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# Electric Discharge Machining of Carbon Fiber Reinforced Plastics: A Review

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**Abstract—***Fiber reinforced plastics is very popularly used in today's time. The use of FRP ranges from sophisticated aerospace industry to the day to day items like sport goods etc. FRP is finding more use in today's time because of its high specific strength and stiffness combined with corrosion resistance, lower maintenance cost, easy handling and installation. Although FRP has a number of advantages but good quality and cost effective standardized manufacturing of FRP is also a challenging job. Drilling of Carbon Fiber Reinforced Plastics (CFRP) composites is an important machining operation in the aerospace industry. Formation of burr during drilling of CFRP is always a severe shortcoming these burrs becomes a source of problem in assembly, inspection and precision components operations.*

*This paper shows how electrical discharge machining (EDM) acts as a de burring method for removal of burrs which are generated during drilling of CFRP composites and the best possible way to do this.*

***Keywords****: Carbon fiber reinforced plastics (CFRP's), Drilling hole, De burring, Electric Discharge Machining (EDM), Exit burr.*

## 1. INTRODUCTION

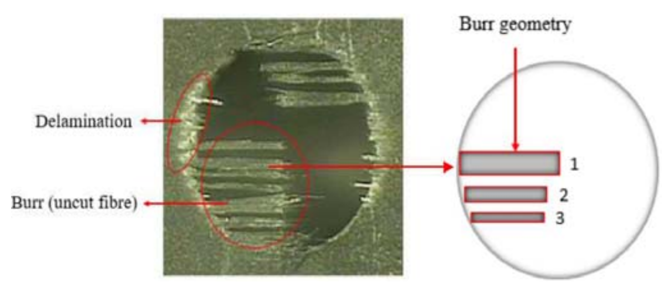
Recently Carbon Fiber Reinforced Plastics (CFRP) has been extensively used in many industries like aircraft, aerospace, automobiles and defense which require high strength-to-weight ratio as well as stiffness to weight ratio[1]. In the aerospace and aircraft industries drilling becomes one of the important process during the assembly of aero structures. These aero structures are assembled with the help of fasteners inserted into drilled holes. As a result it becomes essential for the drilled holes to possess good finish and offer better service life. But during drilling of CFRPs the composite de lamination and formation of burr pose severe problems and become the cause for rejection and loss. The burr formation is in the entry side and exit side of the CFRPs. Amongst the two exit burr posses more problems [2].

Most of the studies in this field has been done regarding the de lamination and burr formation on exit hole [3]. Eshetu *et. al.* have examined the hole surface quality and damage in the unidirectional CFRP composites[4]. Unfortunately sufficient researches have not been done on de burring of drilled hole in CFRPs. Therefore Ping *et. al.* introduced an electrical discharge machining (EDM) process which uses a cylindrical electrode for de burring[5].

Electric Discharge Machining (EDM) is an unconventional machining process generally used to machine difficult to work materials which need high precision. Since 1970s EDM was used for burr removal on macro level[6]. Jeong *et. al.* introduced micro-EDM for burr removal using low discharge energy and a tool of small diameter[7]. The main advantage of EDM is that tool and work piece does not come in contact and make use of electrical discharge and thermal energy. De burring involves both removal of burr as well as maintain proper edge condition[5]. This study briefly reviews how burrs are formed at exit during drilling of CFRP composites and how and what parameters are to be adopted to successfully remove these burrs.

## 1. Formation of burr during drilling of CFRP

Due to retreat in the feed direction of drill bit some of the fibers are not cut and give rise to burr formation. These burr formation are influenced by machining parameters like cutting speed, feed rate, rpm then other factors like fiber orientation, tool geometry (point angle, tool wear), tool type, tool material, drilling type [8]. Mostly during drilling the formation of burr is seen at entrance and exit side of machined hole.




**(a) (b)**

**Fig. 1: Burr formation due to drilling of unidirectional CFRP composites (a) and defined burr geometry (b) [ 5].**

## 2. De burring by EDM process

EDM is widely used non-contact machining process that uses thermoelectric energy between the electrode and the work piece accompanied by discharge. The discharge in the spark gap, melts and vaporizes and thereby removes the unwanted material from the work piece. In CFRP composites, the carbon fiber are electrically conductive but the epoxy resin that acts as a binder is non-conductive [9]. Therefore the carbon fiber can be eroded by the spark and the bonding material is removed owing to high temperatures. These eroded carbon fibers are flushed out by the dielectric fluid. The decomposition of the layer of resin leads to the release of gases in form of intermediate puffs.

