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# ELECTRICAL DISCHARGE GRINDING VERSUS ABRASIVE GRINDING IN POLYCRYSTALLINE DIAMOND MACHINING

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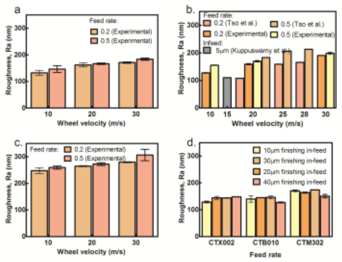
## Graphical abstract



## Abstract

Electrical Discharge Grinding (EDG) and conventional grinding are two different processes with different removal mechanisms and are typically used to machine Polycrystalline Diamond (PCD). This paper addresses the quality issue of PCD tools produced by these two processes in machining sharp cutting edges. Closely similar visible quality indices (surface roughness and tool sharpness) have been obtained by both processes. However, it was found that there is a difference in residual stress directions and graphitization levels. Through the Raman method, the quantitative analysis of residual stress and graphitization inherence by both processes were also presented and discussed in detail.

*Keywords*: Polycrystalline Diamond (PCD), Electrical Discharge Machining (EDM), Electrical Discharge Grinding (EDG), conventional grinding

## Abstrak

Pelepasan elektrik Pengisar (EDG) dan pengisar konvensional adalah dua proses yang berbeza , di mana mekanisme penyingkiran digunakan untuk mesin polihabluran Diamond (PCD). Kajian ini membangkitkan isu berkaitan kualiti alat PCD dihasilkan oleh kedua-dua proses dalam pemesinan pinggir pemotongan tajam . Indeks kualiti penglihatan(kekasaran permukaan dan alat ketajaman) telah diperolehi melalui kedua-dua proses. Walau bagaimanapun , didapati bahawa terdapat perbezaan dalam baki arah tekanan dan tahap graphitization. Melalui kaedah Raman, analisis kuantitatif tegasan baki dan graphitization menjadi bahagian tetap oleh kedua-dua proses.

*Kata kunci*: Polihabluran Diamond (PCD), Pelepasan Elektrik Pemesinan (EDM), Pelepasan Elektrik Pengisar (EDG), pengisar konvensional

## 1.0 INTRODUCTION

Recently, Carbon Fibre Reinforced Plastics (CFRPs) are gaining popularity in aerospace and automotive industries due to its broad advantages, especially towards performances and fuel efficiency, due to the material's strength and weight. Processing of CFRPs require cutting tools that can retain the sharp edges, whereby polycrystalline diamond (PCD) is determined as the best candidate. This causes huge demands among the industries for (PCD) cutting tools, not only in manufacturing but also for maintenance, repair and overhaul (MRO) operations. The reason for this is that PCDs are ideal for speed machining in tough and abrasive materials and often employed in high-abrasion processes such as carbon-fibre and ceramic drilling. Not only does it reduce production time, but it also reduces the cost of drilling due to its durability and ability to cut through relatively everything.

In 2002, Tso *et al*. [1] discovered that PCD tools fabricated with conventional grinding have better tool life as compared to eroded PCD tools. Higher thermal damage and rougher surface for eroded PCD are the some of the reasons for earlier failure. Several grinding parameters have been tested on CTB010 PCD in which rotation speed was found to be the most significant factor for surface roughness. In another manuscript, Liu *et al*. [2] determined the effects of diamond grinding wheel specifications (type of bonding and grit size) on the Material Removal Rate, G-ratio and surface roughness.

Dold *et al*. [3] also investigated the edge quality of ground PCD. They found that smaller grains of ground PCD commonly exhibit large chipping on the cutting edge and results in the formation of torn out grains on the ground regions together with holes particularly on binders. A secondary laser treatment method for ground PCD tools had been introduced to acquire homogenous surfaces specifically on the cutting radius geometry. In their research, 4.3 to 6.5 µm edge radius was achieved by a laser treated PCD. Ishimarua *et al*. [4] in their manuscript, reported that sharp PCD tools with sub-micro meter radii could have been produced after a treatment using ultraviolet ray irradiation assisted polishing method. However, the low polishing rate has been considered as a disadvantage of the process.

