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ORIGINAL ARTICLE

# WEDM condition parameter optimization for PCD microtool geometry fabrication process and quality improvement

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**Abstract** To increase fabrication efficiency for poly-crystalline diamond (PCD) microtools, wire EDM technology was applied and optimized by using a design of experimentation. For roughing, the productivity must be maximized while for finishing, the surface roughness must be minimized to achieve the best overall quality. Using three different grades of PCD, experimental results show a significant increase in productivity with no significant decrease in microtool quality, which was confirmed by hexagonal end-mill fabrication using both non-optimized and optimized conditions.

**Keywords** PCD · Wire EDM · Microtool

## 1 Introduction

The demands for micromachining of hard and brittle materials are increasing. Since hard and brittle materials such as silicon, ceramics, glass, tungsten carbide, and hardened steels have desirable performance characteristics, they can be used in demanding applications such as optical, medical devices, and laser components, which require the utmost accuracy and precision. However, hard and brittle materials are difficult to mechanically machine because they can be damaged by brittle fracture during material removal, cutting force-induced tool deflection or breakage. Microtools made of poly-crystalline diamond (PCD) offer great promise for micromachining of hard and brittle materials [1–7].

A grinding process is currently used in industry to fabricate PCD microtools, despite limitations in feature complexity and low productivity. When examining alternative fabrication methods, the wire electrical discharge machine (WEDM) is an ideal means for manufacturing such tooling due to its ability to cut any conductive material regardless of hardness. With the use of WEDM technology, the productivity of fabricating microtools can be increased while allowing for more intricate tool geometries to be created with high quality.

Past researchers have studied the optimization of chemical vapor deposited (CVD) and PCD microtool blank WEDMing [8–11], but have not widely focused on actual complex tool geometry machining by WEDM. Olsen et al. presented findings in application of WEDM for CVD bulk material slicing and achieved material removal ranging from 0.2 to 1.5 mm/min and surface roughness ranging from 0.2 to 0.7 μm Ra [10, 11] using large diameter, 0.25 mm wire. Tso and Liu compared WEDM and grinding-based PCD machining which resulted in a best surface roughness of 0.27 μm Ra [8]. While these past research efforts present useful findings for WEDMing of PCD bulk material, a comprehensive study specific to PCD microtool fabrication has not yet been studied. Depending on the PCD microtool cutting application, the commercially available PCD grade may vary, which can cause variation in WEDM performance and quality. Small wire diameters must also be used for

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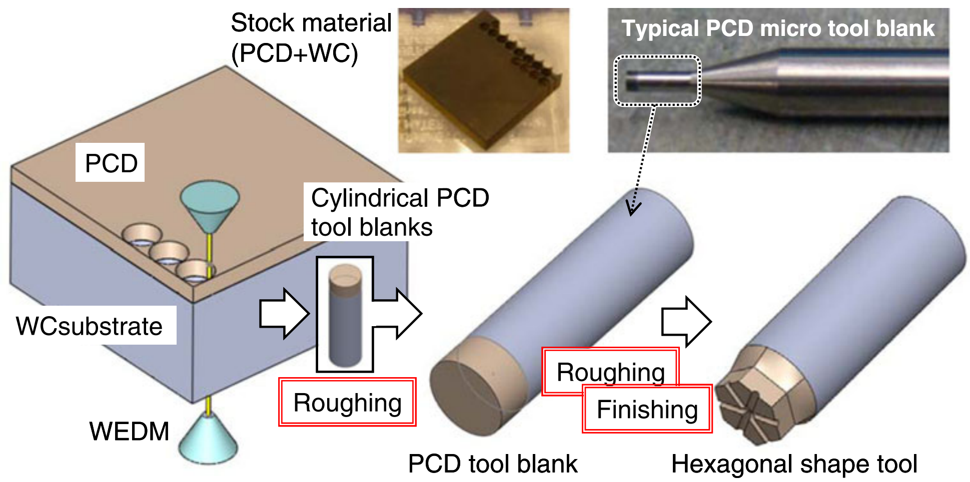


**Fig. 1** Typical PCD tool fabrication process

microtool fabrication to create intricate geometric features, which cannot be created using larger diameter wire and corresponding WEDM machining conditions. Also as the wire diameter decreases, wire breakage is more prominent due to the presence of larger energy densities during discharging, thus, careful selection of machining conditions is necessary.

