Electro discharge machining of carbon fiber reinforced polymer

Joris Claes, Prof. dr. ir. B. Lauwers, Prof. dr. ir. D. reynaerts, Dr. ir. J. Qian, Ir. J. Bouquet, Ing. F Vogeler
Department of Mechanical Engineering
KU Leuven, Leuven
Belgium

Abstract—This paper investigates the feasibility of electro discharge machining (EDM) applied to carbon fiber reinforced polymer (CFRP). Because of the little investigation that has been done until now, this is why first experimental work is carried out. The experiments confirm that industrial CFRP ($\rho = 0,01 \Omega cm$) is machinable by EDM. Thorough research into the phenomena that appear to the material during the EDM process is executed next. The following boundary conditions are relevant: A copper electrode (Ø = 10 mm, negative polarization) is applied to machine each sample to a depth of 1 mm. A machine range with pulse current from 1 to 65 A and pulse time from 0,8 to 200 $\mu$s. During the experiments a machining functionality automatically controls other parameters in an optimal way. The result is examined with a chip analysis, and microscopic, SEM and EDX analysis applied on machined cross sections and surfaces. This allows to conclude four material removal mechanisms. The experiments also determine two optimal technologies. A statistical analysis explains the significance of factors in relation to an output (MRR, Ra and edge quality). The study is completed with the investigation towards the influence of electrode polarity; the influence of a graphite electrode; and an analysis of pulse current and voltage with pulse monitoring.

Keywords—electric discharge machining; materials science, spark technology, polarity, electrode materials

I. INTRODUCTION

In General EDM is used for hard and difficult to machine metals. Other materials are usually machined through conventional processes because of the long running time that characterizes EDM. The spark process doesn’t make use of mechanical energy to remove material. Consequently EDM is known as a non-conventional procedure, being an electro-thermal process. Material is removed through the conversion of electric energy into thermal energy. EDM of metals on an industrial scale has been applied since a long time. However, this is not the case for other conductive nonmetals. Theoretically each material is machineable by EDM on the condition of not exceeding a certain resistance. For conductive technical ceramic composites, this value has to be lower than 100 $\Omega cm$ [1][2].

Carbon fiber reinforced polymer (CFRP) is a strong lightweight material that is extensively used in aviation, aeronautics, vehicle and sport industries. This kind of material is increasing in popularity because of its beneficial characteristics. It possesses a high strength (high E-modulus), low density and has a good thermal and corrosive resistance. The conventional machining of this kind of material is comparable to the machining of metals, although there are a number of disadvantages [3]. Delamination, fiber cracks and the formation of burrs appear frequently. The lifespan of tools to machine CFRP is drastically lower because of the presence of abrasive carbon fibers. As a result, EDM can be a solution for all of these problems.

CFRP is a widely spread terminology that determines a wide span of varieties. The fibers can have a divers distribution on the workpiece surface, resulting in various EDM properties. Accordingly, the outputs (MRR, Ra ...) have variable results depending on the typology of the CFRP. Previous research is carried out, revealing various material removal rates (MRR), see Table 1. The electrodes that are used represent different diameters. Consequently, to be able to compare the different results the material removal speed (MRS) is calculated by dividing the MRR by the frontal electrode surface. The results show a wide variation.

<table>
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Table 1: Comparison of MRS between different papers [4][5][6][7]

The study of previous research provides several insights. A copper electrode shows better results than a graphite electrode. The electrode wear ratio (EWR) is lower and the surface quality is higher. Furthermore a positive electrode results in a minimal EWR and surface craters are lower in depth. To guarantee an acceptable surface quality, high pulse current and high pulse time have to be avoided. High energetic values can cause damage mechanisms such as: fiber swelling, delamination, louse recast layers and more craters at the surface. Further investigation reveals that the machined surface is an alloy consisting of CFRP and electrode material. The chips are spherical shaped and originated from the gas phase. In contrast, recast layers are formed in the liquid phase derived from molten material. Because of limited previous research
available and the old age corresponding, the accuracy can be questioned.