Due to rapid innovations in drilling technology, various cutting tool designs have been proposed, which are often purposely complex in geometry and profiles to increase drilling efficiency. For this reason, the high flexibility of electrical discharge grinding (EDG) is advantageous in machining the intricate shapes of the tools. This is different than the conventional die sinking electrical discharge machining (EDM), where a rotating wheel of the EDG increases the flushing efficiency of the process thus reducing the probability of debris intervention while sparking that causes the formation of concentrated plasma. Efficient flushing is also required to reduce the chance of re-welding of the diamond debris to the eroded surface, which has been reported to increase spark inconsistencies [5]. This current state-of-the-art type of PCD erosion guarantees the production of sharp cutting edges.

It has been asserted that the sharp cutting edge has a significant influence on the production of good quality holes by means of lower delamination [4], which motivates this present investigation. Up till now, the process capability of EDG erosion of PCD materials in comparison to other well-established grinding methods, especially in production of sharp cutting edges, has not been discussed in detail by any researcher. The information presented in this manuscript is important as it serves as the baseline for advanced developments of the machining capability in the production of high-quality cutting tools. The effects of manufacturing process selection to the quality of PCD tools produced in different grades are reported in this manuscript.

**Table 1** Properties of PCD[6-8]

| PCD Types | PCD Grain Size (µm) | Diamond Fraction (Vol %) | Cobalt Fraction (Vol %) |
|---|---|---|---|
| *CTX002* | *2* | *84.8* | *15.2* |
| *CTB010* | *10* | *89.7* | *10.3* |
| *CTM302* | *30 to 2* | *91.4* | *8.6* |

## 2.0 METHODOLOGY

PCDs of different grades were used in this investigation. Table 1 shows the types of PCDs used in this research and their composition properties.

### 2.1 Conventional Grinding Parameter Selection

The COBORN RG16, equipped with vitrified bond D16 diamond grinding wheel – supplied by Trochilics Ltd – was used for conventional grinding processes (Figure 1). The vitrified bond wheel was selected since it has been mentioned as the most suitable wheel type for effective and efficient PCD grinding [2]. Perpendicular grinding was used as it has been found to produce better surface finish results than parallel grinding [1]. For better surface finish result, suitable machining parameters should be selected so that the actual grinding depth is smaller than the on-set depth for brittle to ductile transitions of PCD, which is in the range of 0.0013 to 0.0085µm [9].

As the baseline, most of the parameters used in this study are closely similar to the research done by earlier studies [1, 2]. In fact, a lower oscillation rate was implemented as it had been hypothesized to produce better surface quality. Instead of a larger range of PCD grades, a broader range of wheel velocities and grinding in-feeds were implemented for further exploration on their effects towards the cutting edge sharpness and roughness. The following machining parameters were chosen for this process; cutting feed rate of 0.2mm/min and 0.5mm/min; wheel velocities of 10 m/s, 20m/s, and 30 m/s; contact load of 10kg and a fixed oscillation rate of

15mm/sec. For grinding temperature control, general water-based coolants have been used in the tool insert preparation method. The feed rates used were sufficiently small for ductile removal mechanisms (actual grinding depth ($g_m$) of 0.0004 to 0.0015µm) as calculated using the following formula [9]:

$$g_m = \left(2a\frac{V_{osc}}{V}\sqrt{\frac{(\Delta)}{D}}\right) \qquad (1)$$

where; 2*a* is the distance between the successive grains (~150µm), $V_{osc}$ is the wheel oscillation speed, *V* is the wheel velocity, and *D* is the wheel diameter (150 mm). The maximum grinding in-feed Δ, was calculated by [9]

$$\Delta = \frac{d}{V_{osc}} \times V_f \qquad (2)$$

where; *d* is the oscillation travel distance (21mm) and $V_f$ is the feed rate used.