A typical PCD tool fabrication process is shown in Fig. 1. PCD tool blank machining involves simultaneously rough cutting the WC substrate and PCD layer only using a simple cylindrical toolpath. For actual tool geometry machining, however, only the PCD material is cut with roughing and finishing processes, and must be done so with the utmost accuracy and best achievable surface quality to prevent

**Table 1** L25 roughing condition experimental array

| Test # | Discharge OFF time (μs) | Discharge current level | Arcing sensitivity | Discharge voltage (V) | Servo voltage (V) | Wire speed (m/mm) |
|---|---|---|---|---|---|---|
| 1 | 2 | 10 | 100 | 65 | 40 | 35 |
| 2 | 2 | 20 | 110 | 85 | 45 | 40 |
| 3 | 2 | 30 | 120 | 100 | 50 | 45 |
| 4 | 2 | 5 | 130 | 120 | 55 | 50 |
| 5 | 2 | 8 | 140 | 150 | 60 | 55 |
| 6 | 3 | 10 | 110 | 100 | 55 | 55 |
| 7 | 3 | 20 | 120 | 120 | 60 | 35 |
| 8 | 3 | 30 | 130 | 150 | 40 | 40 |
| 9 | 3 | 5 | 140 | 65 | 45 | 45 |
| 10 | 3 | 8 | 100 | 85 | 50 | 50 |
| 11 | 4 | 10 | 120 | 150 | 45 | 50 |
| 12 | 4 | 20 | 130 | 65 | 50 | 55 |
| 13 | 4 | 30 | 140 | 85 | 55 | 35 |
| 14 | 4 | 5 | 100 | 100 | 60 | 40 |
| 15 | 4 | 8 | 110 | 120 | 40 | 45 |
| 16 | 5 | 10 | 130 | 85 | 60 | 45 |
| 17 | 5 | 20 | 140 | 100 | 40 | 50 |
| 18 | 5 | 30 | 100 | 120 | 45 | 55 |
| 19 | 5 | 5 | 110 | 150 | 50 | 35 |
| 20 | 5 | 8 | 120 | 65 | 55 | 40 |
| 21 | 6 | 10 | 140 | 120 | 50 | 40 |
| 22 | 6 | 20 | 100 | 150 | 55 | 45 |
| 23 | 6 | 30 | 110 | 65 | 60 | 50 |
| 24 | 6 | 5 | 120 | 85 | 40 | 55 |
| 25 | 6 | 8 | 130 | 100 | 45 | 35 |

**Table 2** PCD material properties [13]

| PCD grade | Type A | Type B | Type C |
|---|---|---|---|
| Diamond grain size (μm) | 0.5 | 0.5 | 0.4 |
| Diamond content (vol.%) | 84 | 86 | 90 |
| Hardness, Hv | 80–100 | 90–100 | 110–120 |
| TRS (GPa) | 2.15 | 2.45 | 2.60 |

abnormal tool wear and poor machined surface quality during the micro milling process.

For WEDMing of PCD microtools in industry, the cutting parameters used are based on an individual operator's know-how and experience, therefore variation in cutting performance and quality may arise. For new operators with no prior PCD WEDMing experience, a huge learning curve is inevitable, with high variation in output tool quality. Unlike traditional mechanical milling process with only a handful of cutting parameters, efficient application of WEDM technology involves the manipulation of over 10 cutting parameters, all playing a vital role in the cutting productivity, quality, and accuracy.

The primary goal of this research is to efficiently apply WEDM technology for the fabrication of PCD microtools. This involves careful selection of optimal WEDM machining conditions, taking into consideration variation caused by differences in: commercially available PCD grades' material properties, desired productivity and/or surface quality, and application of a thin wire diameter. Taking into account these factors, the optimal WEDM machining condition parameters will be developed to improve both roughing productivity and finishing quality. A detailed evaluation of the surface characteristics of the PCD tooling fabricated using WEDM technology will also be conducted to improve the fabrication process and avoid microlevel imperfections which can cause catastrophic tool failure during the micromilling process.

## 2 Design of experimentation

In order to optimize the WEDM process for microtool PCD cutting, the critical machining requirements must be identified and their relation to machining conditions. To optimize productivity during roughing operations, high power must be applied by balancing the voltage and current with an adequate discharge OFF time and arcing sensitivity level. For finishing operations, a similar approach must be taken, although quality is the final goal, which entails using the lowest amount of power possible and adequate wire electrode offset to gradually improve the surface quality finish pass by pass. The number of repetitions per finish pass must also be considered to ensure a uniform surface roughness and eliminate larger edge corner radii caused by the previous roughing condition.