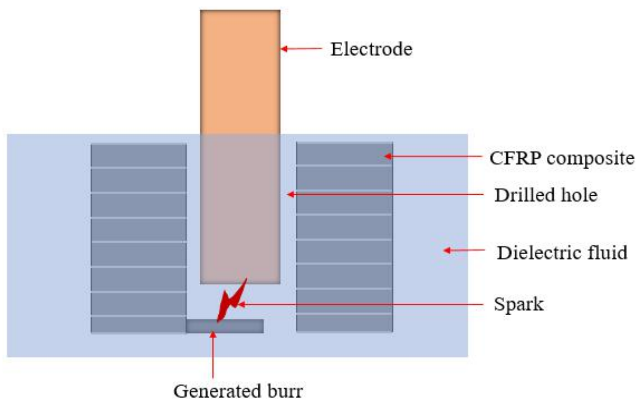



**Fig. 2: Schematic of the EDM de burring method**

Hence, the EDM is an effective de burring process for avoiding mechanical damage of the work piece. By changing the EDM process parameters the rate at which burr can be removed is adjusted. It has been found that when the tool is connected to positive polarity the material removal rate is optimum. The electrode moves in the vertical direction in the drilled hole without any rotation. When the EDM tool of cylindrical shape approaches the bottom of the drilled hole, the exit burr is closest to it. Generally precaution is taken to avoid the machining of the drilled hole wall by covering the side of electrode by some kind of adhesive tape. Thus spark is generated only at the bottom of electrode and the burr and it is removed when the distance between the electrode bottom and top of burr is properly adjusted. The rate of burr removal can be influenced by the various parameters of the process like energy, tool polarity, de burring time, tool type, dielectric being used etc.

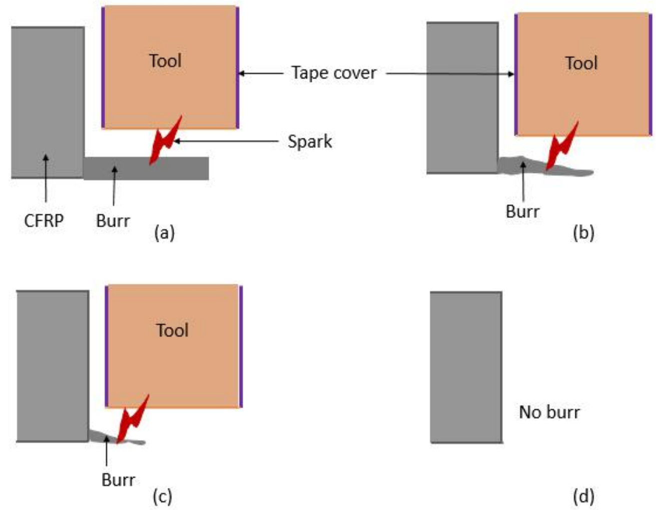



**Fig.:3 Schematic of the de burring procedure for drilled hole using EDM**

Various authors have done analysis of different parameters that affect the burr removal rate which has been shown in the review below:

## LITERATURE REVIEW

| S.No. | Author | Process Review | Output Parameter | Benefit/Conclusions |
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| 1. | Demeng Che<br>Ishan Saxena<br>Peidong Han<br>Ping Guo<br>Kornel F. Ehmann<br><br>March 26, 2014 | Machining of Carbon Fiber Reinforced Plastic/Polymers | • Tool Wear Mechanism and Tool Performance:<br><br>*mechanical wear mechanism* includes dislodging of hard particles from the tools surface due to abrasion, impact or vibration at the CFRP-Tool interface.<br><br>*Thermal Wear Mechanism* includes wear of tool due to cutting temperature which is about 387°C. although this field requires much work to be done.<br><br>• Effect of Tool Geometry and Material on Process:<br><br>In *Tool Geometry* Koplev et al. found that rake angle decreases the cutting force and clearance angle decreases the thrust force. Piquet et al. designed new drilling tool with 3 cutting edges which gave an excellent drilling quality in thin carbon/epoxy plates compared to conventional drilling. Grilo et al. in turn found that SPUR drills produce the least amount of de lamination among three drills (i.e., **SPUR, R950, R415**) in CFRP drilling.<br><br>Talking about *Tool Materials* HSS, Cemented Carbides, coated carbides, ceramics and polycrystalline diamonds are traditionally used tool materials. Later it was found that HSS is not suitable as tool material owing to high tool wear rates and surface finish. Other materials used are PCBN . Tungsten carbide cobalt.<br><br>• Coating and Other Tooling Techniques: Tool life of diamond coated cemented carbide cutting tools is 10 times greater than uncoated tools. Zitoune et al. during CFRP-aluminum multi material drilling found that micro grain K20 carbide tools with nanocrystalline coatings (nc-CrAIN/a-Si3N4) were able to produce holes with better surface quality but less tool wear, compared to tools without coating. | • CFRP's has perfect mechanical properties such as high strength and stiffness, high damping capacity and good dimensional stability.<br><br>• Cutting tools significantly affect the surface finish of CFRP workpieces and the entire performance/efficiency of the machining processes used. |

