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# Observation of EDM plasma behavior influenced by parasitic working gap capacitance

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**Abstract**

Machining large surfaces to good surface qualities is currently difficult, as optimisation of parameters does not always lead to a satisfactory outcome. This appears to be an issue with traditional EDM, and the cause is not understood very well. Observing this effect by looking at current and voltage is very difficult because of the parasitic capacitance. As the capacitance is a function of surface area and gap width, small gaps, as they occur when using small energies, result in a large capacitance. The charge of the capacitance can have the same order of magnitude as the discharge itself. This makes it hard to understand what actually happens in the gap while measuring current and voltage on the outside. In order to understand this phenomenon large, optically transparent SiC electrodes were used to observe the gap with a high speed camera. By doing so it is possible to locate consecutive discharges and to determine if the capacitance has a large effect on the behaviour of the plasma. The goal of this work is to identify the effect that is responsible for the difficulties with the machining of large high-quality surfaces in order to work out possibilities to enable those machining operations.



*Keywords:* EDM, parasitic capacitance, high-speed camera, direct observation

## 1. Introduction

In electrical discharge machining (EDM) a voltage is applied between a workpiece and a tool electrode. Usually the latter approaches the former until the electric field in the gap between them overcomes the breakdown strength of the dielectric. A plasma channel is formed and the electric energy is transformed to heat. This heat melts and evaporates both, the work piece and tool electrode and is responsible for the material removal. However, the heat also causes the dielectric liquid to evaporate and therefore causes a significant change of the properties of the gap [1]. Due to its sensitivity the EDM process reacts strongly to those changes. One example is the large surface quality enhancement as a result of an electrically conductive powder in the dielectric fluid [2]. Another input parameter that strongly affects the EDM process is the surface area. This is because before the discharge occurs the electrodes can be considered as two electrically conductive materials in close proximity separated by an insulator – i.e. a capacitor. Its capacity C can be calculated as

$$C = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{A}{d}, \quad (1)$$

where $\varepsilon_0$ and $\varepsilon_r$ are the permittivity of free space and the relative permittivity respectively [3]. The former is a constant and the latter only depends on the properties of the separating medium. Since the dielectric liquid is subject to changes throughout the process the capacity is mainly be defined by the area A of the electrodes and the distance d between them.


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These two characterizing influences occur in combination when large surface areas need to be machined to good surface qualities, since small discharge energies, which are needed to produce small craters, result in a small working gap and hence increase the capacity. This kind of parasitic capacity can in turn store large amounts of energy, which is subsequently released during the discharge. This leads to the problem that all efforts to increase surface quality are hindered and no decrease in supplied discharge energy will be sufficient to reduce the size of the craters. This effect was described by Mohri et al. [4], who measured discrepancy of the current that is supplied from the generator and the current that actually flows through the discharge channel. The difficulty of this measurement is that it is not possible to measure the current directly. For the purpose of this measurement, they constructed a tool electrode, with two different sized surfaces that machine the workpiece. Since one surface was significantly larger than the other, a current could be measured between them in the case of a discharge at the smaller surface. According to the authors this current could reach up to 75 A, even though the designated generator current was only 2 A [4].

In the present paper two different approaches to measure the energy that is stored in the parasitic capacitor will be presented. While one approach solely aims to define the energy stored, the other focuses on the way the energy is transferred in the gap.

## 2. Initial Investigation

The experiments were conducted on two different machine tools to make sure the described effect is not limited to one of the used machines:

- GFMS Form 2000 VHP,
- OPS Gantry Eagle 800.

Both machines work with the dielectric fluid Ionoplus IME-MH by oelheld. The electrode consisted of the graphite R8510 by SGL Carbon and the workpiece was the cold work steel 1.2767. The electrodes had a size of:

- 100 x 50 mm² (small),
- 140 x 70 mm² (medium),
- 200 x 100 mm² (large).

