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Influence of electrical discharge machining parameters on cutting parameters of carbon fiber-reinforced plastic

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ABSTRACT

Today the use of high-strength carbon fiber-reinforced plastics (CFRP) composite as a material for many engineering applications is showing an increasing demand in the industry. These composites are replacing the traditional use of steel because they offer many advantages such as very light weight, high strength, and high stiffness associated with good corrosion-resistant properties. Unfortunately, there is little technological knowledge on the electrical discharge machining (EDM) process of high-strength composite materials, especially about the CFRP. In this work, a study has made into the possibility of using EDM process as a means of machining CFRP composite. Various cutting conditions such as peak current, pulse-on time, pulse-off time and open-circuit voltage were selected to perform electrical discharge machining. The effect of electrode rotation was also studied. Optimum cutting conditions and machine settings for EDM were chosen for machining CFRP composites.

KEYWORDS

Carbon fiber-reinforced plastic (CFRP); cutting parameters and machining conditions; electrical discharge machining (EDM)

Introduction

There are a great number of known fiber-reinforced composites which are continually increasing. Their composition may vary across a broad range, but structurally they are all similar, consisting of a matrix material in which another material is embedded as fiber components. Carbon fiber composite (CFC), carbon fiber-reinforced plastic (CFRP), ceramic matrix composite (CMC), metals and cement or concrete are utilized as a matrix. Typical fiber components consist of glass, carbon, polymers or ceramics. Boron, steel, aramid or natural substances are also employed. CFRP material consists of a polymer (usually duroplastics, thermoplastics) employed as a matrix material in which carbon fibers with a diameter of a few micrometers are embedded. Different processes are utilized for the manufacturing of CFRP such as fiber winding, autoclave pressing, board pressing, resin transfer molding or manual laminating for individual and small series production.
CFRP materials exhibit considerably greater rigidity, sharply enhanced electrical and thermal conductivity and a lower density. Their positive characteristics (relative to the weight) mean that CFRP materials are typically used for applications in aerospace engineering, automotive industry, sport equipment subject to high levels of stress (bicycle frames) and high-strength and high-rigidity parts in industrial applications, such as robot arms, reinforcement and sleeves in turbo-molecular pumps or drive shafts. Improved manufacturing techniques are reducing the costs and manufacturing time, making it increasingly common in small consumer goods as well, such as laptops, fishing rods, paintball equipment, racquet frames, stringed instrument bodies, classical guitar strings, drum shells and golf clubs.

- However, despite of such vast areas of applications, the carbon fiber-reinforced plastic composite materials are still considered a special group of elements requiring considerable attention in machining and are labeled as difficult to machine materials. Several researchers have cited several reasons for inherent poor machinability of CFRP. The reasons and the principal problems associated therein are as discussed next:
  - The CFRP materials have a very poor thermal conductivity (0.011–0.001 cal. /cm sec°C) compared with general metals, and hence the heat generated during the machining process is not easily conducted to the outside and thus the heat tends to concentrate at the cutting edge (Chen, 1997) and thereby results in rapid tool wear, which adversely affecting the tool life (Lin and Chen, 1996).
  - High strength and hardness impair machinability of CFRP materials as there are more force and stress on cutting edge (Chen, 1997).
  - The low modulus of elasticity of CFRP materials permits greater deflection of the work piece which adds to the complexity of machining these materials (Chen, 1997).

Conventional manufacturing techniques such as drilling, turning, milling, etc. for machining CFRP, have many problems such as delamination, splintering, the presence of burrs (Bhatnagar et al., 1995; Chen, 1997; Hocheng and Tsao, 2005; Koplev et al., 1983; Lin and Chen, 1996). Also, non-traditional machining techniques such as laser, water jet and ultrasonic can be used to cut CFRP but with some difficulties such as some failure modes showing the features typical of impact damage, with steplike delaminations, intralaminar cracks and high density micro-failure zones (Caprino and Tagliaferri, 1988; Cheng, 1990; Muller and Monaghan, 2000; Soundararajan and Radhakrishnan, 1986). Electrical discharge machining (EDM) is an extremely prominent machining process among newly developed non-traditional machining techniques (McGeough, 1988). The merit of EDM machining technique is most apparent in machining difficult-to-machine materials such as ceramics (Wang et al., 2009), composites (Mohana et al., 2004) and tool steel (Che Haron et al., 2001). The EDM process does not involve mechanical energy, thus hardness, strength, or toughness of the work piece does not affect the material removal rate (McGeough, 1988).

