Investigation of Electrical Discharge Grinding of Polycrystalline Diamond with a New Measurement System

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Abstract: A new measurement system with high sampling rate and large storage capacity was developed to measure the electrical discharge grinding of polycrystalline diamond materials. The system was able to record the process continuously for more than 2 hours by using the Type 0 Redundant Array Independent Disks. A series of cutting tests were conducted to analyze the grinding characteristic in grinding polycrystalline diamond materials. Experimental results demonstrated that the input pulse energy was unstable at the beginning of the erosion process; those crater morphology and distribution were influenced by the pulse off time and the debris existing time.

Keywords: Electrical discharge grinding, Polycrystalline diamond, Pulse discrimination, Crater.

1. Introduction

With the advance of material technology, more and more composite material and titanium alloys are used in commercial and military aircrafts to reduce the weight and facilitate part consolidation [1-2]. Due to the special physical structure of composite material and the low thermal conductivity of Titanium, both materials are difficult to machine with conventional cutting tools made of tungsten carbide. Recently Polycrystalline diamond (PCD) has been successfully applied in aerospace industry as a new cutting tool material. However, because of the hardness of diamond particles sintered inside the PCD, the efficiency to grind PCD tools with traditional abrasive grinding machines is extremely low. The Low G ratios, high cutting force, and high wheel cost pose a significant challenge to the production of PCD tools.

Electric Discharge Grinding (EDG) is a non-contact thermal erosion process in which the metal is removed by a series of recurring electrical discharges between the rotating electrode and the electrically conductive workpiece, in the presence of a dielectric fluid. The electric conductivity of PCD caused by the conductive binding material (Cobalt) makes it possible to grind PCD tools with EDG technology. However, as PCD is a relatively low bulk conductivity material, the discharging characteristics of PCD are different from conventional tool material such as Carbide or Carbone Tungsten. Theoretically short ignition delay time, high voltage, smaller current and high frequency (short On-Time) should be applied to achieve better surface quality. Since the discharge occurs in a voltage gap between the electrode wheel and the workpiece, it is critical to keep the gap distance constant to minimize the number of abnormal sparks such as arcing and...
short/open circuit. In practice the performance of the servo control system plays a critical role in reducing the occurrence of abnormal sparks, the optimized machining parameters can only be determined through measurement based the discharging characteristics of the PCD workpiece. Therefore, it is important to investigate the discharging characteristics of PCD with a reliable measurement system and find their impacts on gap width, material removal rate and surface finish.

Thoe, et al. [3] investigated the EDG effects on PCD blanks with various pulse parameters which included pulse on time, peak current, polarity and the direction of wheel rotation. They found that the small pit marks, which were visible on PCD surfaces, were resulted from the dislodgement of diamond grains. The large electrical current would cause poor surface finish because the removal of electrical conductive binding material (Cobalt) led to the loss binding forces and the diamond particles were thereafter dislodged. Also, many approaches to monitor the electrical discharge machining (EDM) process have been developed by different researches. For example, Dauw, et al. [4] developed an on-line measurement system to discriminate pulses with preset values. Their 8-bit A/D converter was able to acquire pulses at a sampling frequency of 10 MHz although the pulse discriminator could merely categorize 512 successive pulses online. Alternatively, some researchers have used oscilloscopes to measure the EDM process. For example, Janardhan, et al. [5] investigated the wire electro discharge turning (WEDT) process; Tee, et al. [6] measured the EDG process by recording both gap voltage and current waveforms simultaneously at a sampling frequency of 2.5 GS/s. The benefits of this method are the high sampling rate and its support for off-line analysis. Yet the limitation is the small onboard memory which becomes quickly full within a short period of time: the acquisition of pulses has to be paused to store the data to hard disks through Ethernet or GPIB bus. In Tee's experiment, only EDG pulse data of 10 ms time length could be recorded in every 5 minutes. This indicates that the data of the entire EDM process, which may last 2 - 30 minutes, cannot be fully recorded. The third method is to measure the data directly with computers. Wong, et al. [7] developed a computer-based integrated measurement system to process the digitized voltage waveforms of EDM; Yeo, et al. [8] used a similar measurement system with more powerful digitization capability and larger memory to monitor both voltage and current signals of a micro-EDM process. The advantage of their method is that EDM processes can be permanently recorded into a computer for the systematical comparison among multiple experiments. But the drawback is that the entire EDM processes cannot be completely captured because the EDM processes digitized with high sampling rates of 1 MHz have much more pulse data than what the computer can acquire with the short and fixed data memory. Although many systems have been developed, unfortunately, none of them has the capability to continuously record EDM pulses for a long duration of time, which is essential for the in-depth quantitative analysis of EDG erosion process to machine PCD tools.