These dimensions were chosen to maintain a constant ratio of 2:1 while roughly doubling and quadrupling the surface area. In order to achieve a uniform gap width, the whole machining procedure was conducted as suggested by the machine tool manufacturers. The plunging depth and discharge energy of each machining step thus suited the surface roughness that needed to be removed. Therefore, it can be assured that the whole surface becomes effective and machining does not only cut down the roughness peaks which would cause a large average gap width. Machining was set to aim for a surface roughness of Ra = 0.6 µm. As illustrated in Fig. 1, the small and medium sized cavities have a lower roughness than the large. The large cavity, even after 19 hours of machining, did not near the required surface finish. As the electrode in the present paper has a working surface area of 200 cm², this indicates that the findings of Mohri et al. [4] are applicable for working surface areas smaller than their surface with an area of 630 cm².

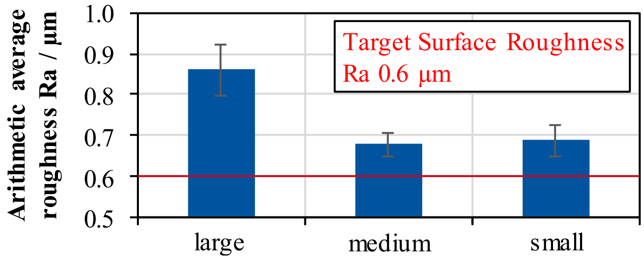


Fig. 1. Arithmetic average roughness Ra of the workpiece after finishing-machining with different electrode sizes.

Another two reasons prevent economic machining of large surface areas to good surface qualities. One is the time finishing steps need until they are successfully conducted. Since an increased machining duration results in an increasing number of discharges, the wear adds up and thus the wear is significantly higher.

In order to verify the cause of the previously mentioned phenomena, the discharges were examined with an Tektronix DPO7104C oscilloscope. Fig. 2 shows a discharge from semi-finish machining. It displays the current and voltage waveforms that characterize the discharge. Even though the energy was already quite low, all the discharges had a similarly smooth and uniform structure.

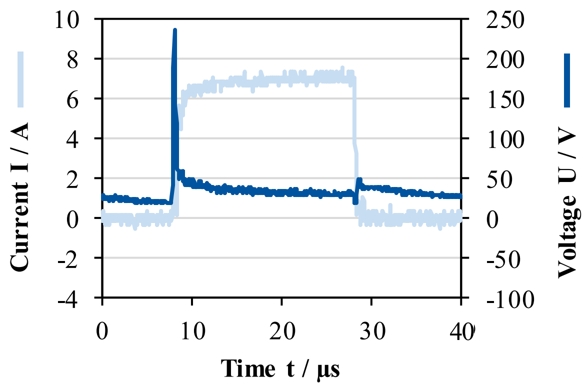


Fig. 2. Current and voltage waveform of an unspoiled discharge with semi-finishing parameters ($i_e$ = 7 A, $t_e$ = 20 µs).

Significantly different current and voltage waveforms are observed when the discharge current $i_e$ is set to 2 A and the discharge duration $t_e$ to 5 µs. The example depicted in Fig. 3 is only one among many that look alike and does not display an exception. After 1.5 µs, the voltage drops and the current rises which gives the indication of a normal discharge. However, after approximately 1 µs the voltage rises even though the current has not dropped. After a short rise in voltage, which is similar to the rise of open circuit voltage, it collapses into the negative and seems to be oscillating around the discharge voltage $u_e$ of approximately 30 V. The current behaves in a very similar manner and oscillates between -1.5 A and 5.5 A. Also after the oscillation stops and the discharge appears to become stable, the current drops and the voltage rises, which indicates another early end of the discharge. When the open circuit voltage reaches its maximum, the current rises for a last time followed by a slow oscillation around the zero level. This can be called the parasitic capacitor effect.