This paper investigates the feasibility of EDM applied on CFRP thoroughly. The objectives is to carry out a study on the influence of various process parameters on a material science level, while taking into account technical outputs from the process (e.g. MRR, Ra ...). The generation of these data can reveal more information about material removal mechanisms. Since previous studies hardly show explanations for their results. All experiments that are carried out can be applied to determine an optimal technology for machining CFRP.

II. EXPERIMENTAL SETUP

A. Material

The prepregs (pre-impregnated fibers) used for the CFRP are originated from Cytec, the international market leader in such systems. First the prepregs get processed as laminate by SABCA NV. Secondly, the laminate is hardened, making use of a vacuum and putting it under pressure in an autoclave. The hardening occurs at 180°C, an overpressure of ±7 bar, 6 bar in the autoclave and -0.7 bar vacuum. The middle structure of the laminate exist of unidirectional layers (UD-layers), obtaining conditions of optimal strength in one direction. The top structure of the CFRP contains woven layers, forming a stronger body with more strength in both directions of the surface. Moreover, the impact resistance is higher. With this paper the feasibility of EDM applied to the woven structure of CFRP is investigated.

Electrical resistance measurements define that the UD structure contains a higher resistance in comparison to the woven structure. To avoid influence from the higher resistance during EDM, the workpiece is clamped with a conductive upper clamp. Consequently, the closed electrical circuit only affects the woven structure. The resistance measurements according to the Van Der Pauw method define an average specific resistance $\rho$ of 0.01 $\Omega$cm. This result is in the order of $10^{-4}$ beneath the required 100 $\Omega$cm [1] [2], being the upper boundary for conductive technical ceramics. As a consequence, the boundary for ceramics can also be applied to CFRP.

B. Parameters

For the experiments, a Roboform 350γ EDM machine of AgieCharmilles and a copper electrode with a diameter of 10 mm are used. The 10 mm diameter is needed to obtain a machining surface that is big enough for executing a material based analysis. To machine several prepreg layers at one sample, the machining depth is set to 1 mm. To ameliorate the flushing, the electrode rotates at 10 rpm. The speed of revolution is relatively low to not influence the spark arc of max. 200 $\mu$s. Total DIEL MS7000 is used as dielectric, this EDM liquid has a flash point of 102°C and a viscosity of 3.4 mm²/s at a temperature of 20°C. For metals this dielectric can achieve a high surface finish.

The EDM machine contains some additional functionalities that help the research. ‘Pilot expert II’ is used to automatically optimize parameters such as pulse-off time and duty factor. The range of pulse current varies from 1 to 65 A and pulse time varies from 0.8 to 200 $\mu$s. This range is chosen to determine results with the widest possible variation and to compare different samples. The level values for pulse current are: 1, 4, 7, 13, 33 and 65 A; for pulse time there are five value levels: 6,4; 12,8; 50; 100 and 200 $\mu$s. These values define an experimental setup of 30 experiments. To limit the number of experiments, the voltage and polarization are kept constant. The voltage has a value of -80 V (electrode negative), experiments prove that with this voltage, the MRR is the highest.

This choice of polarization is opposite to the one that is generally used for EDM of metals [8]. In general, the electrode is positive to guarantee a low surface roughness. The ions flow from the positive to the negative pole, the electrons flow in the opposite direction. A conductive plasma channel arises inside the spark gap. The electrons are lighter and faster than the ions. Consequently, the ion bombardment on the cathode is more intense and heavy than when applied on the anode. The anode material heats up less, resulting in less electrode wear.

However, for machining CFRP, the opposite polarity is used. Combined with high pulse current and low pulse time, this results in removing the material by thermal shock [9]. Where metals appear to evaporate by adding heat, this is not the case with hard and brittle materials. The thermal shock can be represented by a locally enormously high heating of the material. This minuscule heating is realized by the fast moving electrons in the anode material. As a consequence the heated particle swells very shortly and after shrinking off again, the particle is removed from the workpiece. This result is a consequence of the brittle characteristics of carbon fibers.