Due to the high number of parameters that must be considered for both roughing and finishing condition optimization, a design of experimentation (DOE) must be used that can statistically evaluate the input parameters at different levels in order to minimize the number of needed experiments and identify the dominant WEDM parameters that most effect roughing productivity and finishing quality. First, a signal-to-noise ratio (SN) can be calculated for each experiment. Then, by taking the mean of the SN ratios for a parameter's like values, the effect of this factor can be observed [12]. An analysis of variance (ANOVA) can also be calculated for each parameter to ensure the results are accurate and not effected by random error.

For roughing and finishing, an L25 and L18 array were used, respectively. Table 1 lists the test parameters and their different values for roughing condition experimentation. All other EDM condition parameters will be held constant. For roughing, six parameters are involved since only a single pass is necessary, but more variation in these parameters will be observed by using five values per parameter. While the roughing conditions will not directly affect the final surface quality, it is important to ensure that the roughing conditions do not damage the PCD surface and cause any extreme

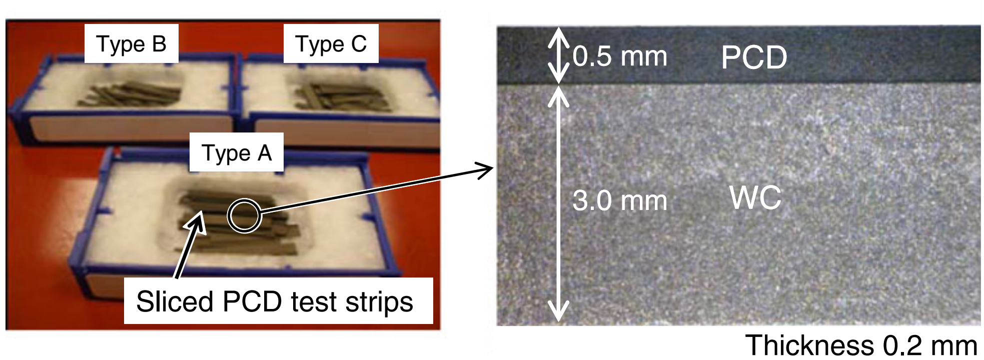


**Fig. 2** Sliced PCD test strips for experimentation

pitting or surface cracking in the PCD material. This would make finishing of the PCD material difficult and weaken its overall strength. For finishing experimentation, eight parameters and three levels per parameter will be considered due to the necessity of multiple finish passes to achieve a desirable part accuracy and surface uniformity.

## 3 Experimental setup

Three different grades of PCD material were tested to observe the effects of grain size and diamond content on the optimal WEDM condition parameters. Table 2 lists the material properties of the three different PCD materials used for experimentation [13].

To simulate the thickness of typical micro tool diameters currently being used in industry, PCD bulk material was sliced into 0.2 mm thick strips, as shown in Fig. 2. A 0.1-mm diameter steel–core brass wire was used for its high strength and small kerf, which is necessary for shaping micro tool geometric features. A Sodick ASX350L six-axes WEDM