The paper introduced the architecture of a new measuring system with high speed data streaming functions, which is capable to measure the EDG process continuously for up to 2 hours with a sampling frequency of 1 MHz. A series of experiments were carried out to investigate the discharging characteristics of PCD materials by relating the energy input to the material removal rate and surface finish. Monitoring the entire EDG process, the new measurement system uncovered the fluctuation of EDG input energy and gave the direction of EDG efficiency improvement.

2. Structure of the Measurement System

An EDG machine normally comprises four integrated parts: a multi-axis computer numerical control (CNC) system, a spindle system, a pulse generator system to supply electrical energy to erode the work piece, and a dielectric circulation system to flush debris and cool down the dielectric fluid. The dielectric continuously flows through the gap between the electrode and the PCD work piece. The proposed system used to measure the EDG process for PCD erosion is shown in Fig. 1.

Because of the difference in the size of diamond particles and the variation in the proportion of binding materials, different PCD material shows different electrical and mechanical properties. Table 1 shows the properties of the commercial PCD material made by Compax Innovation [9]. Based on the experiments and various grinding operations, the ranges of suitable machining parameters for the grinding of PCD are listed in Table 2.

The system to collect EDG discharge data is illustrated in Fig. 2. The system consists of a high-bandwidth data acquisition sub-system, data transfer sub-system, a group of Type 0 Redundant Array Independent Disks (RAID 0), probes and amplifiers.

The data acquisition system includes a digitizer card with an analog-to-digital converter (ADC), a transfer controller with on-board memories, and a hard disk controller. The chips on the ADC digitize the continuous voltage data at a sampling speed of up to 2 G/s and the data is directly written into the on-board device memory. A CPU on the transfer controller board is responsible for selecting the data in the device memory and transferring it to its own memory through PCI and I/O bus. The size of the downstream memory in the transfer controller is usually bigger than the device memory. The CPU divides the transfer processes into two loops: the first loop is to send the data in the device memory on the digitizer board to a queue; the second loop is to read the data from the queue and write it to the memory of the transfer controller. In order to prevent the read-
write race conditions, the queue structure is executed with the first-in-first-out (FIFO) scheme: the dequeue sequence of the second loop to transfer these data is the same as the loading order in the first loop.

The storage capacity of commercially available hard disks can be as high as 2 terabytes per disk. It would be sufficient for the application should multi disks be applied. However, the bottleneck problem of low transfer rate of hard drives could bring down the entire data recording rate in the EDG process. Therefore, a group of redundant array of independent disks was employed: the data can be evenly distributed to many strands, which are written into multiple hard disks, as shown in Fig. 2. By using this approach, the new measurement system is able to continuously record the EDG discharging data to hard disks at a sampling rate of up to 600 MB/s for a long duration.