III. RESULTS AND DISCUSSION

The experiments result in physical outputs. These are MRR, surface roughness and edge quality. All of these outputs, are displayed graphically and the results are explained. Finally, these explanations will be confirmed. For conducting a full research, subsequent material based analysis is carried out. The results of this analysis are not represented in detail to restrict the dimension of this paper. The main insights are mentioned to support the explanations of the material removal mechanisms.

- Microscopic evaluation of cross sections
- SEM evaluation of cross sections
- Analysis of machined surfaces with SEM and macro lens
- EDX analysis on cross sections and machined surfaces
- Chip analysis

Extra experiments are carried out to determine an optimal spark technology. A statistical analysis explains the significance of factors in relation to an output (MRR, Ra and edge quality). The study is completed with an examination of
the influence of electrode polarity and electrode wear, the influence of a graphite electrode, and an analysis of pulse current and voltage with pulse monitoring.

A. Physical outputs

1) MRR

The MRR of each experiment is calculated as the machined volume divided by the machining time (mm³/min). The results are shown in Figure, revealing that the MRR increases with an increasing pulse current, which is also observed in previous research. The experiments at 65 A at 50, 100 and 200 µs are aborted early for safety reasons. Also the experiments at 1 and 4 A at 200 µs are not executed because the parameter combinations do not exist in the machine. The influence of pulse time to MRR can be observed in the figure. In general, there is a zone that determines a maximum MRR. Before and after this zone the MRR decreases. This is explained as follows: a pulse time that is too low results in a shorter energy affection time, consequently less material is heating up (at the same time the energy is too low for a shock effect). As a result, less material melts or evaporates and evoking a low MRR. A too high pulse time causes an energy quantity that affects the material for a longer period, resulting in oversized material particles which melt. The mass of these particles is too big to flush away immediately. The material stays between the gap and, disturbing the further process and causing a decrease of MRR. This explanation cannot be applied for each curve in the graph. The MRR of 13 A is opposite when comparing to the other curves. There occurs a pulse time that results in a minimal MRR. Before and after this minimum the MRR rises again. If a short pulse time is applied, the material is removed by thermal shock. Momentary pulses result in the swelling of material particles, cutting them loose from the workpiece. When increasing the pulse time, the material is heated over a bigger zone. The material swells more homogeneous, preventing the particles to break loose easily and causing the minimal MRR. When the pulse time is further increased, the added energy quantity rises. Because energetic quantities can affect the material for a longer time, bit by bit the heat added to the material increases. As a consequence the material melts and evaporates, making the quantities of the removed material rise correspondence to the increasing pulse time. The MRR will increase until the removed mass of material is again too high and hinders the process. These phenomena cannot be observed anymore on the curve of 13 A. The highest MRR is noted at 65 A - 6,4 µs.

2) Surface roughness

The surface roughness is measured with a profilometer. Three measurements of 5 mm per sample are carried out. The measurements are converted to Ra roughness values. Every measurement is executed at another position on the machined surface, for generating a more realistic result. The influence of pulse current and pulse time can be seen on Figure.

![Figure 2: Ra vs. pulse time for different pulse currents at -80 V](image)

In general, the surface becomes rougher when increasing the pulse time, since the pulse current affects the workpiece for a longer period. This makes material particles cut loose which are too heavy to be immediately flushed away. Finally, after some time the particles leave the surface because of the swirling dielectric, this causing big craters which remain behind in the machined surface. High currents can be combined with low surface roughness. For currents starting from 7 A an optimal surface roughness is achieved. These values are alternated with higher roughness values for pulse times which are situated left and right of the optimum. When applying lower pulse times, the thermal shock effect appears. This causes small particles that cut loose from the brittle carbon fibers, resulting in a rough machined surface. If high pulse times are applied, craters occur as mentioned before. When a pulse time is set in between these previous two material removal mechanisms, a good surface roughness is observed. The pulse time is at the same time too high for a thermal shock and low enough to not melt heavy particles, making material flushing away immediately. The remaining molten material solidifies through flushing on the workpiece surface, resulting in a lower surface roughness. Each optimal roughness value matches with a maximum MRR for the same pulse current, since the ideal material removal mechanism is active. The smallest possible surface roughness (Ra = 8 µm) appears at 65 A - 12,8 µs. To conclude, there exists parameter combinations which combine high MRR with good surface roughness.