Electrical discharge machining of carbon fiber composite plates were performed by Lau et al. (1990). They studied the feasibility of using EDM as a means of
machining carbon fiber composite materials. Machining was performed at various currents, pulse durations and with different tool materials and polarities. They concluded that the EDM process has the capability of producing irregular shaped holes with good surface finish and dimensional accuracy when machining CFRP. Wang et al. (2010) investigated the machining of CFRP materials by EDM process with varying the values of pulse duration and discharge peak current. They compared the machining of CFRP materials with the machining of tool steel (SKD11). They concluded that the removal rate for CFRP was much higher than SKD 11 when discharge current was small and the pulse duration was large. The effect of cutting direction on machining of carbon fiber-reinforced plastic by electrical discharge machining process was investigated by Habib et al. (2013). Ito et al. (2012) discussed the effect of short-circuiting in electrical discharge machining of carbon fiber-reinforced plastics. Teicher et al. (2013) studied the micro-EDM of carbon fiber-reinforced plastics.

The purpose of this work is to study the feasibility to machine carbon fiber-reinforced plastic material by EDM process under a variety of machining conditions such as pulse-on time, pulse-off time, peak current, open-circuit voltage and electrode rotation.

### Experimental work

- The experiments were carried out using NC die sinking EDM (Sodick AQ550L, Japan) with linear servo controller LN1W. This machine has four axes control: x, y, z and u. Kerosene type (Sodick high-tech VITOL2, Japan) was used as working fluid. The electrodes were cylindrical in shape with a diameter of 8.0 mm. In this study, two electrode materials were selected such as copper and graphite (EDM-3). The physical properties of both electrodes were listed in Table 1. The workpiece material selected for this work was carbon fiber-reinforced plastics (F6343B-05P), manufactured by Torayca Japan company (www.torayca.com/download/pdf/prepreg.pdf), with two perpendicular orientations of carbon laminates formed by an autoclave method. With this molding method, a layered product of prepared sheets comprised of reinforcing fibers and high-ductility epoxy resin were pressed together and heated in an autoclave furnace to produce carbon fiber-reinforced plastics as shown in Figure 1. The physical and mechanical properties of the investigated CFRP are listed in Table 2.

In this work, various EDM cutting conditions such as pulse-on time, pulse-off time, peak current, open circuit voltage and speed of electrode rotation were selected for this work for the purpose of obtaining optimum EDM cutting conditions for

<table>
<thead>
<tr>
<th>Table 1. Physical Properties of Electrode Materials.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool material</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Copper</td>
</tr>
<tr>
<td>Graphite</td>
</tr>
</tbody>
</table>

In this work, various EDM cutting conditions such as pulse-on time, pulse-off time, peak current, open circuit voltage and speed of electrode rotation were selected for this work for the purpose of obtaining optimum EDM cutting conditions for
Figure 1. Manufacturing process of CFRP (Autoclave).

Table 2. Physical and Mechanical Properties of CFRP (F6343B-05P).