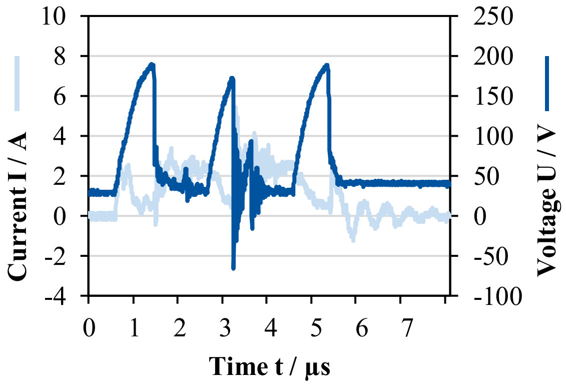


Fig. 3. Current and voltage waveform of a discharge, which is affected by the parasitic capacitor effect ($i_e$ = 2 A, $t_e$ = 5 µs).

The shown instabilities lead to another increase in the number of discharges and a decrease in the discharge duration. These two effects both lead to an attenuation of productivity since, according to Klocke et al. [5], a decreasing discharge duration leads to an increase in tool wear and according to Maradia [6] a decreasing discharge duration results in a smaller material removal rate.

*2.1. Determination of Capacity*

The capacity of the parasitic capacitor from the present paper can be calculated according to equation 1. With $\varepsilon_0 = 8.854 \cdot 10^{-12}$ A·s·V$^{-1}$·m$^{-1}$ and $\varepsilon_r \approx 2.3$ [7], A = 0.02 mm² and the minimum gap width d = 30 µm [6], the theoretical capacity equals C = 13.6 nF. This equals the medium capacity used by Yang et al. [8], who were using the capacity coupling method to enhance the surface of a large machining area. However, the calculated capacity is a lot larger than that estimated by Mohri et al. [4], who were using a surface area thrice as large but estimated the capacity to be C = 0.01 µF. Since the current used by them was 2 A as well and the discharge duration was set to be even shorter at 2 µs, the gap width should be less or equal to the one in the present paper. It can be inferred that the open circuit coltage of 300 V makes the difference as it only reached 200 V in the present research.

To verify the calculated capacity the waveforms shown in Fig. 4 were examined. The voltage waveform indicates with its rise the beginning of the ignition delay time. At this time, the current waveform shows a steep rise followed by a gradual decrease. Since both, current and voltage are rising at the same time this characteristic cannot be caused by a discharge. Hence, the detected current must be responsible for charging the capacitor. In order to compare the current that is used to charge the parasitic capacitor with its capacity the relation between the capacity C and the charge Q, as well as the relation between the charge and the current I are needed. They are described by equations 2 and 3, which employ the voltage U and the time t.

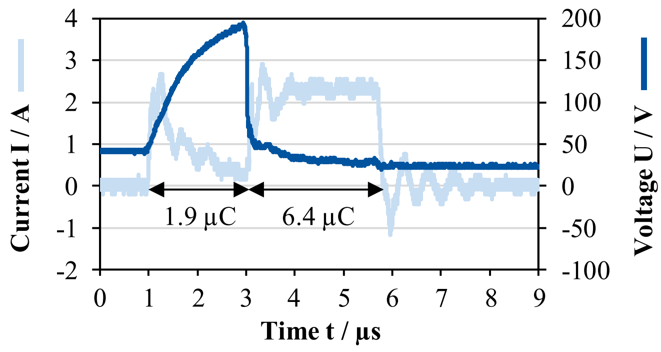


Fig. 4. Current and voltage waveform used to calculate the capacity of the parasitic capacitor ($i_e$ = 2 A, $t_e$ = 5 µs).

For the given current waveform the charge of the parasitic capacity calculates to $Q_c$ = 1.9 µC. In comparison with the charge that is detected during the discharge $Q_d$ = 6.4 µC almost a third is transferred additionally during the discharge. Thus it can be stated that the finishing machining discharges are strongly affected by the capacitor.

$$Q = C \cdot U \tag{2}$$

$$Q = \int I \, dt \tag{3}$$

In order to validate the previously calculated capacity, the measured $Q_c$ is divided by the open circuit voltage $u_i$. The resulting capacity C = 9.5 nF suits the theoretical value well, even though it is closer to the capacity estimated by Mohri et al. [4].