![Figure 1: MRR vs. pulse time for different pulse currents at -80 V](image)
3) Edge Quality

Samples with a high MRR and a low Ra value don’t always appear to have a good edge quality (edge of the machined surface). Therefore a third output is needed to quantify these phenomena. The damage factor S represents the damage factor in function of pulse time and pulse current. If the quotient $d/D$ is closer to one, the edge quality is better. A higher pulse current results in a worse edge quality, and since energetic intensity increases, this results in a bigger heat affected zone. Affecting more surrounding fibers. Higher pulse time results also in a worse edge quality (if the optimal removal mechanism is not active), because of craters that remain in the workpiece surface by using a too high pulse time. The pulse currents starting from 4 A reveal again an optimum. This optimum is mostly lying on a point where the MRR is high and the Ra value is low. This implies that a stable material removal mechanism is working.

![Damage factor S vs. pulse time for different pulse currents at -80 V](image)

To prove that there is a connection between high MRR, low Ra value and good edge quality, Table 2 is created. For each output the optimal pulse current and pulse time is noted. These are mostly pulse times that are equal or nearby each other for a specific pulse current, since the optimal material removal mechanism is active at these parameter values.

![Microscopic cross section of a sample at 65A-12.8µs; recast layer indicated red](image)

The second mechanism to discuss is the thermal shock effect. This effect has been explained earlier (see Experimental setup). The effect can be represented by a local, enormously high heating of the material. The minuscule heating is realized by fast electrons at the anode material. The heated particle swells very shortly. When it shrinks again, it will be removed from the material structure. This is possible because of the brittle characteristics of carbon fibers. The carbon fibers cut loose by applying a short pulse time in combination with a high pulse current. These phenomena are observed at the SEM analysis of the machined surface, see Figure 3. This is a SEM figure of the machined surface of a sample at 13 A – 1,6 µs. It shows that some of the broken carbon fibers are still present at the surface after machining. The sharpened edge contour of the fibers reveal that the fibers are broken brittle, indicating that the shock effect is active.

### Table 2: Comparison between optimal outputs noted by pulse time and pulse current

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### B. Material removal mechanisms

Four mechanisms are noticed and confirmed several times by the material based investigation. In general at each parameter setting there is one of such a mechanism active, (“in general” because the other mechanisms will be active as well, but at a lower scale). The optimal material removal mechanism is one of these four mechanisms that appear. This implies that there is only just enough energy active to melt loose material (optimal pulse current – pulse time combination). The melting zone is not too big resulting in material particles with a sufficient small mass that flush away immediately. A recast layer remains on the workpiece surface. Because of the molten carbon fibers, it is a harder layer than the surrounding workpiece material. In this molten zone the matrix material is already evaporated, because of its lower sublimation point. The recast layer is indicated red on Figure 2, this layer is noted at the sample of 65 A – 12.8 µs. At this sample, an optimal material removal mechanism is active. The recast layer has a low surface roughness since the molten fibers are solidified through flushing of the dielectric. This flushing results in a smooth surface with an Ra value of approx. 9 µm.
There remain two material removing mechanisms that result in a slow or instable EDM process. For the first mechanism, the added energy is too low to remove material in an efficient way. The heat affected zone is small (≈ 0,15 mm) and the carbon fibers do not melt. This is shown in Figure 6, which is a SEM figure of the cross section of a sample at 1 A - 12,8 µs. The energy is only just high enough to melt the matrix material between the carbon fibers making material cracks appear between fibers bundles. These cracks arise because of the swirling dielectric. In a next stage the fibers are removed through flushing. The chips from this mechanism are shown in Figure 7, resulting from a sample at 13 A -0.8 µs. The chips are small, implying a low MRR and the fibers are individually visible (white color), being not molten.