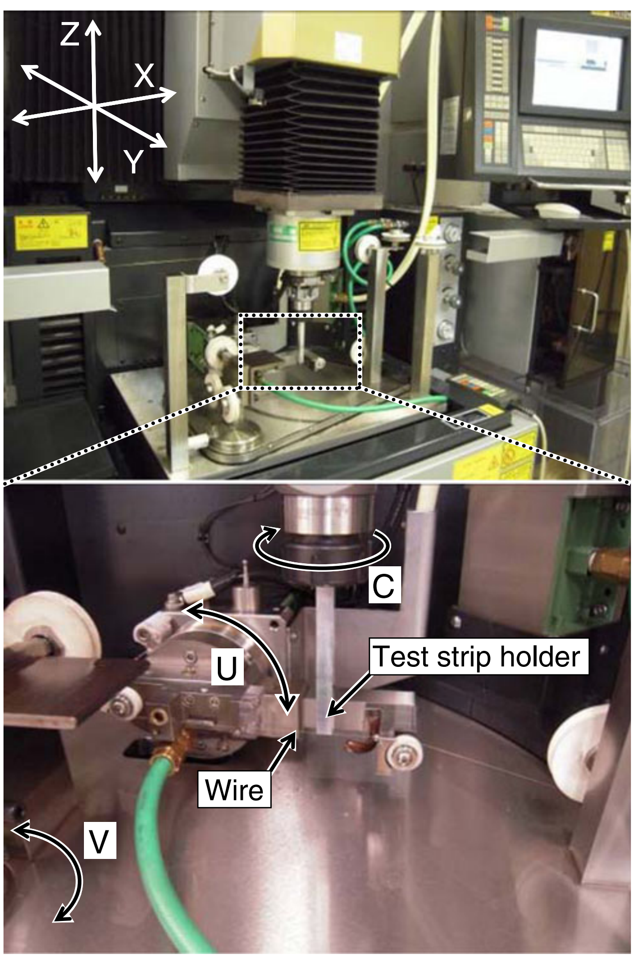


Fig. 3 Sodick ASX350L six-axes WEDM

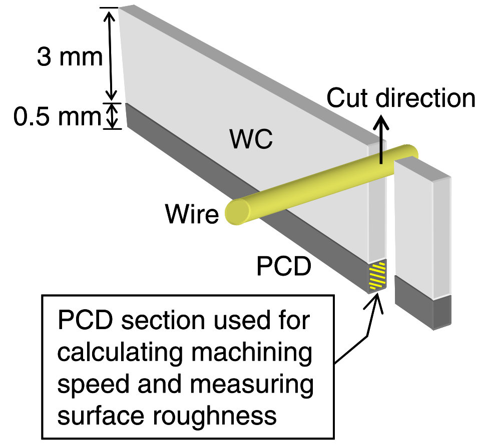


Fig. 4 Side view of PCD test strips used for experimentation

(Fig. 3) was used to conduct all experimentations. The machine tool has a horizontal wire feed direction and an indexing spindle unit which allows for ease of mounting tool blanks and ensuring part straightness. An oil-based dielectric fluid was used, which helps to reduce the discharge gap size and improve the achievable part surface roughness. To accurately measure only the PCD cutting time, a timing function was used on the machine tool's controller to accurately measure a 0.5-mm midsection of the PCD material, as shown in Fig. 4. The overall machining time for cutting through the entire strip (PCD+WC) was also recorded to check consistency in machining times for each PCD grade.

## 4 Experimental results

### 4.1 Roughing condition experimentation

Roughing condition experimentation was performed on all three grades of PCD material. According to the DOE, 25 experiments were conducted on each PCD grade. Each experimental set of 25 was repeated three times per PCD grade in order to use mean machining speed values for analysis. Experiments resulting in a wire breakage were assigned a mean machining speed of zero for analysis. To

Table 3 Effect of each WEDM parameter on machining speed

| Parameter | Type A effect | Type B effect | Type C effect |
|---|---|---|---|
| Discharge OFF time | 15 | 20 | 15 |
| Arcing sensitivity | 13 | 19 | 11 |
| Discharge voltage | 11 | 15 | 11 |
| Servo voltage | 8 | 8 | 11 |
| Discharge current | 7 | 7 | 10 |
| Wire speed | 3 | 5 | 6 |

**Table 4** Type A analysis of variance results

| Parameter | Sum squared | *d.f.* | Mean squared | *F* | *p* Value |
|---|---|---|---|---|---|
| OFF time | 2.64150 | 4 | 0.66037 | 0.41 | 0.8063 |
| Sensitivity | 2.71690 | 4 | 0.67922 | 0.42 | 0.8013 |
| Voltage | 2.69650 | 4 | 0.67412 | 0.42 | 0.8026 |
| Servo voltage | 1.36130 | 3 | 0.45375 | 0.28 | 0.8437 |
| Current | 2.02190 | 4 | 0.50549 | 0.31 | 0.8509 |
| Wire speed | 1.06550 | 4 | 0.26639 | 0.17 | 0.9301 |

calculate a signal-to-noise ratio (SN), simple calculations were performed using Eqs. 1–5 [12], where $N$ is the number of trials per experiment and $T$ is the machining speed in millimeter per minute.

$$S_{m1} = (T_1 + T_2 + \ldots + T_N)/N \tag{1}$$

$$S_{T1} = {T_1}^2 + {T_2}^2 + \ldots + {T_N}^2 \tag{2}$$

$$S_{e1} = S_{T1} - S_{m1} \tag{3}$$

$$V_{e1} = S_{e1}/(N-1) \tag{4}$$

$$SN = 10\log[(1/N)(S_{m1} - V_{e1})/V_{e1}] \tag{5}$$

A "higher the better" nominal output is desired for the case of machining speed. The effect for each parameter is found by taking the largest difference of the SN ratio means for each parameter's level. By observing the different values for the effect of each parameter on machining speed as