![Block diagram of EDG measurement system.](image)

**Fig. 1.** Block diagram of EDG measurement system.

**Table 1.** Properties of Compax PCD materials.

<table>
<thead>
<tr>
<th>No.</th>
<th>PCD</th>
<th>Grain size (μm)</th>
<th>Cobalt (% Vol)</th>
<th>Density (g/cc)</th>
<th>Knoop hardness (kg/mm²)</th>
<th>Electrical resistivity (ohm-m x 10⁻²)</th>
<th>Thermal conductivity (W/mk0)</th>
<th>Transverse rupture strength (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1600</td>
<td>4</td>
<td>10</td>
<td>4.1</td>
<td>400</td>
<td>1.5</td>
<td>500</td>
<td>1.7</td>
</tr>
<tr>
<td>2</td>
<td>1300</td>
<td>5</td>
<td>8</td>
<td>4.0</td>
<td>400</td>
<td>2.0</td>
<td>525</td>
<td>1.4</td>
</tr>
<tr>
<td>3</td>
<td>1500</td>
<td>25</td>
<td>6</td>
<td>3.9</td>
<td>400</td>
<td>4.0</td>
<td>600</td>
<td>0.8</td>
</tr>
<tr>
<td>4</td>
<td>1800</td>
<td>25 &amp; 4</td>
<td>5</td>
<td>4.0</td>
<td>400</td>
<td>4.5</td>
<td>600</td>
<td>0.9</td>
</tr>
</tbody>
</table>

**Table 2.** Specifications of EDG machines for PCD erosion.

<table>
<thead>
<tr>
<th>No.</th>
<th>Item</th>
<th>Range</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pulse current</td>
<td>0.1 – 30</td>
<td>A</td>
</tr>
<tr>
<td>2</td>
<td>Open circuit voltage</td>
<td>10 - 300</td>
<td>V</td>
</tr>
<tr>
<td>3</td>
<td>Pulse ON time</td>
<td>1 - 1000</td>
<td>μs</td>
</tr>
<tr>
<td>4</td>
<td>Pulse OFF time</td>
<td>1 - 1000</td>
<td>μs</td>
</tr>
<tr>
<td>5</td>
<td>Polarity</td>
<td>Positive/Negative</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Wheel material</td>
<td>Copper tungsten</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Wheel diameter</td>
<td>20 - 150</td>
<td>mm</td>
</tr>
<tr>
<td>8</td>
<td>Wheel speed</td>
<td>1 - 15</td>
<td>m/s</td>
</tr>
<tr>
<td>9</td>
<td>Wheel runout</td>
<td>1</td>
<td>μm</td>
</tr>
<tr>
<td>10</td>
<td>CNC axis</td>
<td>≥4</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>CNC speed</td>
<td>0.1 - 1000</td>
<td>Mm/s</td>
</tr>
<tr>
<td>12</td>
<td>CNC position repeatability</td>
<td>0.1</td>
<td>μm</td>
</tr>
<tr>
<td>13</td>
<td>Dielectric flow rate</td>
<td>2 - 20</td>
<td>l/min</td>
</tr>
<tr>
<td>14</td>
<td>Dielectric grain size</td>
<td>≤1</td>
<td>μm</td>
</tr>
<tr>
<td>15</td>
<td>Dielectric</td>
<td>Hydrocarbon oil</td>
<td></td>
</tr>
</tbody>
</table>
The probes are used to measure current and voltage in the system. The amplifiers convert the current signal to voltage or just attenuate voltage signals to match the input range of the digitizers.

Because the voltage signal in the EDG process can be up to 300 V and the frequency can be as high as 1 MHz, an active voltage probe with high impedance was integrated into the measurement system to minimize its impact on the EDG gap voltage. The amplifier of the probe has the capability to isolate the EDG circuit from the measurement system and attenuate the voltage to the range of the digitizer. A differential probe and amplifier are preferred to filter the common-mode noise out of the differential signal with the high rejection ratio. The voltage probe can measure the maximum voltage of 2000 V_RMS with a bandwidth of 200 MHz.

The EDG is a thermal process, according to Joule heating effects [10]. It is needed to analyze the EDG thermal energies. Therefore the current probe in the system is included with the transformer technology to measure alternating currents and use Hall Effect sensors to measure the DC and low frequency components of the pulse current. The advantage of this method is that the current probe does not directly connect to the EDG circuit and no additional error is introduced into the measurement. The bandwidth of the probe is 50 MHz and its amplitude is 50 A.