The second inefficient mechanism is a kind where the pulse time is too high. The applied energy is active on a zone of material which is too big, causing melt of carbon fibers. The matrix material evaporates at surface layers, while the material stays present at other layers and provides a thermal isolating effect, causing not melted fibers surrounded by a molten zone of fibers. These phenomena are observed in Figure 8, representing a microscopic view of a chip originated from a sample at 13 A – 100 µs. The chip is big, which indicates that big particles are removed. At the inside of the chip there is not melted material, which is surrounded by melted carbon fibers. Because of the big mass of the chip, it does not flush away immediately, which may cause loose layers between the electrode and the workpiece disturbing the spark process.

The various material removal mechanisms show that the matrix material evaporates before the carbon fibers melt. This is show in Figure 9. The black arrow indicates the direction of machining. The black parting line indicates the transition between the machined surface and the embedded material. The heat affected zone extends until the red line. The figure makes clear that matrix material evaporates to a greater depth which is due to a lower sublimation point of polymer in comparison to the one of carbon. The evaporation of the matrix material is demonstrated by the more dark shade of the heat affected zone in microscopic figures. The polymer evaporates between the fibers, resulting in tiny cavities filled by dielectric. When flushing the sample with a degreasing fluid, it is largely adopted in the place of the dielectric fluid. Afterwards, the degreaser evaporates due to its volatile character. As a result, these cavities are be filled up by ambient air, causing an optically darker view (only for microscopic figures).
C. Statistical analysis

The effects of pulse current and pulse time on MRR, surface roughness and edge quality are verified by analyzing the DOE. The DOE contains two factors, current and pulse duration. The current contains six levels and the pulse duration five. The results are plotted, these figures make optically clear that the current exerts the greatest influence on MRR and S (Only the influence on MRR is represented in Figure 10). A higher current produces a much deeper heat affected zone. As a result, the quality of the edge is worse because it is more deeply affected. For example, a higher current ensures a higher MRR because of the addition of more energy intensity, which ensures a larger melt volume. Pulse duration determines which material removal mechanism occurs at a given current (shock effect, melting or melting of a too heavy mass). However, the scope of action of such a mechanism is determined by the current. As a result, the influence of pulse time on MRR and S is optically less visible than pulse current. The influence on Ra of the pulse duration is of the same order of magnitude as the pulse current. This result is expected from the material removal mechanisms. A higher pulse time allows a larger melt volume (while a higher current causes several small melt volumes). This melt volume is too heavy to be flushed away immediately, however these volumes are flushed away after some time. After completion of the operation some craters remain in the workpiece surface since large volumes have been removed all at once. The result is a poorer surface quality.

The above optical observations are confirmed by the analysis of statistical significance. For example, the P-value (Probability value) determines whether a factor is statistically significant or not. When the effect on MRR and S is analyzed, only the pulse current is significant. In contrast, when analyzing the effect on Ra, both the pulse current and the pulse time appear to be significant.

\[
\bar{x} = \frac{\sum_{i=1}^{6} x_i}{6} = 16.50 \text{ min}
\]
\[
S^2 = \frac{\sum_{i=1}^{6} (x_i - \bar{x})^2}{4 - 1} = 0.59
\]
\[
\sigma = \sqrt{S^2} = 0.35
\]

D. EDX analysis

To obtain a more extensive study, EDX analyzes are carried out. These analyzes determine which atoms are present on a selected spot, in the workpiece.

An analysis of a sample at 7 A - 12.8 µs is shown in Figure 11. The selected spot shows fibers that are completely melted into each other. This is seen by the rounded contour of the considered zone. The analysis shows the same peaks as when a spot in the non-melted zone of the same sample (not shown) is analyzed. In addition, the copper peak has increased. The mass percent Cu rises from 3.62 to 15.9%. The result is logical, since there are more electrons that are active in a melting zone, hence more copper atoms are left.