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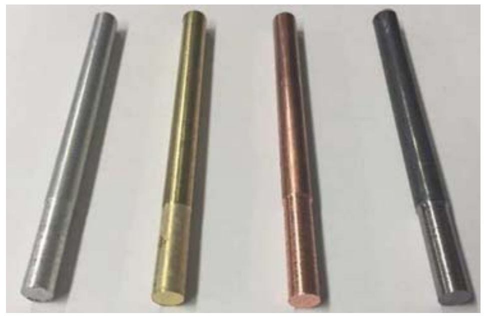
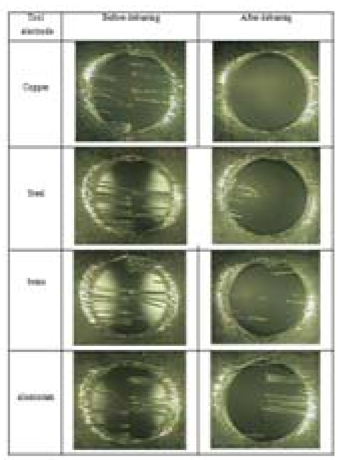
| 2. | Md. Mofizul Islam<br>Chang Ping Li<br>Sung Jae Won<br>Tae Jo Ko<br><br>December 26, 2016 | A de burring strategy in drilled hole of CFRP Composites using EDM Process. | • <u>Tool Materials</u>: Aluminum (AL6061), Brass (CW 614N), Copper (C110), Steel (SM 45 C). It is observed that within 60 sec of de burring copper electrode removes 100 % generated burr. However burr removal in steel brass aluminum were 81% 73% and 58% respectively. This is due to higher electrical conductivity of copper.<br><br>• <u>Tool Diameter (mm):</u> 5.9<br>• <u>Capacitance (pF):</u> 10 100 1000 10000pF. Changing the capacitance values and keeping the time constant it was found that copper electrodes give best de burring. The image below shows de burring at 10pF capacitance with machining time 60 sec with all four electrodes i.e, copper, steel, brass, aluminum. Left image is of before de burring and right is of after de burring.<br><br>Image below shows the de burring at 10000 pF capacitance with machining time 60 sec. | • A de burring method has been developed using EDM for removal of burrs from CFRP.<br>• Generated burrs of the drilled hole were successfully removed by the proposed strategy.<br>• Copper electrode obtained the highest performance among the four electrodes.<br>• No morphological changes were observed in drilled hole after de burring. |

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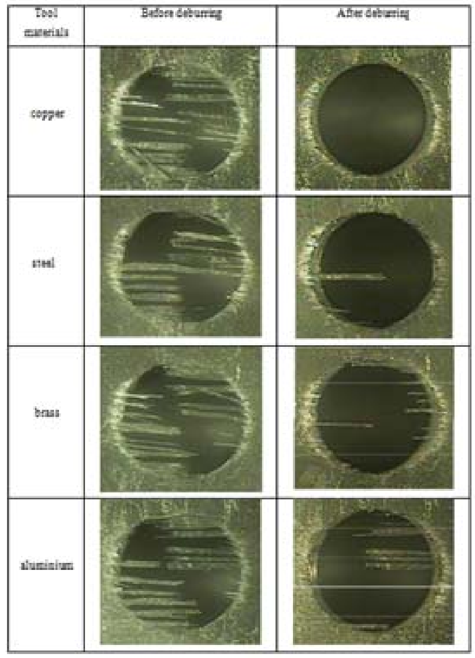
| | | | <br>• <u>EDM time (min):</u> 1, 1.5, 2.<br>• <u>Dielectric fluid :</u> EDM oil<br>• <u>Voltage ( V ):</u> 220 | |
| 3. | Md. Mofizul Islam<br>Chang Ping Li<br>Tae Jo Ko<br><br>April 2017 | Dry Electrical Discharge Machining for De burring Drilled Holes in CFRP Composites. The process conditions were:<br>Tool Electrode is copper (C110),<br>Tool dia 5.9mm<br>Capacitance varies from 10, 100, 1000 and 10000 pF.<br>De burring time 30, 45, 60,90 sec.<br>Dielectric Medium were oxygen, Air, Oil.<br>Voltage(v) | • <u>Effect of Capacitances on the De burring Performance:</u><br><br>The MRR increased moderately with the increase in capacitance. Maximum MRR was obtained using oxygen while oil EDM showed the lowest MRR for all capacitance. | • In this study dry EDM uses oxygen and air as a dielectric for the removal of burrs from CFRP composites<br>• The influences of capacitance, voltages, tool polarity, and gas pressure were also investigated.<br>• The MRR significantly increased with the capacitance, voltage, and gas pressure in both dry EDM and oil EDM.<br>• The positive tool polarity showed higher MRR than the negative polarity.<br>• Compared to conventional oil EDM oxygen showed |

