Prototype machine for micro-EDM

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1. Prototype Machine for Micro-EDM

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Abstract This chapter presents constructive details for a micro-electrical discharge machine (µEDM) that is adequate to study the fundamentals of the process and to educate upcoming engineers in the latest industrial technologies. The machine was designed, fabricated and instrumented by the authors and consists of a rigid structure, electrical and electronic components, a dielectric flowing system and positioning control devices. The machine operates with low voltage, low energy, high-frequency short electrical pulses and makes use of tool electrodes that are capable of drilling holes with diameters in the micrometer range. The presentation provides constructive details for those readers who may be interested in developing an in-house µEDM machine and puts emphasis on its adequacy for investigating the influence of operative parameters on electrical spark discharges, morphology of craters and material removal mechanisms.

1.1 Introduction

Electrical discharge machining (EDM) is a material removal process based on controlled erosion of metals by the intense heat of electric spark discharges. There are three main variants of EDM; conventional (or sinker) EDM, wire EDM and hole EDM drilling.

In conventional EDM the workpiece is immersed into a dielectric (electrically non-conducting) fluid and connected to a terminal of a DC power supply while the tool-electrode (hereafter called ‘electrode’) is immersed at some distance (hereafter called ‘gap’) from the workpiece and connected to the other terminal (see Fig. 1.1a). The first machines were developed in the mid 1950’s and the main applications of conventional EDM are the fabrication of blind cavities and hole drilling using electrodes machined from graphite or copper to the desired shape of the cavities and holes.

The development of CNC systems in the 1970’s brought dramatic improvements to EDM technology that lead to significant gains in accuracy, quality, productivity and earnings. One of the key innovations of that period was the development of wire EDM that makes use of computer-numerically controlled (CNC) systems to cut extremely complicated shapes, automatically, precisely and economically (Fig. 1.1b).
The working principle of wire EDM is similar to that of conventional EDM but instead of using and electrode that slowly plunges into the workpiece it uses a travelling wire electrode (made from copper, brass or molybdenum with diameters ranging from 0.01 to 0.5 mm) that passes through the workpiece to remove material. In order to feed the wire electrode through the workpiece an initial hole must often be drilled in the workpiece prior to wire EDM.

The third variant of EDM is used for drilling of holes in any electrical conductive material, whether hard or soft, including tungsten carbide (Fig. 1.1c). The term ‘fast hole EDM drilling’ is used to distinguish the process from conventional EDM which can also be used for drilling holes but in much slower speeds. The working principle of fast hole EDM drilling is similar to that of conventional EDM and major differences are related to the fact that electrodes rotate and are hollow. The rotating electrode help ensuring better concentricity and reducing wear, while the hollow features allow dielectric fluid to flow through the electrode directly to the working gap.

EDM technology offers significant advantages against conventional machining due to its capability of fabricating complex blind cavities, deep holes and extremely complicated cutting shapes without mechanical contact between the electrode and the workpiece and regardless of material hardness [1].

The abovementioned advantages, together with the flexibility and short manufacturing times of EDM in small batch production, have been focusing attention of researchers and industrial companies engaged with the production of micro-mechanical parts to the possibility of taking EDM technology a step forward to meet the precision requirements of tool making in the micrometer range [2]. The growing demand on micro mechanical parts is driven by a global trend towards the miniaturization of products originated not only from consumers, who want small and highly sophisticated electronic equipment, but also from recent applications in medicine, electronics and optoelectronics.

However, EDM technology and its machine-tools cannot be simply scaled down to be applied on the micro-level. Scaling down requires combining information on key operating parameters of EDM at micro-level and their influence in the morphology of the craters with new solutions and concepts for the design and fabrication of micro-EDM (µEDM) machines.

In the past years, several well-known manufacturers started to offer sophisticated, high-performance, µEDM machines capable of producing very fine finishes and fabricating very small features in micro-tools such as deep-holes with up to 30 µm of diameter. µEDM is one of the most promising technologies in terms of size and precision [3]. However, commercial µEDM machines are generally expensive and very often do not provide key functionalities that are needed for education and research purposes. Commercially available µEDM machines commonly prevent free selection of the operative parameters (such as duty cycle and frequency of electrical pulses), and are not designed for generating single and different types of electrical spark discharges as it is necessary for investigating the fundamentals of µEDM, namely the material removal mechanisms. A state-of-the-art in the field is provided by Rajurkar et al. [4].