To compare the impact of the additional charge carriers that are loaded on the surface of the electrodes several discharges were assessed regarding the ratio of charge that already exists in the capacitor to that which is additionally supplied by the power supply. The result for fine machining is summarised in Fig. 5. In comparison to Fig. 1 it becomes apparent that despite the additional charge ratio of 20 %, the surface roughness does not seem to be affected. Only the large electrode with a ratio of over 30 % cannot reach the aimed surface roughness.

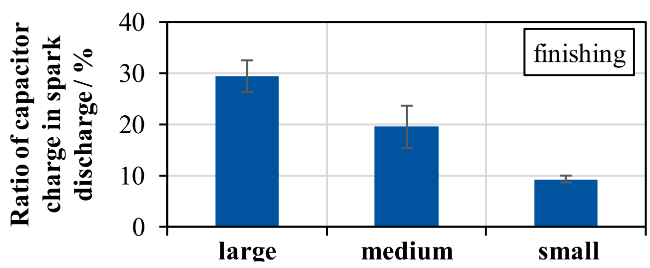


Fig. 5. Ratio of charge that was transferred to the capacitor before the discharge to the charge that was transferred during the discharge.

Due to the location of measurement, it is not possible to detect the current that flows between the electrodes during the discharge. Therefore, this method allows an indirect measurement of the capacity of the parasitic capacitor that can detect the critical state.

### *2.2. Intermediate Discussion*

The reason for the frequent interruption of the discharge after already been ignited was not yet found in this study. According to Hayakawa et al. [9] the deionization of the plasma channel takes a few microseconds. This would allow the formation of a consecutive discharge in the same place right in the moment the energy is supplied from the generator. Still, as depicted in Fig. 3, the open circuit voltage needs to build up all the way to where it went for the initial discharge. Only then, the breakthrough strength can be overcome and another discharge can be formed. In an attempt to explain this phenomenon a hypothesis is formulated in this paper.

Once the discharge is ignited, a relatively low resistance allows all the charge carriers that were on the surfaces of the electrodes to balance the difference of potential. As shown by Mohri et al. [4] this results in a large current that only lasts for 0.1 µs. This large current will shape a large plasma channel as described by Kojima et al. [10] and shown in Fig. 6. After the short peak current, only the small fraction that is supplied by the generator reaches the working gap. These charge carriers do not convey enough energy to keep the whole plasma channel ionized and the recombination process becomes dominant [11]. This way the electrically conductive plasma channel collapses and the charge carriers start to gather on the opposing surfaces.

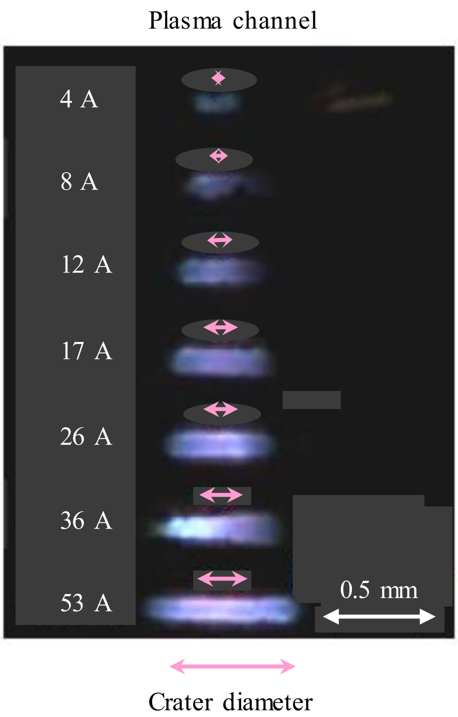


Fig. 6. Images of plasma channels at different currents [10].