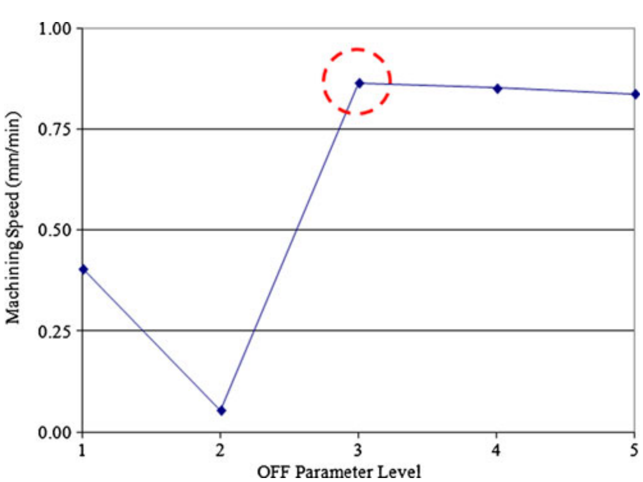


**Fig. 5** OFF time vs. mean machining speed plot

**Table 5** Optimized roughing parameter values

| OFF time (μs) | Current level | Arcing sensitivity | Voltage (V) | Servo voltage (V) | Wire speed (m/min) |
|---|---|---|---|---|---|
| 4 | 10 | 140 | 120 | 60 | 35 |

shown in Table 3, it is clear which parameters have the largest influence on the machining speed output. The discharge duration parameters (discharge OFF time and arcing sensitivity) as well as the discharge voltage, have the largest effect on machining speed. To confirm these values, ANOVA was conducted in parallel. Table 4 shows the ANOVA results for type A experimentation. Ideally, the $p$ values should be less than 0.1, indicating a 90% confidence level in the results, with the smallest $p$ value having the largest effect on machining speed. While the resulting $p$ values are much larger than 0.1, the numerical values have most likely all been shifted in value due to the presence of experimental results that resulted in wire breakage, thus, causing a productivity value of zero. If the $p$ values are examined in comparison to the effect of each parameter from signal-to-noise ratio calculations, the results coincide; the discharge OFF time, arcing sensitivity and voltage, have the largest effect on the machining speed.

While the discharge OFF time directly increases the resting period between discharges, the arcing sensitivity parameter also adds additional discharge OFF time when an unstable discharge occurs. The power parameters (current, voltage, and servo voltage) have a slightly lower effect on machining speed. These parameters control how much voltage and current are applied for discharging. While these are very important parameters in being able to achieve higher machining speeds, the actual energy applied to the workpiece is still dependent on the discharge duration parameters mentioned above. The wire speed has the smallest effect on machining speed. By setting this value to its lowest tested value, wire can be conserved, which results in lower production costs for PCD micro tooling.

We are also able to plot each parameter's levels and their corresponding mean machining speeds to extract the optimal parameter settings. Figure 5 shows a representative plot of the discharge OFF time for type A experimental results. With this plot, the optimal parameter can easily be extracted,

**Table 6** Optimized roughing speed for each PCD grade

| PCD grade | Type A | Type B | Type C |
|---|---|---|---|
| Machining speed (mm/min) | 2.37 | 1.19 | 1.52 |
| Diamond content (vol.%) | 84 | 86 | 90 |

**Table 7** Effect of each WEDM parameter on surface roughness

| Parameter | Type A effect | Type B effect | Type C effect |
|---|---|---|---|
| Finish condition, numnber of repetitions | 5 | 3 | 4 |
| Mean discharge current | 4 | 3 | 3 |
| Mean discharge voltage | 3 | 3 | 3 |
| Mean discharge OFF time | 3 | 2 | 2 |
| Mean finish condition offset | 2 | 2 | 2 |
| Semifinish condition offset | 2 | 1 | 2 |

as shown by the data point circled. This value yield the highest machining speed, thus should be used in favor of lower machining speed yielding parameter values.

After extracting the optimal parameter level for each PCD grade, the specific optimized parameter values can be observed in Table 5. Using these optimized parameters, three sets of confirmation experiments were conducted for each PCD grade. In Table 6, the compiled machining speed data are listed. Observing the resulting machining speeds, some inconsistencies were observed for two PCD grades, type B and C. The mean machining speeds that were calculated showed a higher machining speed for type C when compared to type B, despite higher diamond content for type C. This is thought to be caused by poor grain uniformity present for the type B material, which causes varying levels of conductivity during WEDMing when the wire electrode transitions from nonconductive diamond grains to the highly conductive cobalt binder. The constant varying of conductivity serves to create an unstable discharge environment, thus, reducing overall machining speed. Type C is manufactured with a more uniform and consistent grain distribution, which results in a higher machining speed when compared to type C. While past researchers have cited the importance of diamond content in relation to WEDM productivity for PCD machining, it is important to note the importance of grain distribution as well.