The EDG data was analyzed by using programs developed with Matlab. As shown in Fig. 3, the program consists of two loops. The detailed steps in the two loops are listed as follows:

1. Initialization of the software with preset thresholds of voltage and current for the detection of start time of pulse ignition, stop time of each pulse, and arc identification.
2. Read one batch of voltage and current data to the memory.
3. Convert all the raw data to ASCII format.
4. Identify the new pulse and its sequential order by comparing the voltage to the threshold of ignition voltage.
5. Identify the start time and stop time of the pulse and calculate the pulse on time, off time, ignition delay time and period. Save them into the arrays.
6. Calculate and save the mean voltage, mean current and total energy per pulse to arrays.
7. Categorize the pulse type by comparing pulse voltages to the threshold.
8. Repeat above sequences until the last pulse in this batch.
9. Repeat above calculation from Step 2 until all EDG data is processed.
10. Plot the mean voltage, current and energy and save all arrays to hard disks.
3. Implementation of the Measurement System

A measurement system with fast sampling rates and huge data storage capability has been implemented. The gap voltage of the EDG machine (Fig. 4) was directly measured by a high voltage differential probe (Tektronix P5200).

Fig. 4. EDG experiment setup.

The pulse peak current was detected by a split-core current probe and was converted to a proportional voltage. The subsystem includes a Tektronix current probe (TCP305A) and a Tektronix amplifier (TCPA300). The signals were collected by digitizer card (National Instruments PXIe-5122), which has two analog input channels with 14-bit 100 MS/s sampling rate. The NI PXIe-8199 embedded controller with Intel Core i7-3610QE processor transferred these data through NI 8264×4 cabled PCI express module at the writing rate of 600 MB/s to RAID 0 array of twelve 250 GB SATA II hard disks, which were in the NI HDD-8264 enclosure. The host computer with 32 GB memory processed those EDG data by using the Matlab programs to count the entire pulse numbers, current and voltage curve, delay time, on time, pulse time and total energy of each pulse. The arcing and open/short circuits could also be identified by the ignition voltage level method or the burning voltage threshold method [11-12]. The statistical characteristics of the entire process were further analyzed by using another Minitab program.

The CNC controller measured the wheel speed driven by EDG spindle and the change in the dimension of the PCD workpiece caused by EDG erosion. The material removal rate was calculated with the change of workpiece length over experimental time. By controlling the pulse number and using extreme long pulse off time, single craters on the PCD workpiece had been created.

Instead of the Taylor Hobson profilometer used by [13], an Alicona IF-Edgemaster 3D microscopy was used to evaluate the roughness of the finished PCD workpiece. The topographical information of the workpiece was obtained by the focus-variation technique, which combined the small depth of focus of an optical system with vertical scanning to provide the 3D information from the variation of focus [14]. The advantage is to prevent the finished PCD workpiece from scratching because the microscopy does not directly touch its surface. The 3D image of the surface (Fig. 5) was stored in the stereolithography format and further exported to a host computer to analyze the volume and morphology of each individual crater.

Fig. 5. Six craters on the PCD surface.

4. Experimental Results and Discussions

More than 200 experiments were carried out to investigate the discharging characteristics of PCD blanks. The voltage and current waveforms of 100 kHz in the EDG process were simultaneously discretized and recorded on the hard disks at the sampling rate of 1 MS/s. Fig. 6 shows a section of
the waveforms of the discharge current and voltage recorded in one of the experiments.

The PCD strip (CMX850, Element Six) of 95 µm were removed in 107 seconds and 234 million pulses were recorded. The shapes of the current were similar but the shapes of the voltage, particularly the ignition delay time, exhibited a big variation. This indicates that arcing and low efficient pulse with longer delay time occurred more frequently.