Another possible reason why the discharge does not ignite immediately can be explained with Fig. 6 as well. The whole diameter of the plasma channel was ionized and does not have the dielectric effect on the capacitor anymore. Therefore, only a small amount of charge carriers gather in the vicinity of the former plasma channel. This is illustrated by Fig. 7. The lack of charge carriers results in a smaller electric field, which cannot overcome the weakened breakthrough strength in this area.

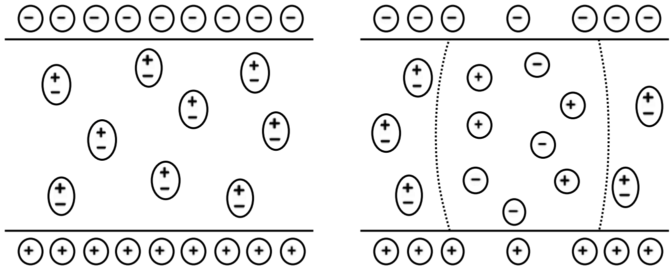

Fig. 7. Capacity enlarging effect of dielectric liquid (l.) and effect of ionized particles on capacitor surface (r.).

With a rising open circuit voltage, two possibilities arise. The weaker electric field may use the opportunity of the weakened breakthrough strength to cause a discharge in the same spot. Alternatively, it becomes possible that a consecutive discharge ignites where more charge carriers have gathered and the electric field is stronger. Whereas according to Kitamura et al. [12] the i+1$^{st}$ discharge is most likely to occur in the close vicinity of the i$^{th}$ discharge.

## 3. Consecutive Investigation

Even with modern gap monitoring and control systems it is not possible to distinguish whether one of the previously mentioned hypotheses is correct. This is because a measurement of current can only be conducted in the periphery of the capacitor and not in the discharge channel. In order to improve understanding of these kind of phenomena, Kunieda et al. [13] proposed to use direct observation techniques to visualize the process. An observation setup very similar to the one introduced by Kitamura et al. [14] was used in the present paper and is depicted in Fig. 8. The key feature of this observation setup is the transparent SiC electrode. Due to its conductivity, it may be used as an electrode and allows perpendicular observation of the machining gap. The graphite electrode was circular and had a diameter of 80 mm. The machine tool was a Sodick C32 and machining was conducted horizontally. An oscilloscope was used to track current and voltage waveforms and to trigger the camera in order to synchronize them. The camera was an i-SPEED 7 series by the company iX-cameras that was provided by the company NAC.

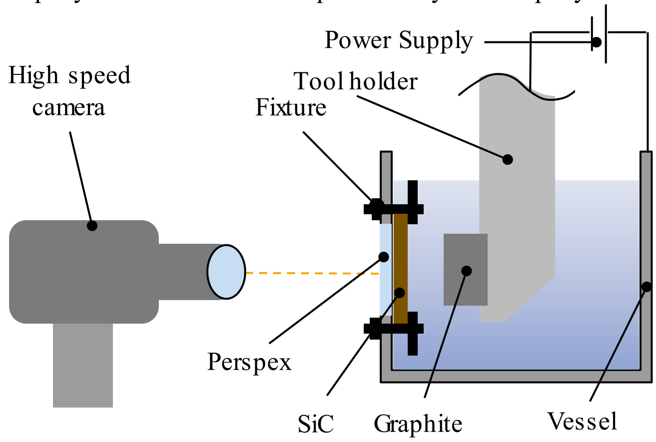


Fig. 8. Experimental setup with transparent electrode.

Because of the large area that had to be observed and the speed of the phenomenon, a compromise regarding temporal and spatial resolution had to be found. The framerate was set to 200,000 fps, which predefines a shutter speed of 4.4 µs and a maximum resolution of 320x320 pixels with a pixel size of 0.25 mm.

For this part of the investigation, it was not necessary to machine the workpiece with all the machining steps. Because of the transparent electrode, it was possible to observe the location of the discharges. Machining was started with a relatively small energy and the position of the workpiece was adjusted until the whole surface was equally machined. After several minutes, the finishing technology was applied.