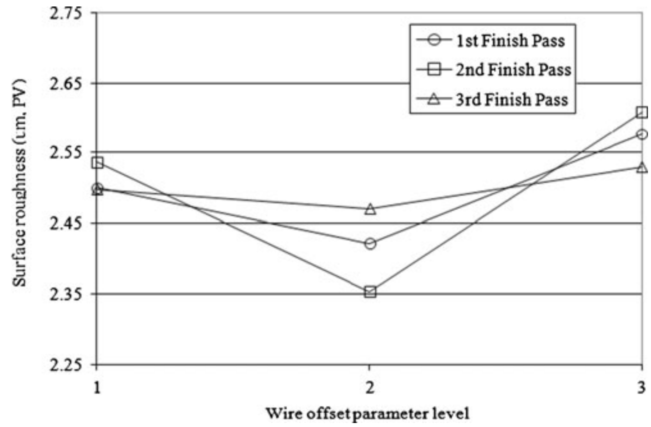


**Fig. 6** Type A wire offset level vs. surface roughness plot for condition parameter extraction

**Table 8** Type A analysis of variance results

| Parameter | Sum squared | *d.f.* | Mean squared | *F* | *p* Value |
|---|---|---|---|---|---|
| 1st Finish offset | 0.27280 | 2 | 0.13640 | 1.14 | 0.3736 |
| 1st Finish current | 0.47350 | 2 | 0.23675 | 1.97 | 0.2091 |
| 1st Finish voltage | 1.29749 | 2 | 0.64874 | 5.41 | 0.0380 |
| 2nd Finish OFF | 0.32972 | 2 | 0.16486 | 1.37 | 0.3138 |
| 2nd Finish current | 0.49545 | 2 | 0.24773 | 2.06 | 0.1973 |
| 2nd Finish voltage | 0.71048 | 2 | 0.35524 | 2.96 | 0.1170 |
| 3rd Finish OFF | 0.24102 | 2 | 0.12051 | 1.00 | 0.4135 |
| 3 rd Finish current | 0.49404 | 2 | 0.24702 | 2.06 | 0.1981 |
| 3 rd Finish voltage | 1.04727 | 2 | 0.52364 | 4.36 | 0.0588 |
| 1st Finish offset | 0.63662 | 2 | 0.31831 | 2.65 | 0.1388 |
| 2nd Finish offset | 1.16526 | 2 | 0.58263 | 4.86 | 0.0476 |
| 3rd Finish offset | 0.06121 | 2 | 0.03061 | 0.26 | 0.7817 |
| Repetition no | 1.47797 | 2 | 0.73898 | 6.16 | 0.0286 |
| Semifinish offset | 0.17827 | 2 | 0.08913 | 0.74 | 0.5098 |

## 4.2 Finishing condition experimentation

For finishing condition experimentation, 36 experiments were conducted for each PCD grade. While the roughing process consisted of only a single pass, the finishing operation consists of three different passes, each with different set parameter values, offsets and repetitions. Also, the output for finishing experimentation is surface roughness, not machining speed. For all calculations, the peak-to-valley surface roughness will be used. To help minimize the number of needed experiments, only three values were used per parameter. Upon completion of all experimentation, the effect of each parameter was found using Eqs. 6–10, where $N$ is the number of trials per experiment and $T$ is the machining speed in millimeter per

**Table 9** Optimized finishing conditions

| Parameter | Value |
|---|---|
| 1st, 2nd, 3rd Finish OFF | 10, 3, 10 μs |
| 1st, 2nd, 3rd Finish current | 10, 8, 5 A |
| 1st, 2nd, 3rd Finish voltage | 100, 85, 65 V |
| 1st, 2nd, 3rd Finish offset | 2, 1, 0.5 μm |
| Semi-finish offset | 10 μm |
| Finishing repetitions | 3 Times |

**Table 10** Optimized surface roughness for each PCD grade

| PCD grade | PV (μm) | Ra (μm) |
|---|---|---|
| Type A | 3.553 | 0.184 |
| Type B | 3.800 | 0.186 |
| Type C | 4.041 | 0.239 |

minute [12]. For finishing condition surface roughness, a "lower the better" nominal output is desired.

$$S_{m1} = (T_1 + T_2 + \ldots + T_N)/N \tag{6}$$

$$S_{T1} = {T_1}^2 + {T_2}^2 + \ldots + {T_N}^2 \tag{7}$$

$$S_{e1} = S_{T1} - S_{m1} \tag{8}$$

$$V_{e1} = S_{e1}/(N-1) \tag{9}$$

$$SN_1 = 10\log[(1/N)V_{e1}/(S_{m1} - V_{e1})] \tag{10}$$

Table 7 lists the effect of each parameter by PCD grade. For the current, voltage, OFF time and finish offsets, a mean value is used to gain better insight into the overall effect of these parameters, and not just how each finish pass is effected by a specific parameter. For each PCD grade, the number of repetitions per finish pass has the largest effect on surface roughness.