<table>
<thead>
<tr>
<th>Fiber type</th>
<th>T300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon fiber content weight fraction %</td>
<td>56</td>
</tr>
<tr>
<td>Tensile strength kgf/mm²</td>
<td>360</td>
</tr>
<tr>
<td>Elasticity 10^3 kgf/mm³</td>
<td>23.5</td>
</tr>
<tr>
<td>Elongation %</td>
<td>1.5</td>
</tr>
<tr>
<td>Breaking expansion %</td>
<td>1.3</td>
</tr>
<tr>
<td>Density g/cm³</td>
<td>1.76</td>
</tr>
</tbody>
</table>
CFRP material. The electrical discharge machining conditions selected for this work can be shown in Table 3. EDM cutting parameters such as material removal rate, electrode wear rate, gap size and surface roughness were evaluated when cylindrical cavity of 1.0 mm in depth was machined as shown in Figure 2. Material removal rate was calculated as the weight difference after machining from it before machining of workpiece per required cutting time. Changes in the tool weight, material weight, and elapsed time were recorded after each machining. The workpiece weight was measured by using an electronic balance of sensitivity 0.1 mg. Electrode wear rate was calculated as the percentage of electrode wear length to the depth of the machined workpiece cavity. For the purpose of obtaining the experimental data, electrical discharge machining was performed on the top plane of the laminates.

The surface roughness of the CFRP machined area was measured with the help of surface texture measuring instrument tracing driver Surfcom (Tokyo Seimitsu). The $R_a$ values are used to quantify the surface roughness. The cutoff length for each measurement was taken as 0.8 mm. Examining of the machining accuracy and damage of the as-machined surface can be done using both a Keyence VH-7000 (USA) optical digital high definition microscope with different magnifications and Keyence VE-8800 (USA) scanning electron microscope (SEM) at a beam voltage of 20 kV.

<table>
<thead>
<tr>
<th>Table 3. EDM Machining Conditions.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak current (A)</td>
</tr>
<tr>
<td>Open circuit voltage (V)</td>
</tr>
<tr>
<td>Pulse-on-time (µs)</td>
</tr>
<tr>
<td>Pulse-off-time (µs)</td>
</tr>
<tr>
<td>Machining fluid</td>
</tr>
<tr>
<td>Electrode material</td>
</tr>
<tr>
<td>Electrode rotation speed (rpm)</td>
</tr>
</tbody>
</table>
Results and discussion

The feasibility of electrical discharge machining process for machining CFRP was investigated in this work. The physical phenomenon that occurs during EDM process of the CFRP is generally similar to that which occurs in metals. CFRP is electrically conductive material, but the bonding material (fibers) is non-conductive material. The presence of the non-conductive fibers does not affect the machining efficiency adversely because in the EDM process, workpiece and tool must be good electrical conductive materials. The effects of variation of different EDM parameters are also discussed in order to get optimum cutting conditions. Each of the pulse-on time, pulse-off time, peak current, open circuit voltage and electrode rotation were discussed and related to the following machining parameters: material removal rate (MRR), surface roughness, gap size and electrode wear rate (EWR).

When a sufficient amount of discharge current is applied between the EDM electrode and CFRP surface, much sparks were generated and directed towards the CFRP workpiece surface and by increasing the amount of pulse duration, the amount of thermal energy that is transferred to the CFRP surface is increased and causes more material to be melted. In addition to melting, the high amount of heat generated at high currents caused thermal expansion of the fibers. After that, the resins were squeezed out from the CFRP matrix causing the material to be removed. The epoxy resin part in CFRP composite is easily melted and removed by high temperature of sparks.

In electrical discharge machining process, the discharge energy that is transferring on machining gap is divided between tool electrode, CFRP workpiece, and dielectric fluid in discharge channel. When increasing the discharge energy, the amount of melted and vaporized materials increased and led to an increase in the electrode wear rate. As the electrical resistivity of the CFRP workpiece material is much higher than that of the graphite or copper tool electrodes, more heat is generated on the CFRP workpiece and less heat is generated on the electrode surface so relative smaller tool electrode wear resulted.