From what was mentioned before, there is great interest in developing low cost µEDM laboratory machines that can be used for educational and research objectives. This chapter is concerned with the above mentioned gap between developers and users of µEDM machines and is organized in two main parts. The first part aims to provide constructive details of a µEDM prototype machine that is capable of generating single or multiple electrical spark discharges. The machine was designed, fabricated and instrumented by the authors and is capable of drilling holes with dimensions in the micrometer range. The second part of the chapter analyses how operative parameters such as the electrode diameter, frequency and voltage influence electrical spark discharges and material removal mechanisms namely, material removal rate (MRR) and morphology of the craters.
1.2 Review of the fundamentals of EDM

When sufficient voltage is applied between the electrode and the workpiece, the dielectric fluid ionizes and forms a plasma channel that melts and vaporizes the material located on the surface of the workpiece. Once the electrical spark discharge is complete, the vaporized cloud solidifies and the resulting tiny solid material particles (debris) are removed from the gap between the electrode and workpiece by flowing dielectric fluid (Fig. 1.2).

The main operative parameters of EDM are; (i) the polarity between the electrode and the workpiece, (ii) the open circuit voltage, (iii) the frequency and intensity of the electric current pulses, (iv) the tool or wire electrodes and the (v) the dielectric fluids.

In what concerns polarity, the common practice in EDM is to make electrode negative and workpiece positive (direct polarity) in order to achieve higher metal removal rate. However, researches showed that reverse polarity, in which electrode is positive and workpiece is negative, may be a better option for diminishing roughness and improving surface quality of workpiece [5].

The open circuit voltage is the critical ionization voltage below which there is no electrical spark discharge and, therefore, no electricity flowing between the electrode and the workpiece. The discharge energy during EDM is provided by a direct current pulse power generator system (RC or transistorized) and the frequency is characterized by the pulse on time \( t_{on} \), the pulse off time \( t_{off} \), the period \( T = t_{on} + t_{off} \) (seconds) and the duty cycle \( D \), which is defined as follows,

\[
D = \frac{t_{on}}{t_{on} + t_{off}}
\]

The average discharge current \( \bar{I} \) (Amperes) in the period \( T \) is calculated from the amplitude of the pulse current \( I \) (also known as the ‘peak discharge current’) as follows,

\[
\bar{I} = \frac{t_{on}}{t_{on} + t_{off}} \cdot I
\]

The material removal rate MRR (mm\(^3\)/h) in EDM is primarily a function of the average discharge current \( \bar{I} \) (Eq. 1.2) and melting temperature \( T_m \) (Celsius) of the workpiece material,
where $C$ and $a$ are process and material constants that depend on the material and geometry of the electrodes, on the type and flow rate of dielectric fluids and on the nature of electrical spark discharges, among other parameters.

Electrical spark discharges are commonly classified into four different categories; (i) gap open, (ii) normal sparks, (iii) arc sparks and (iv) short-circuits, and research work is currently ongoing to determine the relation between the type of sparks, MRR and surface finishes [6 - 8]. The possibility of generating single electrical spark discharges in a µEDM laboratory machine is crucial to analyse the different types of sparks, to provide a new level of understanding on plasma formation in the dielectric and to explain how these phenomena influence material removal mechanisms. In fact, as concluded by Schumacher [9] and Kunieda et al. [10] there are fundamental concepts of electrical discharge machining that need to be further investigated because they are not properly well understood. Some of these concepts will be addressed later in the presentation.

1.3 The µEDM prototype machine

Fig. 1.3 shows a schematic representation of the µEDM experimental apparatus that was developed by the authors for educational and research purposes. The design of the µEDM prototype machine follows some of the issues, trends and needs for the development of equipment for electro-physical micromachining that were previously identified by Rajurkar et al. [2].