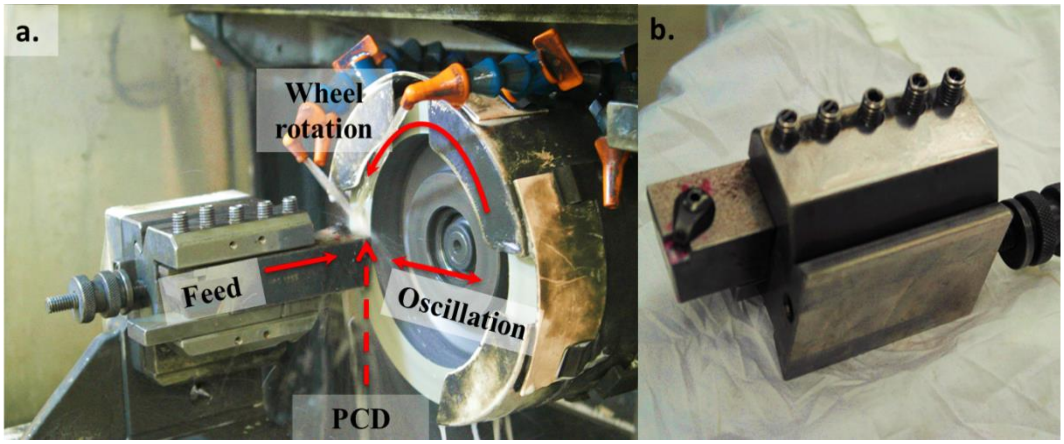


**Figure 1** Grinding process of PCD a. Machine setup b. PCD insert holder

**Table 1** EDG machining parameters

| Operation | Wheel Polarity | Open-Voltage (V) | Wheel rotation speed (rpm) | Current (A) | On-time (µs) | Off-time (µs) | In-feed (mm) |
|---|---|---|---|---|---|---|---|
| Roughing | Positive | 120 | 250 | 12 | 40 | 20 | 0.5 |
| Finishing | Negative | | | 1 | 1 | 1 | 0.01-0.04 |

## 2.2 EDG Machining Parameters Selection

A rotating tungsten-copper wheel electrode with rotational speed of 2m/s has been used in this process. Previous works on EDG machining of PCD (Figure 2) have focused on the effect of the machining parameters and finishing in-feed to the final surface quality [10]. It is known that the short pulse duration with long pulse interval is suitable for the finishing by reducing the heat damage (residual stress, graphitized structure) on the eroded surface. Table 1 shows the EDG parameters used in this study.

Two-stage machining of roughing and finishing was implemented. It has been theorized that higher in-feed would increase the small energy machining depth, thus reducing the total residual stress generated by the roughing process. As a further investigative means into the in-feed effect towards the morphological change, higher in-feeds than that applied in the present study (0.02 mm in reference [10]) were implemented. As shown from the preliminary result of the craters depth generated by the roughing (Figure 3), 0.01mm was determined as the minimum in-feed (lowest finishing depth) required to clean the rough residue surface generated by the preceding roughing process.

## 2.3 Morphological, Structural Quality and Residual Stress Analysis

Alicona (IF-Edge Master) 3D microscope fitted with 50x magnifications lens was used for the prepared tools sharpness and roughness analysis. The non-contact measurement applied here enables more sensitive and highly accurate measurement results. The edge radius values were obtained by the analysis of the extracted 3D images using the robust Gaussian fitting circle method similar to that described by Wyen *et al*. [11].

For structural quality and residual stress assessments, Raman Spectra with a 785nm (near-infrared) laser wavelength (Perkin Elmer Spectrum Raman Station 400) was used to analyze several types of carbon formed on the surface. With a 100µm laser spot size on the inspected surface, good average Raman values were obtained. The tensile residual stress value could be calculated using the following Equation [10]:

$$\sigma = -\frac{vs - vr}{\chi}$$

where; σ is the tensile residual stress (GPa), *vs* is the measured Raman shift value of the diamond, *vr* is the unstressed Raman value (1330 $cm^{-1}$) and χ is the coefficient of stress-induced frequency shift (2.88 $cm^{-1}$/GPa).