Effect of pulse-on time

The relationship between pulse-on time and MRR can be shown in Figure 3a for copper and graphite electrodes. The MRR for copper electrode increases from 0.0085 to a maximum of 0.0107 g/min when the pulse-on time was increased from 50 to 100 µs. For graphite electrode, MRR increases also from 0.0075 to a maximum of 0.0109 g/min for the same period of pulse-on time. After that, the MRR deceases again for the both electrodes. During the discharging, ions flow from the positive to the negative pole, and electrons flow in the opposite direction, hence forming a conductive passage between the electrode and the workpiece. At the beginning, fast moving electrons on the anode were generated as they were lighter than the positive ions and took less time to accelerate. With increase in pulse-on time, the cathode area will be subjected to more heavy number of the positive ions and hence
more heating leading to increase the MRR and with further increase in pulse-on time cause an increase in the melting of the resin material. The melted resin goes over the conductive carbon fiber surface and interferes with the discharging process, leading to a reduction of the MRR. The resulted trend of MRR with pulse-on time was the same that were studied by Meshcheriakov et al., (1988).

Figure 3b also shows that the surface roughness increases with increasing discharge durations for both electrodes. The surface damage of the machined CFRP resulting from EDM with different pulse-on times can be shown in Figure 4. The increase of surface roughness with pulse-on time may be due to the increase tendency of the molten metal to transfer and deposit on the surface of the cathode. Figure 3c shows the relationship between gap size and pulse-on time. The gap size values increase directly with the increase of pulse-on time. As was discussed previously that increasing the pulse-on time means increasing the heat energy in machining area, leading to increase the MRR and the gap size. With further increase of pulse-on time, although, the MRR decreased, the gap size increased. This may be due to the side removal rate from the electrode.

The relation between EWR and pulse-on time for both copper and graphite electrode can be shown in Figure 3d. In the beginning, the EWR for both electrodes decreases very rapidly in an inverse relation with pulse-on time when the pulse-on...
time increased from 50 to 100 µs. After that the EWR for copper electrode increases with pulse-on time but for graphite electrode, the EWR, decreases slightly with pulse-on time. The long pulse duration provides a better heat removal around the surface of the electrodes, which are normally good thermal conductors. The decrease in temperature on the surface of the electrodes causes less wear on the electrodes. With further increase of pulse-on time, the amount of heat was increased causing the increase of the EWR for copper electrode.

**Effect of pulse-off time**

The relationship between pulse-off time and EDM parameters for both copper and graphite electrodes can be shown in Figure 5. The MRR increases with the increase of pulse-off time until it reached a peak value around 200 µs and then the MRR decreased again. A longer pulse-off time means more time for deionization of the dielectric, resulting in an increase of the breakdown voltage and the discharge explosion force and thus the crater size generated by a single pulse becomes larger and deeper; therefore, with an increase of pulse-off time, the MRR increases. As the pulse-off time increases to more than 200 µs, the breakdown voltage and the discharge explosion force do not increase leading to decrease of the amount of crater generated by electrical discharge; therefore, the MRR decreases with more increase of pulse-off time.

The surface roughness increases with the increase of pulse-off time as illustrated in Figure 5b. At 100 µs, a smaller amount of epoxy resin that covered the carbon fibers was removed as shown in Figure 6. With further increase of pulse-off time, the amount of the resin removed was increased leaving the carbon fibers alone on the surface resulting to increase of the surface roughness. The gap size values increase directly with the increase of pulse-off time from a value of 1.99 to 2.1 µm as shown in Figure 5c. EWR of the copper electrode decreases rapidly with the increase of pulse-off time until it reached a peak value around 200 µs and then the surface roughness rose again. For graphite electrode, the EWR decreased directly with the increase of pulse-off time as shown in Figure 5d. The optical microscope images for EDM machined surfaces with different pulse-off times by copper and graphite electrodes are shown in Figure 6.

<table>
<thead>
<tr>
<th>$T_{on}$ (µs)</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>(b)</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
</tbody>
</table>

*Figure 4.* Optical microscope images for EDM with different pulse-on times (a) copper electrode and (b) graphite electrode (x100).
Figure 5. Relationship between pulse off-time with (a) MRR, (b) \( R_a \), (c) GS and (d) EWR.