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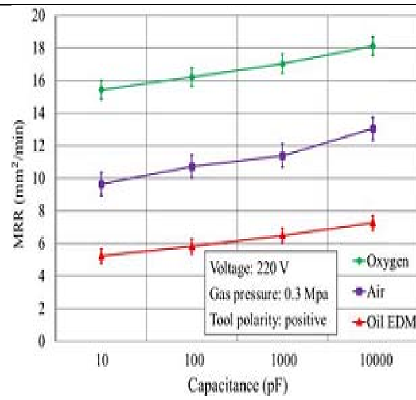
| | | 100,150,220.<br>Gas Pressure(Mpa) 0.1, 0.2, 0.3. | <br>• <u>Effect of Tool Polarity on the De burring Performance:</u><br><br>TOOL ATTACHED TO POSITIVE POLARITY<br><br>*In Case of Oxygen:* The MRR with positive tool polarity is about four times greater than that with negative tool polarity.<br><br>*In Case of Air:* The MRR with positive tool polarity is three times higher than that with negative tool polarity .<br><br>*In Conventional EDM:* The MRR is also three times greater than negative tool polarity.<br><br>When tool was attached to positive polarity, the MRR with oxygen was approximately three times higher than that in oil EDM, and that with air is nearly two times higher.<br><br>TOOL ATTACHED TO NEGATIVE POLARITY<br><br>The MRR of dry EDM was almost double than that of oil EDM. The optimum material removal rate can thus be achieved with a positive tool polarity. Lau et al. obtained similar results when machining CFRP composites using conventional EDM. Zhang et al. in his research showed that positive polarity transferred more energy than negative polarity.<br><br>• <u>Effect of Voltage on the De burring Performance:</u><br><br>Initially the MRR increases moderately with increase in voltage from 100 to 150 V in both dry and oil EDM. The MRR then sharply increases with increase in voltage up to 220V. Due to low voltage the spark gap width was very small, resulting in several | almost three times higher MRR and in case of air the MRR was nearly two times higher.<br>• Dry EDM was more effective than oil EDM for the removal of burrs from CFRP composite. |

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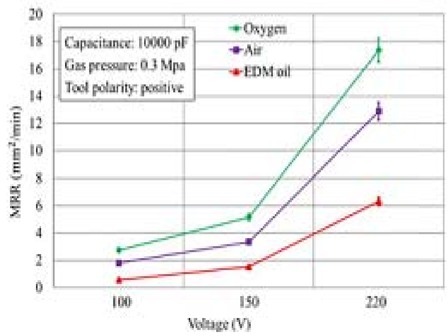
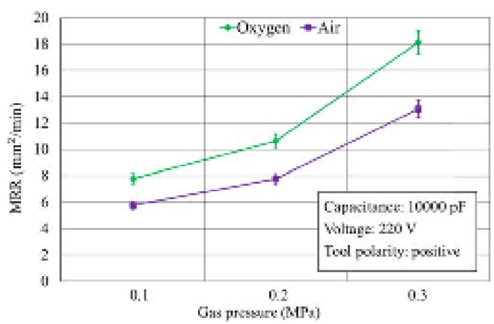
| | | | short circuits during the de burring and thus low MRR. With increase in voltage , the spark energy increases and leads to higher MRR. Maximum MRR was found when using oxygen and minimum with oil EDM.<br><br><br>• <u>Effect of Gas Pressure on the De burring performance:</u><br>MRR increases with Gas Pressure because of the high pressure gas flow cooling the machining gap better and expels more of debris. In dry EDM oxygen showed nearly 1.4 times better performance than air at all gas pressures.<br><br><br>• <u>Effect of De burring on Surface Quality:</u><br>This study examined the morphology of the de burred hole wall and face using scanning electron microscope (SEM). It is observed that proposed method effectively removed only the burr without damaging the drilled hole wall and face. | |
| 4. | U. Teicher<br>S. Muller<br>J. Munzner<br>A. Nestler<br>2013 | Micro – EDM of Carbon Fiber Reinforced Plastics. Tool used here is of Tungsten Carbide. | • <u>Tool Wear and Material Removal Rate:</u><br>Tool wear is less with low abnormal discharge pulse rates and a minimum of short circuits.<br>Material removal rate of long pulses can | • Drilling holes in CFRP by Micro EDM rather than machining operations gives burr less machining and high dimensional accuracy. |