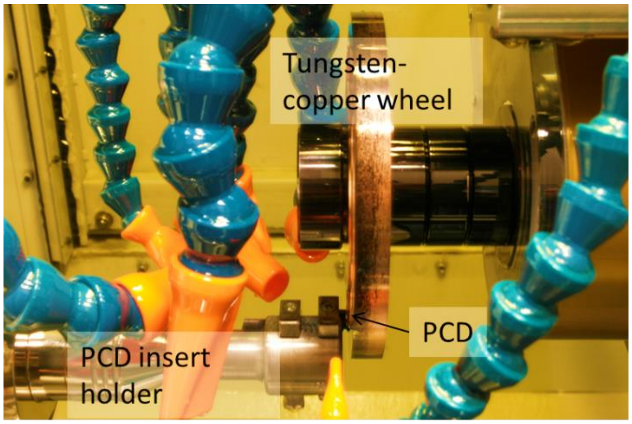


**Figure 2** EDG process of PCD

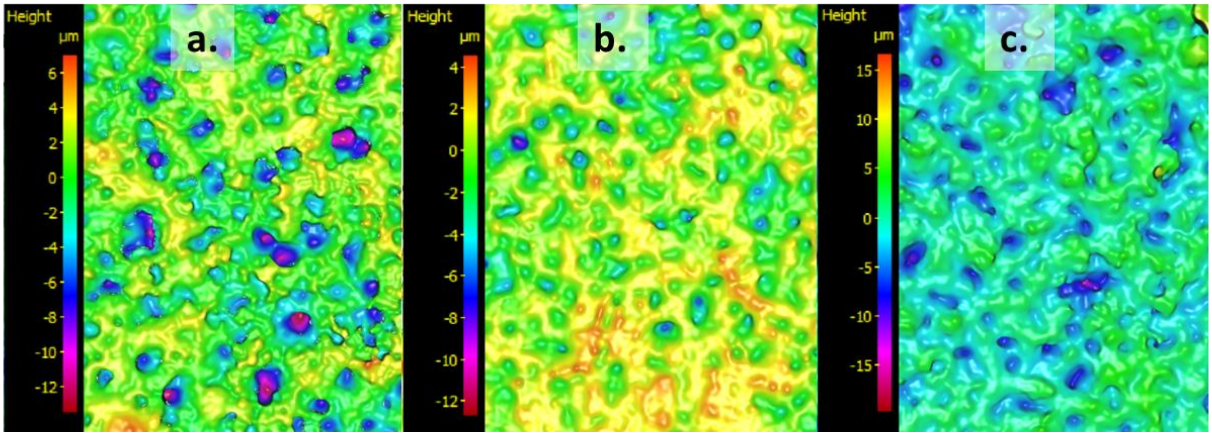


**Figure 3** Craters produced by the roughing operation a. CTX002 b.CTB010 c.CTM302

## 3.0 RESULTS AND DISCUSSION

### 3.1 Morphological Analysis

Figure 4 shows the surface roughness Ra, obtained from this study. The surface roughness obtained from the experiment was compared with the published results in the reference [1], [9]; as shown in Figure 4b. In line with their findings, it was found that the roughness value reduces with slower wheel velocities and lower feed rates.

With the selected machining parameters, most of the surfaces prepared by the conventional grinding process exhibited excellent roughness values in the range of 0.1 to 0.2 µm. Except for CTM302, the roughness value was relatively high, which was caused by the difficulty in cutting the bigger grains directly as it has greater hardness values. On the other hand, different finishing in-feeds did not result in any changes to the surface roughness value of the eroded PCD (Figure 4d). Approximately 140nm of Ra was obtained by CTX002 and CTB010, which is relatively similar to the PCD ground by the slowest wheel velocity and lowest feed rate.