The discharge current and voltage also have a large effect on roughness, followed by the discharge OFF time and offset values, which have a minimal effect on surface roughness. With the signal-to-noise ratio calculations exposing the optimal parameter values, an ANOVA was conducted to confirm that the experimental results. Table 8 shows the ANOVA calculation results for type A experimentation. The underlined parameters exhibit a very low $p$ value, with the repetition numbers having the lowest $p$ value, hence, the largest effect on surface roughness. This agrees with our signal-to-noise ratio calculations where the number of repetitions also has the largest effect on surface roughness.

As with roughing experimentation, the optimal parameter values were extracted using plots of the specific parameter levels versus the output peak-to-valley surface roughness. Figure 6 shows a representative plot for type A experiments, which compares the wire offset levels for the three finish passes with the output surface roughness values. After extracting the optimal parameter values for each finish pass, the optimized finishing parameter values can be observed in Table 9. Some important trends can be seen from the optimized finishing conditions. First, each of the three finish passes should be repeated three times each, for a total of nine finish passes. Second, the current and voltage are reduced on each consecutive finish condition. Last, the finish offset distance is also reduced on each consecutive finish condition. In combination with a consecutive reduction in discharging power, the energy applied to the surface of the PCD is minimized, which helps to gradually reduce the surface roughness with each consecutive finish pass and repetition.

Confirmation experiments were conducted using the extracted optimized parameter values to confirm the output surface roughness for each PCD grade. Six measurements were made for each PCD grade using a Zygo NewView 5000 metrology system in order to obtain mean surface roughness values, as shown in Table 10.

From the measured surface roughness values, PCD type A and B have similar results for both peak-to-valley (PV)

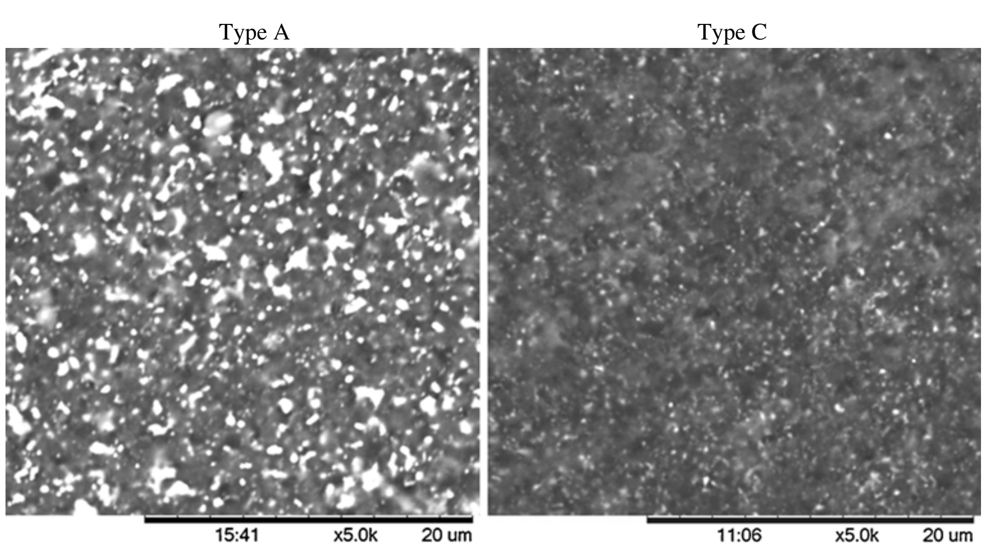


**Fig. 7** SEM images of type A and C

and average (Ra) surface roughness values. Type C, which has the highest diamond content, resulted in the largest surface roughness values of 4.041 μm PV and 0.239 μm Ra. Previous research has been reported where a best average surface roughness of 0.27 μm Ra was achieved using large diameter wire, although the PCD material properties were not disclosed. For all three of the PCD grades tested in this study, all exhibited a superior surface quality in comparison to previously reported results for both PCD and CVD WEDMing studies [8–11].

Scanning electron microscope (SEM) images were taken for all three PCD grades after applying the optimized finishing conditions. Figure 7 shows SEM images for type A and C at ×5,000 magnification. Some interesting observations can be made from these images. While both surfaces are uniform, there is a high presence of "white spotting" on the type A surface, as compared to the type C surface. While the initial cause of the "spotting" was not known, it was assumed that the difference in concentration of the spots is caused by the difference in diamond content for the PCD grades. For instance, type A has the lowest diamond content and the highest cobalt content, while type C has the highest diamond content and the lowest cobalt content.