One reason that might lead to such a phenomenon was the poor machining parameters or the slow response of the servo system in compensating the gap distance. Other possible reasons were related to the poor flushing and the accumulation of debris. Fig. 7 shows the trend of the mean values of the voltage and current in the first 10000 pulses of this experiment.

A total of 1,048,576 pulses was obtained, the distribution of the voltage and current of all pulses are shown in Fig. 8 and Fig. 9, respectively. Two peaks are shown in both figures: the main peak depicts the efficient pulses and the low peak represents the arcs.

Experimental results also show that it is necessary to measure both voltage and current of pulses because the pulse current may change dramatically when there was no change in the preset cutting parameters. It was found that some pulses had big electrical currents, which were three times higher than normal pulses (Fig. 10). The phenomenon happened because of the different electrical conductivities between the PCD and the tungsten carbide substrate on the PCD blank. When the discharge took place at the interface between the PCD and the carbide, the low electrical resistant of the carbide caused high current.
However, Fig. 12 shows that there is a big variation in the pulse periods, which indicates the big variation of the ignition delay time. Many factors, for instance the bandwidth of the servo system, the dielectric flushing and the wheel speed, have big impacts on the delay time.

**Fig. 11.** EDG ON time distribution with pulse of 1048576, mean of 12.26 $\mu$s and standard deviation of 0.79 $\mu$s.

**Fig. 12.** EDG discharge period distribution with pulse of 1048576, mean of 43 $\mu$s and standard deviation of 46.8 $\mu$s.

With the availability of the values of voltage and current, which were obtained by the proposed measurement system, the total energy per pulse in the EDG process can be calculated with the following equation:

$$E(i) = \sum_{j=1}^{n} V_j I_j \delta t_j,$$

(1)

where $E(i)$ denotes the total energy per pulse; $V_j$ and $I_j$ are the voltage and current of a sampling point; $\delta t_j$ is the time interval of the sampling point.

The energy of 1,048,576 pulses in the experiment was calculated. The data of the first 10000 pulses is shown in Fig. 13. A big fluctuation of discharge energy at the beginning of the EDG process can be observed. This fluctuation was caused by the transient from the open circuit period with the voltage of 120 V to the normal erosion period with the gap voltage of around 20 V.

**Fig. 13.** EDG pulse energy waveform.

**Fig. 14.** EDG pulse energy distribution with 1048576 pulses (unit: $\mu$J).

As shown in Fig. 15, there are fluctuations in the output pulse energy: the peak-to-peak amplitude is around 2800 $\mu$J and the mean is around 3000 $\mu$J when the wheel speed was 5 m/s, the pulse on time was 10 $\mu$s and the pulse off time was 20 $\mu$s.

**Fig. 15.** EDG pulse energy oscillation.
The fluctuation of the pulse energy output is related to the periodic gap variation, which is caused by the high speed rotating wheel. The existing CNC servo system shows the slow response and cannot compensate the quick gap variation, which is caused by the repeatable run-out of the rotating wheel with the linear speed of around 1.8 m/s. The high bandwidth servo system can be used to compensate it to improve the EDG removal rate.

5. Conclusions

The architecture of a new measurement system with high sampling rates and large storage capacity was developed to measure the entire EDG process. Considering the parameters of the EDG machine, a series of experiments were conducted to investigate the PCD erosion processes and the following conclusions have been drawn:

1. The voltage and current waveform of the entire EDG process with long duration can be continuously recorded by the new measurement system. This allows offline investigation of the entire PCD erosion process, including the initial period from the open circuit to the erosion, roughing operation, the transition period, and finishing operation.

2. Different from the single voltage measurement system, both the voltage and current signals of PCD erosion processes need to be measured to improve tool surface quality. The high current of the discharges may cause higher depletion of material at the interface of diamond and tungsten carbide.

3. A big fluctuation of the EDG pulse energy exists at the beginning of the erosion.

4. The pulse energies of the EDG process show oscillation. It is related to the rotation of the electrode wheel and the gap width changes in the periodical way during the EDG process.

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References


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