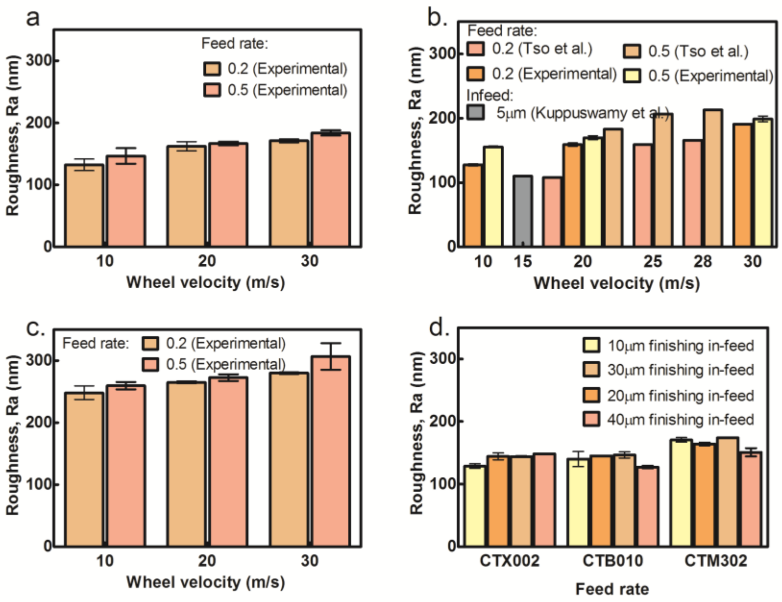


**Figure 4** Surface roughness a.CTX002 ground surface b.CTB010 ground surface c.CTX302 ground surface d. Eroded surface

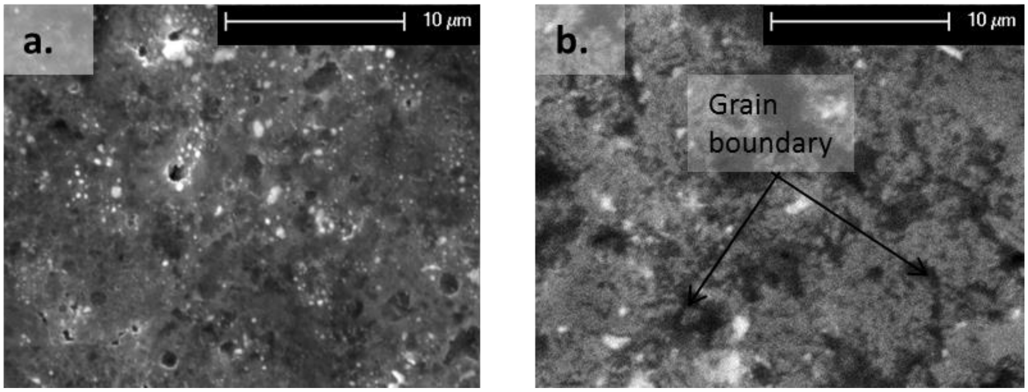


**Figure 5** SEM Images of CTB010 a.Eroded PCD  b.Ground PCD

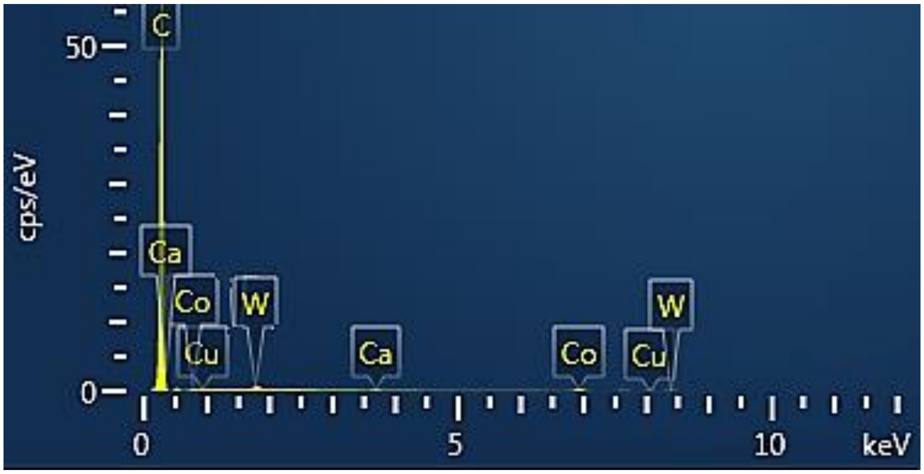


**Figure 6** EDS analysis of the eroded surface

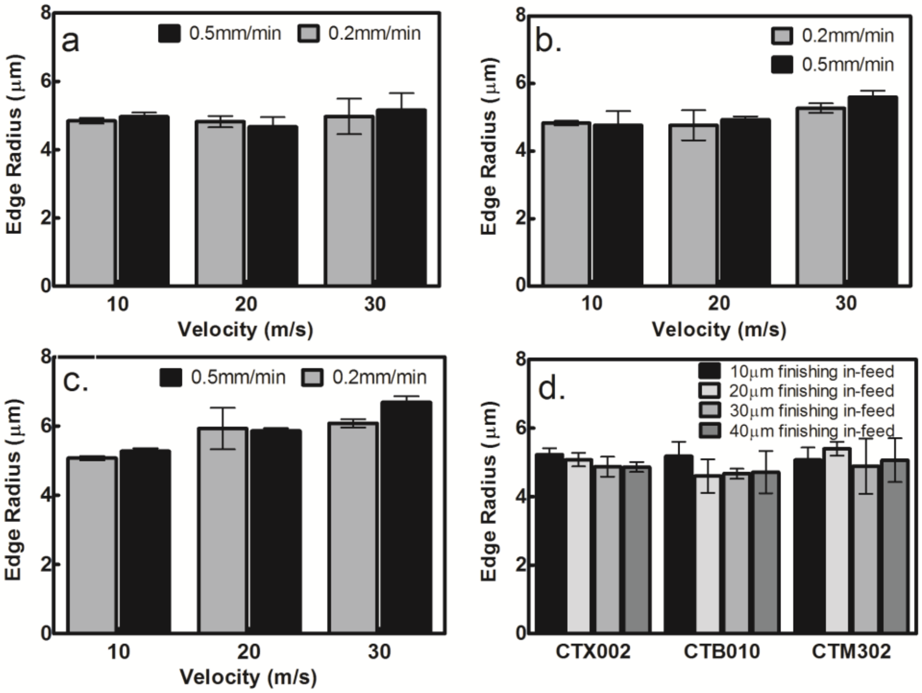


**Figure 7** Cutting edge radius a.CTX002 ground surface b.CTB010 ground surface c.CTX302 ground surface d. Eroded surface