## 4. Results and Discussion

Upon analyzing the results of the investigation, contradictory observations were made. The frames of the video show two bright spots in close vicinity, as it can be observed in Fig. 9. This would indicate that interrupted discharges do not ignite twice in the same spot. However, the brightness of the two spots appear to be connected. They are either both getting brighter or both getting darker. Only when the brighter spot becomes very dark does the other one disappear. This contradicts the expectation since the two discharges ignite in sequence and should therefore result in two bright spots that successively become bright and dark again, and not in the same time. Another possibility was that the discharge ignites again in the same spot. This would be detectable with an intermediate drop of the brightness of the discharge spot. This cannot be observed, whereas this can be caused by the aperture open time of 4.4 µs.

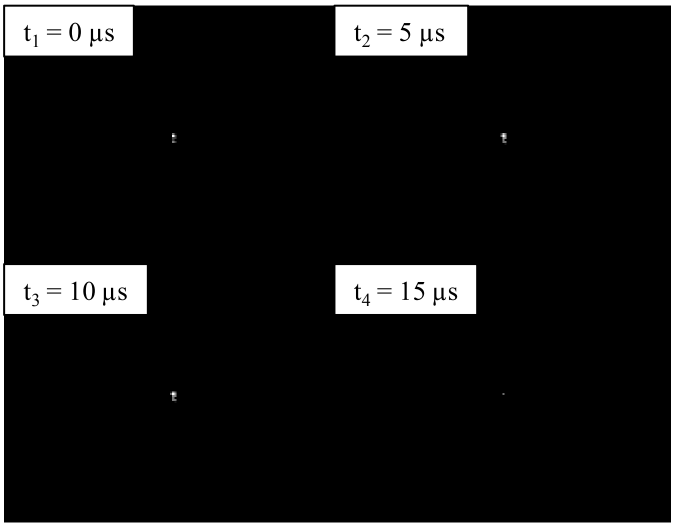


Fig. 9. Frames from one discharge ($i_e = 3$ A, $t_e = 5$ µs), observed through a transparent SiC electrode

The detailed observation of frames as shown in Fig. 9 gives the impression of a reflection that causes these two simultaneous spots. This could result from the perspex front that the SiC was mounted to for stability. However, numerous observations show that the two spots are always shifted vertically, whereas the brighter spot is sometimes located above the darker spot and sometimes it is located underneath. Therefore, it is suspected, that the camera has difficulties handling the high local intensity emitted by the plasma and generates an overflow in another pixel.

The corresponding current and voltage waveform, as shown in Fig. 10, confirms that the discharge was not interrupted and hence only one discharge spot should be visible. However, since the discharge duration was set to 5 µs, it is more than twice as long. This was observed in most discharges and some even stayed lit for more than 50 µs. Since the resisitivity of the SiC is very high, it is considered that the voltage drop was not sufficient for the machine to detect the discharge and therefore kept supplying energy.

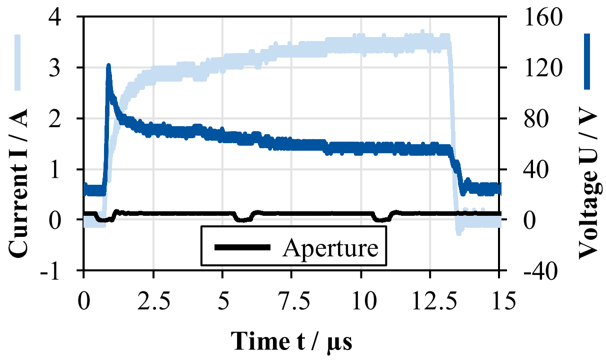


Fig. 10. Current and voltage waveform of unspoiled discharge that was observed through the transparent SiC electrode ($i_e = 3$ A, $t_e = 5$ µs).

The aperture opening time is displayed in Fig. 10 as well. The value 0 indicates the time between the frames and a value other than 0 indicates the opening of the aperture. Using this, it is possible to exactly determine what happened during one of the frames. According to Fig. 10, there are three frames that were taken during the discharge. Correspondingly, Fig. 9 displays these as the first three frames. However, the fourth frame still contains a bright spot. Since this frame starts 2.5 µs after the discharge ends, it must have been capturing the afterglow of the plasma or the glow of the molten pool.

