the 3-step EDG process, the roughness of CTX002 and CTM302 was increased compared with that of after the 2-step EDG process. The roughness of tool surface after finishing process is depended on the status of spark generated during the finishing process. Compared with the roughing process, the values of cutting
parameters including voltage, current, time-on and time-off were smaller in the finishing process, and it means that the status of plasma was relative stable during the eroding process. In EDM sub-finishing and finishing machining processes, the cathode is treated as workpiece while anode plays the role of “cutting tools”. In the finishing process, PCD was the anode. This was different from the polarity which was in the roughing process. As a result, the roughness of eroded surface tended to fluctuate around certain values instead of showing an increasing or decreasing trend.

As mentioned in previous section, the peaks which indicate the material of diamond (Figure 6) and their shift in a Raman spectrum reflect the existence and status of different phases of carbon within the scanned area (Chen, Zhang, Arsecularatne, & Montross, 2006). Using the shifted diamond peak value, residual stress after EDG can be calculated based on the following equation (Catledge, Vohra, Ladi, & Rai, 1996):

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

where $\sigma$ is the residual stress (positive means compressive stress, negative means tensile stress), $v_s$ is the measured peak value of the diamond, and $v_r$ is the unstressed peak value of diamond (1,330/cm), $\chi$ is the coefficient of stress-induced frequency shift (1.98 GPa/cm) (Prawer et al., 2000).

Table 6 lists the measured values of diamond peaks of each sample (four machined surfaces for each sample) and the result of the calculation of residual stress respectively. According to previous study, the status of residual stress is compressive after both sintering and conventionally abrasive grinding process (Jia et al., 2011). In contrast, the stress status was tensile for all the inserts after EDG process (peak value < 1330/cm). This changing of stress direction was caused by the conversion of microstructure of diamond which is the result of heat effect generated by plasma. Also, for inserts machined by both the 2-step and the 3-step processes, the residual stress within CTM302 was less than that of within CTX002 and CTB010. The reason on this phenomenon is ascribed to the difference in their grain sizes and volume percentage of cobalt. Residual stress after EDG process which is caused by the mismatch of coefficient of thermal expansion (CTE) exists at the diamond-cobalt and

![Figure 6. Raman spectrum of different phases of carbon (CTB010).](image)
within the diamond structure. The micro deformation of diamond reflecting the amount of residual stress mainly is affected by the PCD grain size. For example, compared with the smaller-size grains, 30 μm diamond grains within CTM302 suffered less deformation because its larger size makes it difficult to deform. Also, the cobalt fraction affects the forming of residual stress as well. Smaller volume percentage of cobalt reduces the area of diamond-cobalt interface and the effect brought by the difference in CTEs is less. As a result, the thermal residual stress caused by the shrinking cobalt during the cooling down process is smaller.

Furthermore, it was found that residual stress on the surface machined by 3-step EDG was smaller than that on the surface machined by the 2-step process. The decrement of residual stress for three kinds of inserts were 0.92 GPa (33%), 0.96 GPa (37%), 0.19 GPa (32%) respectively. For all the workpieces, approximately one third of their original residual stress was reduced, which means that the addition of sub-finishing stage refined the stress status on finished surface. As shown in Figure 7(a), in the roughing process, the tungsten-cooper wheel was the cathode and the PCD inserts played the role of the anode, and the plasma was generated to erode the materials on the surface of PCD inserts. The temperature of plasma was around tens of thousands of degrees (Celsius), which was far above the melting point of diamond. In the eroding process, the heating time was long enough to melt and vaporize the PCD material due to the longer time-on. However, the energy of plasma was not totally used in eroding the PCD materials. A proportion of the heat was transferred to the areas beneath the machined surface forming the “heat effect zone”, which had large tensile residual stress and high level of graphitization. It has been proved that the depth of the “heat effect zone” was around 20 beneath the machined surface (Andreev, 1999). As a result, the tool surface has to be refined by the finishing process to release the residual stress. In the finishing process, when using smaller discharging current to erode the surface of workpiece, the energy of plasma is far less than the energy in roughing process and graphitization within a smaller area is the material removing mechanism (Figure 7(b)). Therefore, the finishing process tends to remove the superficial workpiece material without creating extra residual stress. It was found that the larger finishing in-feed, the smaller residual stress was left (Ding & Mo, 2015). During the sub-finishing process, a 40 μm in-feed and 4 A current was adopted in the semi-finishing process. Compare to 2-step machining, the total finishing in-feed of 3-step machining was larger (30 μm in-feed for sub-finishing and 40 μm in-feed for finishing). The added sub-finishing removed the “heat effect zone” firstly without having excessive thermal effect on machined surface. Then the finishing process which used the smallest current among all the steps removed workpiece material continuously leaving the machined surface with little residual stress in the end.