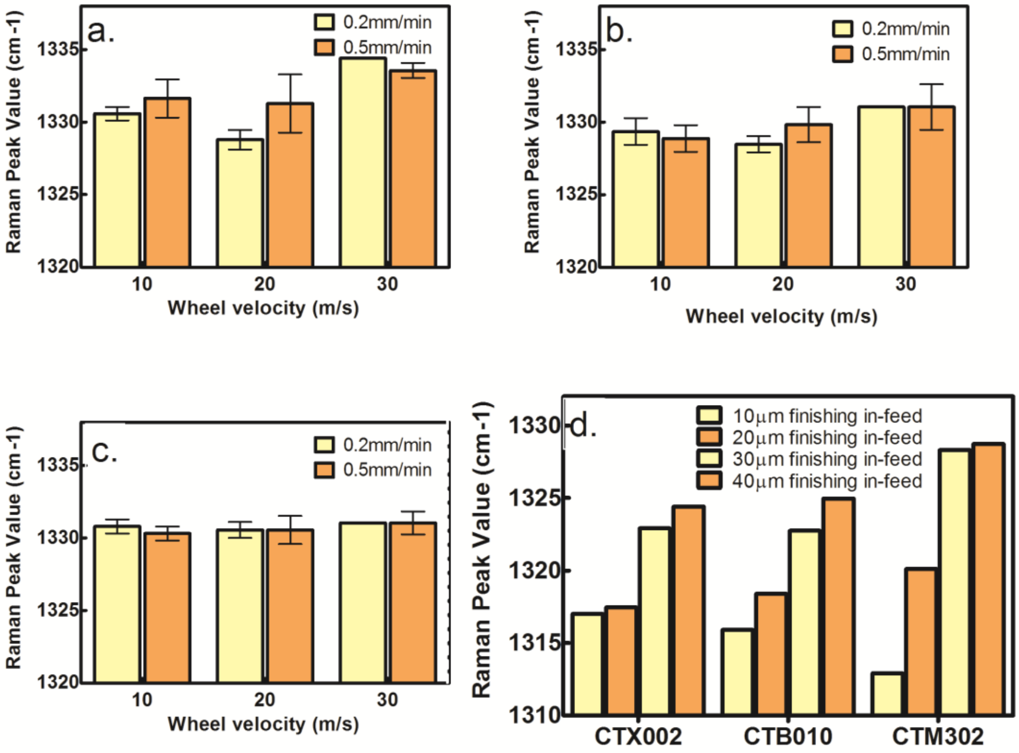


**Figure 8** Raman value a.CTX002 ground surface b.CTB010 ground surface c.CTX302 ground surface d. Eroded surface

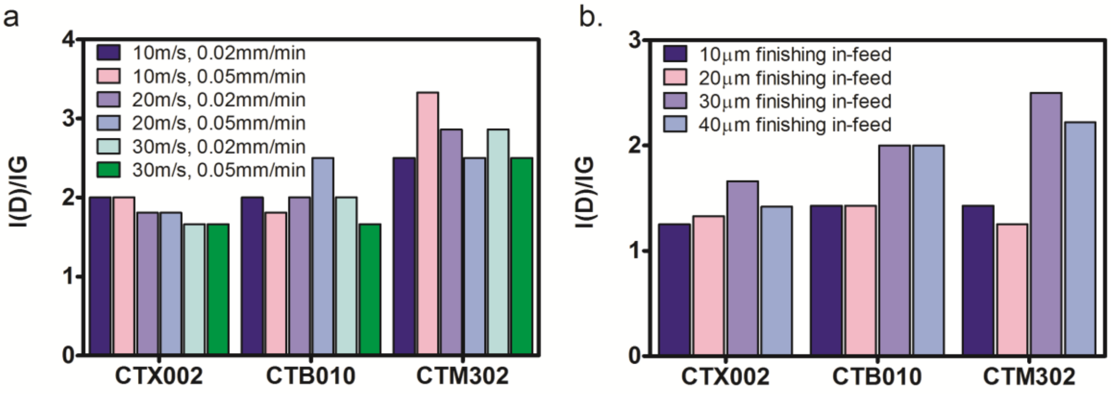


**Figure 9** A comparison of graphitization degree of three different PCD a. Ground surface b. Eroded surface

Although the readings are almost similar in terms of surface roughness values, microscopic observations have revealed differences in morphological appearance. Figure 5 shows the Scanning Electron Microscope (SEM) images of the CTB010 machined surface as obtained by these two different processes. As reported by recent publications [10], graphitization mechanisms affect the finishing erosion. During the process, the diamond grains on the top surface would graphitize and dissolve into the molten cobalt before being flushed away by the dielectric. Since only a small amount of energy was applied, which is lower than the energy for breakage mechanism to occur, the appearance of a smooth surface without crater pores could be expected (as shown in Figure 5a). In this case, the grain intersection disappeared as it is filled up by the re-casted molten material. Energy-dispersive X-ray spectroscopy (EDS) analysis (Figure 6) proved the availability of other constituent elements aside from carbon (diamond or graphite) such as the re-casted cobalt and the deposited wheel elements. These include tungsten (W), copper (Cu) and calcium (Ca). As the finishing process was done in negative polarity (negative polarity of the wheel electrode), the surface plating phenomenon, as aforementioned, happened on the anode electrode (PCD) during erosion, which explains the presence of such elements [12].

In another image (Figure 5b), as the theorized ductile mode grinding happened for ground PCD, tiny little grooves without cracks were observed on the surface. This proved that the implemented grinding process has successfully cut through the grains of the PCD. Flatten grains with boundaries were obviously observed. The discontinuous grain boundary indicates the availability of diamond-to-diamond bonding as discussed by Rahim *et al*. [10]. This type of diamond bonding has also been discussed in several publications, which mentioned it as the main PCD bonding that holds the diamond particles together in place [13, 14]. This bonding was created during the sintering process, caused by the catalyst effect of cobalt.