Even though machining was conducted for several hours and the discharge current was reduced, as in the initial investigation, to 2 A, no interrupted discharges like depicted in Fig. 3 could be observed. The reason for this could be due to the size of the electrode, which is only one fourth of the large electrode used in the initial investigation. Nevertheless, since the graph shown in Fig. 3 was taken from a discharge with the small electrode with the same surface area as the circular graphite electrode used for the investigation with the transparent electrode, the interrupted discharge should still be visible. A further reduction of discharge current and duration was performed to decrease the contamination of the gap, which causes a smaller gap width and increases the capacity. This resulted in unstable machining and short-circuiting.

In order to determine whether the parasitic capacitor has a capacity to significantly influence the discharge, the previously introduced method to measure the capacity was applied to the current and voltage waveform displayed in Fig. 11. The measurement of charge accounts to 0.23 µC and therefore the capacity calculates to 1.9 nF. In comparison with the capacity

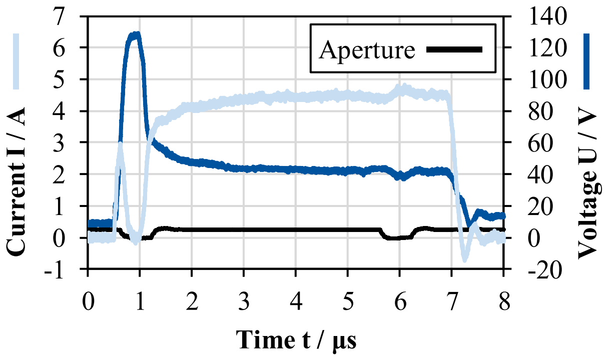


Fig. 11. Current and voltage waveform of a capacitor charging proceeded by a discharge ($i_e$ = 4 A, $t_e$ = 5 µs).

of the small electrode from the initial investigation, which was 4.5 nF, the capacity has shrunk significantly. The reason the parasitic capacitor did not have the expected effect on machining might lie in the different material used as a workpiece. According to Chow et al. [15], SiC powder increases the gap width. Thus, the capacity of the parasitic capacitor might be significantly smaller and therefore does not influence the discharge as much.

## 5. Conclusion and Outlook

In this paper the effect of large electrodes on the surface roughness was investigated. Firstly, the theoretical background was described and compared with the research results in this paper. It was found that a working surface area of 200 cm² can result in a strong influence of the parasitic capacitance, when machining aims for a surface roughness of less than 1 µm Ra. Additionally due to machining to a low surface roughness, increased wear and machining time became a problem. The reason for this was found in interrupted discharges and thus a grown number of discharges with a shorter discharge duration. In order to investigate whether these interrupted discharges stay in the same spot, an experimental setup with a transparent electrode was chosen to directly observe the working gap. Neither a spatial nor a temporal shift of the discharge was detected with the visual method. This complied with the current and voltage waveform, since they also did not indicate such an event. The interrupted discharge, as it was presented in the initial investigation, was not found during the observation with the transparent electrode. Nevertheless, the current waveform showed the characteristics of the charging of a capacitor. However, the parasitic capacitor was found to be less than half as large as in the initial investigation. The reason for this was attributed to the different workpiece material that changed the gap properties and thus increased the gap width.

Further research on this topic has to be conducted. The visual observation would need to be improved. Either temporal or spatial resolution should be enhanced to gain further insight into the process. A larger electrode could create a larger capacity and therefore have the investigated effect on the discharge. Since these measures thwart each other, a possibility to still conduct the research could be to first determine whether effects occur over the whole working surface. After that an observation of only a fraction of the electrode could be conducted. However, a larger number of observations would be necessary in order to find a discharge that allows decent analysis.

## 6. Acknowledgements

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