Effect of peak current

The effect of peak current on the MRR, surface roughness, gap size and EWR when using both copper and graphite electrodes can be shown in Figure 7. For both electrodes, the value of MRR increased with peak current reaching a maximum of 1.0 ampere and then it began to decrease again. The surface roughness increased

![Table showing effect of peak current](image)

<table>
<thead>
<tr>
<th></th>
<th>( T_{off} = 100 \mu s )</th>
<th>( T_{off} = 200 \mu s )</th>
<th>( T_{off} = 300 \mu s )</th>
<th>( T_{off} = 400 \mu s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td><img src="image" alt="Image" /></td>
<td><img src="image" alt="Image" /></td>
<td><img src="image" alt="Image" /></td>
<td><img src="image" alt="Image" /></td>
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<tr>
<td>(b)</td>
<td><img src="image" alt="Image" /></td>
<td><img src="image" alt="Image" /></td>
<td><img src="image" alt="Image" /></td>
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Figure 6. Optical microscope images for EDM with different pulse-off times (a) copper electrode and (b) graphite electrode (x100).
with peak current ranged from $8.2 \ \mu m$ at 0.5 A to $8.5 \ \mu m$ at 2.5 A for copper electrodes and ranged from $8.5$ to $10 \ \mu m$ at the same range of peak currents for graphite electrodes. At low currents, some fiber material is removed largely by vaporization, leaving relatively little disturbance of the remaining fibers. With increasing peak currents, there is growing dissipation of heat energy in the workpiece and an increase in the melting of the resin material. The melted resin smears over the more conductive carbon fiber surface and interferes with the discharging process, leading to a reduction of the MRR and a rapid deterioration of the surface quality. As was discussed previously when the pulse-on time increases, it resulting in the reduction of MRR and thus a rapid deterioration of the surface quality. The surface damage of the machined CFRP resulting from EDM with different peak currents can be shown in Figure 8.

**Figure 7**. Relationship between discharge peak current with (a) MRR, (b) $R_g$, (c) GS and (d) EWR.

**Figure 7c** shows that, the gap size increases directly with the increase of peak current for both electrodes. Also, EWR decreases gradually with the increasing of peak current as shown in **Figure 7d**. By increasing peak current from 0.5 A to 2.5 A, the spark energy applied between the workpiece and tool electrode is increased and thus the gap size increased. Although the spark energy is increased, the EWR decreases. This may be due to the sticking of the tiny carbon particles resulted from the EDM process with the electrode surface resulting to decrease the EWR.
Effect of electrode rotation speed

The effect of electrode rotation speed for both copper and graphite electrodes on MRR, surface roughness, gap size and EWR can be shown in Figure 9. The MRR increases with the increase of electrode rotation speed for both electrodes. MRR increases rapidly from 0.008 g/min at zero rpm to 0.011 g/min at 1000 rpm after that with the increase of electrode rotation speed the MRR extremely constant. This
is possibly due to the superior debris removal effect of the rotating electrode. For both electrode materials, the resulted surface roughness decreases gradually with the increase of electrode rotation speed until it reaches a minimum value at 1000 rpm and any increase of electrode rotation speed, the surface roughness increases again. The surface roughness decreases gradually with increasing the rotation speed of the both electrodes until it reaches 1000 rpm, the surface roughness increases with further increase of the rotation speed. Figure 10 shows optical microscope images for the surface resulted from EDM machining.

The gap size decreases slightly with increase of electrode speed rotation from 2.063 µm at no-rotation electrode to 2.05 µm at 1000 rpm for copper electrode. After that the gap size begins to increase rapidly with further increase of electrode rotation speed, it increases to 2.115 µm at 2000 rpm. The resulted gap size values from graphite electrodes are smaller than that for copper electrodes. This may be because the material removal rate with machining using graphite electrode is relatively higher than that when using copper electrode for all machining conditions. The debris at the machining gap is removed effectively by the centrifugal force generated by the rotating electrode which leads to increase the gap size. Also, it can be shown that the EWR decreases directly with the increase of the speed of electrode rotation.