The quantitative analysis results of the tool sharpness analysis are shown in Figure 7. Considering the standard deviation of the mean results, it was found that the in-feed does not contribute much on the edge radius, especially for the smallest grains of PCD. The obvious difference could only be observed when high wheel velocity is implemented. The reason for such findings was not investigated and could only be explained by further experimentation. However, there is a relationship between the roughness and the tool sharpness, where they are relatively proportional. In general, the edge morphology for eroded and ground PCD (with lowest wheel velocity and feed rate) was found identical.

### 3.2 Residual Stress and Graphitization Analysis

Figure 8a-c shows the Raman value of the diamond peak (D-peak between 1310 and 1335 $cm^{-1}$) obtained from the ground surface. Considering Equation 3, the results indicated that the ground PCD exhibited compressive residual stress as the values were more than the unstressed D-peak value of $1330cm^{-1}$. The result was found matched with reported values in the references [15]. Comparing the deviation in Raman values for every PCD grades, PCD with smaller grain size deviates more, thus indicating a significant change in the residual stress values with different grinding parameters. The smallest PCD grain (CTX002) produced a maximum Raman value of $1334cm^{-1}$, indicating a 1.4 GPa residual stress. Due to higher fracture toughness of coarser PCD grades [16], CTM302 exhibited a smaller shift in D-values, where a maximum compression residual stress of only 0.7 GPa was obtained.

On the contrary, the erosion process stressed that the surface was in a tensile direction. It should be noted that, even with no morphological changes discovered with the different finishing in-feeds, there is a noticeable difference in the residual stress values. As shown in Figure 8d, the residual stress reduces with higher finishing in-feeds implemented. As mentioned in reference [10], a series of mechanical phenomena known as grain fracture were the PCD removal mechanism for roughing with a high energy erosion. Besides, graphitization was found to be the removal mechanism for the finishing stage caused by lower erosion energy.