Furthermore small peaks bromine and sulfur are observed in both analyzes. The presence error for these elements is less than or equal to 20%. This explains that these elements do occur in the machined surface. In order to determine whether these elements are originally present in the CFRP, an analysis on a raw zone is carried out at the CFRP surface (not shown). Here, only three peaks are visible, one of carbon (by far the largest), oxygen, and sulfur. Sulfur can be added to ensure the curing of prepregs [10]. However, this is only a forecast, additional information from the manufacturer is to be obtained to provide more certainty about this. Furthermore, oxygen probably occurs by oxidation of the prepregs with the environment. This is also a forecast and should be confirmed by the manufacturer, since the datasheet from the CFRP doesn’t display any Lewis formulas of the chemical composition. The source of bromine is researched as well. This element is added to the material during the EDM process. It is possible that the residual dielectric leaves tracks in the CFRP. As with the matrix material, the chemical composition of the dielectric does not appear in the datasheet. Further research shows that bromine is an outstanding flame retardant.
It can be used to increase the flash point of kerosene to 102°C to yield a useful and safe dielectric. This observation explains the origin of bromine in the EDX analysis.

The various EDX analyzes confirm the literature, stating that copper particles originating from the electrode are observed in the machined surface, since these are taken along with the electrons that make possible the material removal at the anode. The larger the preset energy amount, the more copper particles in the surface are observed. Furthermore, the influence of dielectric is observed in the machined surface.

E. Optimal technology

In addition to the determination of the different material removal mechanisms, extra experiments are carried out in order to determine an optimal spark technology for the CFRP. The technology that determines a maximum MRR (= 6.55 mm³/min) with acceptable roughness (Ra = 9 µm) and edge quality (S = 0.908) has a pulse current of 65 A, and pulse time of 12.8 µs. On the other hand, a pulse current of 13 A and pulse time of 3.2 µs determines optimal roughness (Ra = 8 µm) and good edge quality (S = 0.921) with acceptable MRR (= 2.98 mm³/min). These parameter settings are applied each time at a voltage of -80 V.

F. Effect of polarization

All 30 main experiments are repeated with a positive electrode. A lower MRR, a lower roughness and an approximately uniform edge quality are observed in respect of a negative polarization. The influence on MRR is shown (Figure 12).

G. Effect of electrode material

The influence of a graphite electrode is investigated. The parameter settings and results for MRR, Ra and S are shown in Table 3. This table presents ass well the results of similar experiments with a copper electrode (white cells). Four experiments are carried out with a graphite electrode. The results for pulse current and pulse time are shown. All the results of the graphite electrode are similar or to the use of a copper electrode. Thus, not only the lower MRR, also the surface roughness and damage factor are of inferior quality. This result is in contrast to [6], in which a single graphite electrode leads to a higher electrode wear and a lower surface roughness (for machining CFRP). The effect of lower MRR is opposite to what is observed when machining steel with graphite [12] where the electrode is also negatively polarized. The inferior results are probably to be explained by the processing of carbon by carbon. Both the CFRP and graphite have a high percentage of carbon. Further research is needed to explain the exact cause of the occurring results.

<table>
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<th>Set parameters at -80 V</th>
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Table 3: Effect of electrode material

H. Puls monitoring

The pulse current is measured with a current clamp. The current meter has a conversion where 100 mV corresponds to 1 A. The result of a measurement (33 A - 12.8 µs) is shown in Figure 13. The pulse current for each measurement corresponds well to the set value. The upper flank of the block pulses indicates a noise value. This noise value is more pronounced at higher pulse duration since the plasma channel is exposed over a longer duration to ambient influences. If the block shapes are compared with literature, strong similarities are shown [13]. The round off at the beginning of a block is also observed. The rounding occurs because the plasma channel is gradually formed. The pulse time corresponds exactly to the set value. This means that the parameters are accurately implemented by the machine. The set parameter
values provide a reliable representation of the actually occurring values.

![Figure 5: Pulse monitoring of pulse current at 33A-12.8µs](image)

Furthermore, an attempt is made to measure voltage pulses by connecting the test probes of the oscilloscope with the electrode and machine bed. When connecting the voltage measurement the signal block of the pulse current has changed in a different form. The spark process is unstable and there is hardly removed any material. Due to the large input impedance of the oscilloscope the servo-system of the machine is deceived. Consequently, the spark gap takes on a wrong value making that the machining process is not going well. The measured voltage is no longer corresponding to the original process during a normal operation. As a result, the method used is not appropriate for the voltage measurement. Further research to find a proper method is needed.