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<td>basically be increased by increasing the frequency or pulse duration, if the open circuit voltage and discharge current are optimally used.<br><br>
• <u>Gap between Tool and Work piece:</u><br><br>
Measured values of working gap latitudes<br>
<table>
<tr><th>Pulse duration type</th><th>Discharge energy</th><th>Lateral working gap</th></tr>
<tr><td>Ultra short</td><td>13;15</td><td>30 – 35 µm</td></tr>
<tr><td>Short</td><td>100; 114</td><td>32 – 38 µm</td></tr>
<tr><td>Long</td><td>200; 365</td><td>34 – 44 µm</td></tr>
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• <u>Surface Roughness:</u><br><br>
At low discharge the non conductive matrix structure melts which cannot be flushed. This can lead to a removal of the electrically conductive fiber structure leaving a thermally damaged structure. At high energies the material removal is high at hole bottom. Therefore the surface roughness of bottom hole increases with increase in pulse energy.<br><br>
• <u>Thermal Damage:</u><br><br>
Due to high thermal conductivity of carbon fibers, a strong anisotropy of the HAZ can be observed. The low conductivity of epoxy resin proves to be problematic.</td>
<td>• With increasing pulse energies both a high tool wear and low surface finish can be produced.<br><br>
• Neglecting the tool wear mainly medium and high pulse energies with low discharge current offer a good performance for productivity and quality.<br><br>
• Low pulse energies have the disadvantage of low material removal rate despite the low tool wear and increased surface quality.</td>
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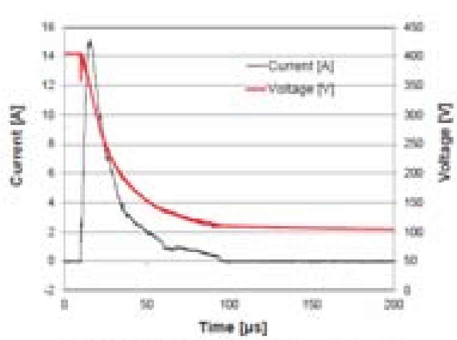
<td>5.</td>
<td>Yoshiaki Akematsu Kazuro Kageyama Hideaki Murayama<br><br>2016</td>
<td>Basic Characteristic of electrical discharge on CFRP by using thermal camera.</td>
<td>• <u>Electrode –supply- point distance (perpendicular):</u><br><br>
As the electrode supply point distance, increases the peak current decreases where as the rise time and half-value time increases.<br><br>


(a) Electrode–supply-point distances of 10 mm</td>
<td>• It was found that the discharge energy increases as the size of EDM traces.</td>
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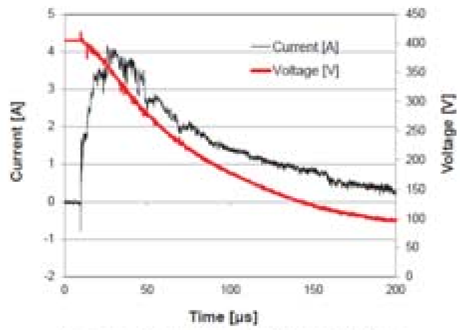