The results of the orthogonal cutting test reflect the wear resistance of each sample (Tables 7a and 7b). It is found that the CTX002 tool and the CTB010 tool machined by the 3-step EDG process have better wear resistance compared with the ones machined by the 2-step process. According to the calculated results, the wear amount of CTX002 insert and CTB010 insert decreased 27 and 29% respectively. Correspondingly, the thrust force of CTX002 insert and CTB010 insert reduced 28 and 33% respectively. In contrast, the CTM302 machined by 3-step EDG did not show obvious improvement in tool wear resistance during the cutting test, 17% decrease in wear amount and 9.5%
decrease in cutting force. To most of the sintered materials, intergranular fracture was the typical fracture mechanism as the formed grain-grain bonding after sintering process is weak (German, Hanafee, & DiGiallonardo, 1984; Hu, Chen, Ramesh, & McCauley, 2012). Based on the results of McNamara, Alveen, Carolan, Murphy, and Ivankovića (2016), the interfacial angle between the smaller-size PCD grains was smaller compared to large-size grains. During the orthogonal cutting process, the tips of the CTX002 and CTB010 tools suffered shear stress and the internal residual stress.

Table 7a. Depth of grooves and wear amount of each sample

<table>
<thead>
<tr>
<th>Measure no.</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
<th>Sample 4</th>
<th>Sample 5</th>
<th>Sample 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>82</td>
<td>88</td>
<td>87</td>
<td>90</td>
<td>85</td>
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<td>89</td>
<td>82</td>
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<tr>
<td>Ave depth (μm)</td>
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<td>89.75</td>
<td>84</td>
<td>86.75</td>
</tr>
<tr>
<td>Wear amount (μm)</td>
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<td>13.25</td>
<td>14.5</td>
<td>10.25</td>
<td>16</td>
<td>13.25</td>
</tr>
</tbody>
</table>
stress, these encourage the initiated crack to develop along the grain boundaries as well as the cobalt-diamond interface, causing the fracture of PCD structure. By adopting the 3-step EDG process, the residual stress within PCD layer was reduced, which made the PCD structure of CTX002 and CTB010 more stable. In contrast, the decrease in residual stress did not increase the wear resistance of the CTM302 insert. It is found that the fracture of CTM302 is more sensitive to the cobalt pool size, shape and its distribution (McNamara et al., 2016). The mix of diamond grains strongly influenced the size and distribution of cobalt pools in the PCD layer of CTM302. Compared with the cobalt pools in CTB010 and CTX002 which were small-size and mainly even distributed, the cobalt pools in CTM302 were large, distributed randomly. This made the influence of residual stress less significant on the fracture of CTM302. As a result, the wear amount of the 2-step eroded tool and the 3-step eroded tool was stochastic, and the reduction in average cutting force was insignificant (3.5 N).

4. Conclusion
Two kinds of EDG machining strategies were investigated through experimental research and a comparison of the tool quality of eroded PCD inserts was conducted. Tool morphology after machining showed that there was no distinct difference on surface roughness among the inserts machined by both 2-step grinding and 3-step grinding processes. Based on the results of Raman spectrum, PCD consisting of larger grain size had smaller residual stress after EDG. Also, there was a nearly 30% decrease in residual stress when utilizing 3-step EDG machining method. It is found that a “heat effect zone” with large tensile stress was formed after roughing process, and the finishing process removed this layer without bringing in extra residual stress. For 3-step EDG, the total in-feed in finishing process is larger and this removed the heat effect zone thoroughly without inducing excessive residual stress. The results from cutting tests showed that CTB010 and CTX002 PCD inserts had better tool wear resistance which was reflected by the reduction in wear amount and thrust force. In contrast, CTM302 machined by the 3-step EDG process did not show obvious improvement in tool wear resistance during the cutting test.

Table 7b. Recorded thrust force during the cutting test

<table>
<thead>
<tr>
<th>Measure no.</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
<th>Sample 4</th>
<th>Sample 5</th>
<th>Sample 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>71.3</td>
<td>50.6</td>
<td>49.4</td>
<td>37.5</td>
<td>36.8</td>
<td>33.5</td>
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<td>2</td>
<td>73.5</td>
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<td>52.2</td>
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</tr>
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<td>Ave thrust force (N)</td>
<td>71.9</td>
<td>51.8</td>
<td>50.3</td>
<td>34</td>
<td>37.2</td>
<td>33.7</td>
</tr>
</tbody>
</table>

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