IV. CONCLUSION

The few literature that is available of EDM applied on CFRP shows that a good spark process occurs when custom parameter combinations are used. Only four papers containing relevant results from different types of carbon composites are found. The literature is to initiate the research. The information of this paper is often not confirmed by analysis or explained, consequently the reliability of the results have to be questioned.

This paper aims to investigate the active material based phenomena that occur when EDM is applied on industrial used CFRP. This analysis is used to support the obtained results. Additional experiments are carried out in order to develop an optimum spark technology for the corresponding CFRP. In addition, different influences of various parameters are analyzed. Below follows the summary of the realization of these objectives.

The machine provides additional functionalities that can assist the investigation. Pilot expert II turned out to be helpful to automatically control the parameters such as pulse off time, referential voltage (RF) and duty factor (SV). Resistance measurements determine that CFRP has a resistance of 0.01 Ωcm. This is order $10^{-2}$ below the 100 Ωcm that is need. The value is determined as the upper boundary for conducting technical ceramics in [1] [2]. Preliminary experimental tests determine that the industrial CFRP can be machined by EDM. Furthermore, a preliminary examination determines which material based analysis is applicable to support the explanation of results. 12 samples with very different pulse current and pulse time are used for this analysis in order to assess their impact. Subsequently, EDX analyzes of the cross-sections, and machined surfaces are carried out in order to determine the composition of the processed material. Finally a chip analysis provides more information about the removed material from the workpiece.

In the experimental research stage, 30 experiments are used with different pulse current and pulse time (negative electrode) to determine three output quantities. These are the material removal rate (MRR), the surface roughness (Ra) and the edge quality (S). It is observed that a higher pulse current and/or pulse time result in a higher MRR and poorer edge quality. The pulse current appears to create the greatest influence (pulse current is significant). A higher pulse current combined with higher pulse time provides a higher surface roughness. This pulse current almost carries out as much influence as the pulse time (pulse current and pulse time are significant). A statistical analysis determines the significance of pulse current and pulse time. Furthermore, the use of only one replica in this statistical analysis appears to be justified.

The quantitative results (MRR, Ra and S) are explained from a materials based point of view. These explanations are confirmed in the materials research. Four occurring material removal mechanisms are observed, the optimal material removal mechanism is one of them. This mechanism means that sufficient energy appears to melt loose material in an efficient way (the optimum combination pulse current - pulse time). As a second mechanism, there is the shock effect, letting carbon fibers break down by the short pulse time and high pulse current. The two remaining mechanisms ensure a slow or unstable spark process. A first type contains supplied energy which is too low to efficiently remove material. The second type uses a too high pulse duration, allowing the melting of too big fiber bundles with a too big mass. As a result, the bundles are not immediately removed and they remain in the spark gap, hindering the further process. All these mechanisms occur in various analyzes, confirming their existence.

Furthermore, an optimal spark technology is found for max. MRR (65 A - 12.8 µs) and min. Ra (13 A - 3.2 µs), by executing additional experiments. The highest MRR found, is 11.2 mm³/min which corresponds to a MAS of 0.14 mm/min. In comparison to the literature (four papers) this is the third highest occurring value. EDX analyzes of the machined surface confirm the literature. Copper particles coming from
the electrons occur in the workpiece surface, the amount of them increases with higher energy intensity. The EDX analysis also confirms the presence of dielectric in the machined surface. It should be further examined whether the effect of the presence of copper and dielectric particles provide other material properties. All the main experiments are repeated with a positive electrode. This results in a lower MRR, lower Ra-value and equivalent S-value. Electrode wear is not sufficiently studied, this is for future research. The use of a graphite electrode provides inferior output results. The explanation for this should is to be investigated in future studies. Finally, pulse monitoring confirms an accurate implementation of the pulse current set by the machine. A proper method for measuring the pulse voltage needs further research as well.

REFERENCES