To confirm any correlation between the PCD material properties and the "white spotting", energy dispersive spectroscopy (EDS) was applied to the surface of a type A WEDM sample to find the chemical composition of the "white spotting". Figure 8 shows an SEM image with an EDS line measurement through a "white spot" on the PCD surface. Directly at the spot on the PCD surface, there is a peak in cobalt content and drop in carbon content, indicating that the "white spotting" observed are concentrations of cobalt on the PCD surface. We can also see that the remaining region of the PCD surface is carbon, specifically graphitized diamond. Studies on the graphitization of the PCD surface and presence of cobalt deposits will be conducted in the near future.

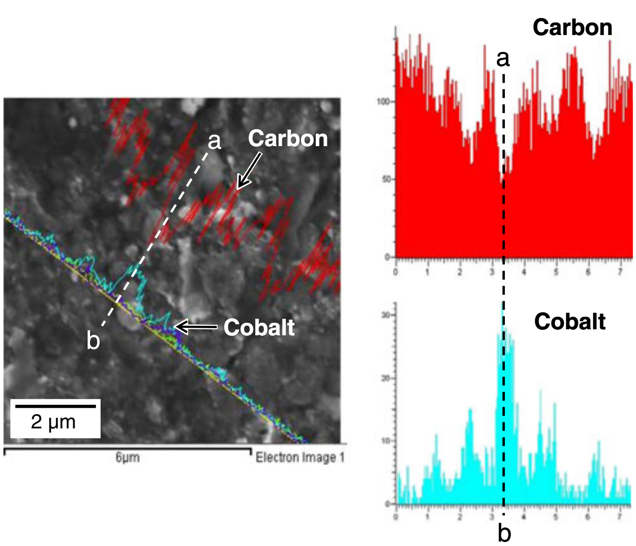

**Fig. 8** Type A SEM surface with EDS chemical composition line measurement

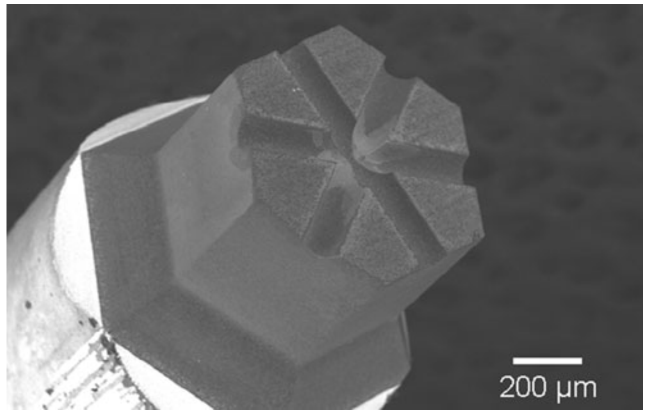

**Fig. 9** SEM image of fabricated hexagonal shape tool

## 5 Case study

To verify the performance of the resulting WEDM optimized conditions from this study, a hexagonal micro end mill was fabricated using type C PCD material (Fig. 9). The tool shape has previously been fabricated using non-optimized conditions by previous research conducted using a custom CAM system for six-axes WEDM [3–5]. The same NC data was used for both tools, although the WEDM parameter and wire offset values were changed for the optimized test.

The corresponding cycle times and surface roughness values for the fabricated tools are shown in Table 11. From the table, it is clear that the productivity of microtool fabrication has been significantly increased, with no decrease in tool surface quality.

## 6 Conclusions

An overview of the PCD WEDMing condition optimization research was given along with the proposed research approach, detailing the crucial control parameters for WEDMing of PCD. Using a DOE, the roughing and finishing condition experimentation was completed. A signal-to-

**Table 11** Hexagonal end mill machining comparison

| | Cycle time (min) | PV (μm) | Ra (μm) |
|---|---|---|---|
| Non-optimized | 100 | 3.520 | 0.209 |
| Optimized | 65 | 3.641 | 0.216 |

noise ratio was calculated for each experiment and was used to calculate the effect of each parameter on machining speed for roughing and surface roughness for finishing. Analysis of variance was also completed for finishing experimentation to confirm the effect of each parameter found by using the signal-to-noise ratios.

It was found that the discharge duration parameters (discharge OFF time and arcing sensitivity) have the largest effect on machining speed, while the number of repetitions of finish passes has the largest effect on surface roughness. Extraction of the roughing and finishing optimal parameter values allowed for confirmation experiments to be conducted, where for roughing, it was confirmed that type A yields the highest machining speed.

A hexagonal PCD microtool has also been fabricated using type C PCD to confirm the increased productivity without reduced quality in comparison to previously fabricated microtooling.

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