**Effect of open circuit voltage**

The effect of open circuit voltage on MRR, surface roughness, gap size and EWR for both copper and graphite electrodes can be shown in Figure 11. The MRR increases with an increase in voltage values for both electrodes. An increase in voltage implies higher discharge energy applied between the two electrodes as well as increased the rate of gas bubbles formation, resulting in more MRR.

Surface roughness is also increased with voltage increased for both electrodes. Also, the gap size is increased with increasing voltage. Since material (in EDM) is removed simultaneously by the leading face and the side surface of the electrode, the gap size between the workpiece and electrode increases. Figure 12 shows optical microscope images for the surface resulted from EDM machining. Therefore,
an increase in MRR also implies an increase of gap size. In the other hand, EWR is decreased when voltage is increased. When the voltage value increased, the discharge energy increased also resulting in increasing MRR and thus the amount of tiny carbon particles removes from CFRP workpiece and as a result they stick to the electrode surface and protect it from wear.

Figure 11. Relationship between open circuit voltage with (a) MRR, (b) $R_{a}$, (c) GS and (d) EWR.

Figure 12. Optical microscope images for EDM with different open circuit voltages (a) copper electrode and (b) graphite electrode (x100).
Shape of machined workpieces

To study well the effect of EDM cutting parameters for machining CFRP, the resulted shape of machined workpieces were examined as shown in Figures 13 and 14. It shows the microstructure of CFRP under different machining conditions using both copper and graphite electrodes. The damage is frequently observed in the form of isolated craters, disorientation of the fibers, thermal expansion and distortion of the fibers and the delamination of the fibers and cracking of the matrix interface. Also, machining using graphite electrodes had less circular damage than that machined with copper electrodes.

Optimum machining conditions

The optimum combination of cutting conditions for electrical discharge machining of carbon fiber-reinforced plastic are listed in Table 4. It suggests that to cut CFRP
Table 4. Optimal Values of EDM Parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse-on time</td>
<td>100 µs</td>
</tr>
<tr>
<td>Pulse-off time</td>
<td>200 µs</td>
</tr>
<tr>
<td>Peak current</td>
<td>1 A</td>
</tr>
<tr>
<td>Speed of electrode rotation</td>
<td>1000 rpm</td>
</tr>
<tr>
<td>Open circuit voltage</td>
<td>120 V</td>
</tr>
</tbody>
</table>

material by EDM effectively at a constant level of electrical power consumption, short pulse-on time, relatively longer pulse-off time, small peak current, high open circuit voltage and rotary electrode should be employed. These values were selected based on maximizing the material removal rate, minimizing the surface roughness, gap size and electrode wear rate.

Conclusions

This work evaluates the feasibility of machining carbon fiber-reinforced plastic composite by electrical discharge machining process. Based on the results from the investigations described under the consideration of this study, the following conclusions were reached:

- The machining process of the CFRP materials by EDM using copper or graphite electrodes is more feasible than other machining processes.
- Experimental results confirm that the material removal rate increases with pulse-on time, pulse-off time, peak current, speed of electrode rotation and open circuit voltage until it reaches its maximum value when these parameters values are 100 µs, 200 µs, 1.0 A, 1000 rpm and 120 V, respectively.
- The material removal rate with machining using graphite electrode is relatively higher than that when using copper electrode for all machining conditions of this study.
- The resulted surface roughness increases with pulse-on time, peak current and open circuit voltage. Also, it decreases with both pulse-off time and speed of electrode rotation until it reaches its minimum value when these parameters values are 200 µs and 1000 rpm, respectively.
- The surface roughness resulted with machining using copper electrode is smoother than that resulted when using graphite electrode for all machining conditions of this study.
- The resulted gap size increases with pulse-on time, pulse-off time, peak current and open circuit voltage. Also, it decreases with speed of electrode rotation until it reaches its minimum value when it was 1000 rpm.
- The electrode wear rate of both copper and graphite electrodes decreases with pulse-off time and speed of electrode rotation. Also, it decreases with pulse-on time, peak current and open circuit voltage until it reaches its minimum value when these parameters values are 100 µs, 1.0 A and 120 V, respectively.
References