(b) Electrode–supply-point distances of 50 mm<br>
Fig. 2 Typical current and voltage signal waveforms
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<td>6.</td>
<td>Akihiro Ito<br>Shinya Hayakawa<br>Fumihiro Itoigawa<br>Takashi Nakamura<br><br>January 11, 2012</td>
<td>Effect of Short Circuiting in Electrical Discharge Machining of Carbon Fibre Reinforced Plastics</td>
<td>
<ul><li>Table below shows the Material properties in evaluating the ratio of the short-circuiting.</li></ul>
<table>
<tr><td>Thickness</td><td>11.50 mm</td></tr>
<tr><td>Fiber Orientation</td><td>0°, ± 45°,90°</td></tr>
<tr><td>Fiber Diameter</td><td>8 µm</td></tr>
</table>
<ul><li>Experimental conditions for evaluating the ratio of the short-circuiting.</li></ul>
<table>
<tr><td>Tool Electrode</td><td>Cu (ϕ10mm)</td></tr>
<tr><td>Polarity</td><td>Tool electrode (+)</td></tr>
<tr><td>Open Circuit Voltage</td><td>85 V</td></tr>
<tr><td>Discharge Current</td><td>24 A</td></tr>
<tr><td>Discharge Duration</td><td>32 µs</td></tr>
<tr><td>Pulse Interval Time</td><td>128 µs</td></tr>
<tr><td>Dielectric Fluid</td><td>Deionized Water</td></tr>
</table>
<ul><li>Consequently it was found that the estimated gap voltage is consistent with the measured one when the short circuiting due to frayed carbon fiber occur. It was also found that the number of carbon fiber in short-circuiting determining from the condition concerning the gap voltage is 80 to 260, which coincides with the number derived from the condition concerning temperature. The temperature of the fibres can be estimated to be 1000 to 3600°C, which is much higher than the melting point of the matrix resin. These estimations indicate that the short-circuiting contributes to material remoal in EDM of CFRP.</li></ul>
</td>
<td>
<ul><li>Short-circuiting due to frayed carbon fibers frequently occurs in sinking EDM of CFRP. The ratio of short-circuiting pulses to total pulses is varied from 10% to 60% under the machining conditions used in this work.</li>
<li>Short-circuiting caused due to frayed carbon fibers contributes to material removal in EDM of CFRP.</li></ul>
</td>
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<td>7.</td>
<td>Sameh Habib<br>Akira Okada<br><br>April 2016</td>
<td>Influence of Electrical Discharge Machining Parameters on</td>
<td>
<ul><li><u>Effect of Pulse on Time:</u><br><br>For copper electrode MRR increases with increase in pulse on time to some extent then</li></ul>
</td>
<td>
<ul><li>EDM of CFRP by copper or graphite electrode is more feasible than any other method.</li></ul>
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| | | Cutting Parameters of Carbon fiber reinforced plastic. | decreases. Same is with graphite electrode.<br>• Effect of Pulse Off Time:<br>The MRR increases with increase in pulse off time until it reached a peak value around 200μs and then the MRR decreased again.<br>• Effect of Peak Current:<br>The effect of peak current on the MRR, surface roughness, gap size and (electrode wear ratio) EWR when using both copper or graphite electrode the value of MRR increased with peak current reaching a maximum of 1.0 ampere and then it began to decrease again. For both electrode 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.<br>• Effect of Open Circuit Voltage:<br>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.<br>• Effect of Electrode Rotation Speed:<br>MRR increases with the increase of electrode rotation speed. | • 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 and values are 100 μs, 200 μs, 1.0 A, 1000 rpm and 120 V, respectively.<br>• 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.<br>• 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. |

## RESULTS AND DISCUSSION

Many experiments were carried out and it was discovered that Material Removal Rate (MRR) was influenced by various parameters like material of electrode, spark gap, short-circuiting, capacitance, tool polarity and many more. We can modify the above parameters depending upon the amount of MRR we require. Copper electrodes give the best result at increased capacitance values. Electrodes with different types of coatings can enhance surface finish.

## CONCLUSION

The conventional secondary processing laws and rules for isotropic materials and alloys does not comply while doing secondary processing of Carbon Fiber Reinforced Plastics (CFRPs). Drilling is one of the most important secondary operations on CFRPs to enable the joining of various composite parts to obtain the endmost assembled product. The machining of the CFRPs is difficult due to the embedded abrasive reinforcements like glass fibers and carbon fiber which causes the tool wear and deteriorates the quality characteristic of drilled holes or in simple language it leads to burr formation. EDM de burring is most widely used for the drilled holes. Other techniques like dry-EDM, micro-EDM has also proved beneficial. Although there has been some researches regarding machining of CFRPs but still fields like specially designed cutting tool material (other than HSS, Coated HSS, TiC), tool geometry and profiles are profiles are under investigation to reduce the machining challenges of CFRPs.

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