The thermal stress generated by the roughing process is the main contributor to the final residual stress on the surface. Higher finishing in-feeds resulted in better surface quality due to higher stressed structure removal. Irreversible conversion of diamond to graphite by erosion causes permanent volume expansion of the phases. In this case, residual stress is generated. As simulated by Rahim *et al*. [17], the PCD erosion through the breakage mechanism happened at a temperature limit of 1100K. Under that temperature, the surface of PCD suffers from high-stress values. It could be estimated that the residual stress under the surface went up to a certain level until the temperature lower than the graphitization temperature is obtained (about 700°C ) as reported by [18]. It is clear that, for every sample, highest D-peak value was obtained by samples prepared with the highest finishing in-feed, indicating better surface stress due to the reduction of tensile residual stress. However, even with the highest finishing in-feed implemented, the D-peak values were found approximately 2cm$^{-1}$ lower than the unstressed diamond, which indicated a certain degree of tensile residual stress. Due to the closely similar Raman D-peak value as obtained from 30 and 40µm finishing in-feeds, the CTM302 achieved the minimum limit of the tensile residual stress. Bigger grains together with lowest cobalt percentage (as described in Table 1) among the other PCD grades contributed to the lowest expansion difference between the diamond and cobalt matrix in the system.

Raman analysis of the machined surface provided evidence for the existence of graphite material. However, it is not accurate to directly conclude that the graphitization happened due to grinding since graphite material is part of the PCD elements that were composed during the sintering process [10]. The graphitization phenomenon could only be explained by the relative comparison of the graphite levels before and after the process. In this study, the relative comparison of the graphitization level of ground and eroded PCD was done by referring to the Raman intensity ratio between the graphite peak, G-peak (1580- 1800 cm$^{-1}$) and D-peak. It was stated that, lower D/G intensity ratio will give a higher graphitization degree [19, 20]. Figure 9 shows the intensity ratio value calculated from the Raman spectrums of ground and eroded surfaces. In comparison of these two machining methods, higher graphite peak belongs to the erosion process due to higher processing temperatures. Also, changing the finishing in-feed from 10 to 40µm shows a significant difference in graphitization levels in EDG.

It was reported that the graphitization modifies the hardness, making the surface softer thus encouraging abrasive wear during the application. As reported in [21], diamond-graphite conversions could also result in a severe diffusive wear mechanism that would affect the consistency of the tool quality. This reason highlights the requirement of the finishing process in which it is not only to achieve the desired surface topography, but also to get rid of the highly stressed and graphitized structure. The high graphitization level of machined PCD tools could be the reason for the diffusive wear that was reported during ultra-precision machining. Since the temperature of ultra-precision machining is expected to be lower than the diamond-graphite conversion temperature [21], the application of induced graphitization is unjustifiable.

## 4.0 CONCLUSION

In this study, it has been found that increasing the wheel speed for conventional grinding process produces worse surface finishing aside from reducing the sharpness value of the tools. In EDG, the roughness and sharpness value were found unchanged with the implementation of different finishing in-feeds. This proves that the implementation of a minimum finishing depth would successfully clean the residues on the surface left by the preceding roughing process.

In comparison, both grinding and erosion processes are capable of producing similar visible surface quality (Ra) and sharpness value under the investigated process parameter. In this study, 10m/s grinding speed with 0.2mm/min was found to produce identical morphologies with the eroded PCD. Higher roughness value is obtained by conventional grinding processes, except for the coarsest PCD grade, due to higher hardness values.

Although the visible quality indices (surface roughness and sharpness) are closely similar for both processes, it does not guarantee that similar surface qualities (residual stress and graphitization level) have been achieved. Overall, the ground PCD produces lower graphite than the erosion process due to lower processing temperatures. The machining force introduced by grinding has caused the generation of compressive residual stresses on the surface. On the other hand, high-temperature EDG erosion stresses the surface towards the tensile direction as caused by the thermal expansion of the diamond grains. Better surface quality could be achieved by increasing the finishing in-feeds by means of lowering residual stress and graphitization levels.

For many years, industry-acceptable PCD tools have been judged by both the fabricator and end users alike on visible surface quality such as surface roughness and edge sharpness. However, residual stress and graphitization levels inside the PCD tool is currently a factor that is not measured post machining. Moreover, in this study, these factors were found significantly affecting the selected machining parameters and process selections. Thus, this highlights the importance of the evaluation of these invisible quality indices.

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