For purposes of presentation, and although not corresponding to what readers directly observe in Fig. 1.3, the µEDM prototype machine will be split into four broad groups of components; (i) basic structure, (ii) electrical circuit, (iii) dielectric flowing system and (iv) position control devices.

![Diagram of µEDM prototype machine](image)

**Fig. 1.3.** Schematic representation of the µEDM experimental apparatus.

1.3.1 Basic structure

The primary function of the structure is to support and position the tool-electrode and workpiece. The µEDM prototype machine was built upon a robust C-frame structure which consists of a base, an X-Y table, a column and a servo head (Fig. 1.4).

The X-Y table includes means of attaching the workpiece to the table surface and allows moving the workpiece into position. The servo head holds the electrode and is reinforced with lateral guides to reduce vibrations and undesirable
side motion. Lateral guides ensure the electrode to move accurately over the entire length of travel and to be precisely feed into the workpiece.

The C-frame structure of the µEDM machine combines rigidity with flexibility and slim design. Rigidity is necessary for maintaining very precise control over the working gap between electrode and workpiece. Flexibility allows easy changing of components and integration of new accessories. The slim design concept offers excellent accessibility to the working area from the front and the sides.

![Schematic drawing and photograph of the µEDM prototype machine.](image)

**Fig. 1.4.** Schematic drawing and photograph of the µEDM prototype machine.

### 1.3.2 Electrical circuit

The electrical circuit of the proposed µEDM machine is different from those currently utilized in commercial EDM machines because it allows generating single and multiple electrical spark discharges. The modular construction of the electrical circuit comprises a power system with a main bank of capacitors and easily interchangeable discharge circuits that quickly adapt the machine to meet specific requirements of education and research (see Fig. 1.5).

The EDM power system consists of a variable-voltage transformer, a constant current rectifier for converting the single-phase AC supplied with 220 V to DC with voltage in the range 20-330 V and current rating up to 4 A and a main bank of capacitors (Fig. 1.5a).

Fig. 1.5b to 1.5d shows three different interchangeable discharge circuits. The circuit shown in Fig. 1.5b (named ‘impulse generator’), makes use of a variable resistance and a metal–oxide semiconductor field effect transistor (abbreviated named as ‘MOSFET’) to control discharge and to generate square pulses of electric current with frequencies in the range 1 Hz to 500 kHz over a duty cycle $D = 0.5$. The impulse generator is utilized both in single and multiple electrical spark discharge modes. When the µEDM machine is set to single spark mode, the MOSFET behaves as a switch that opens and closes the discharge circuit by supplying control voltage and pulse on time to a PCI-MIO-16E board from National Instruments. The variable resistance in the impulse generator circuit controls the current and, therefore, the total discharge energy available for the sparks.

Changing the impulse generator by the discharge circuit shown in Fig. 1.5c allows the user to utilize a ‘RC type relaxation generator’ to create and control square pulses of electric current. In the RC relaxation generator the discharge energy comes from a capacitor that is connected in parallel with the machining gap. As a result of the low impedance of the plasma channel, the ionization time is larger (although the peak voltage is the same), the discharge duration is shorter and the discharge current is higher than in the ‘impulse generator’ discharge circuit (refer to the graphics included in Fig. 1.5b and 1.5c).
The circuit shown in Fig. 1.5d is named ‘electronic pulse generator’ and is a modification of the impulse generator (Fig. 1.5b) to allow studying the influence of current flow with time in single electrical spark discharges.

![Diagram of electrical circuits](image)

**Fig. 1.5.** Scheme of the electrical circuit of the µEDM prototype machine. (a) Power system consisting of a variable-voltage transformer, a constant current rectifier and a main bank of capacitors, (b) discharging circuit consisting of a variable resistance and a transistor, (c) discharging circuit consisting of a RC circuit and a transistor and (d) discharging circuit consisting of a variable resistance, a pulse generator and a transistor.

All the electrical circuits shown in Fig. 1.5b to 1.5d allow users to control the discharge frequency by adjusting the on-time and off-time of the transistors that control the pulses of electric current.

### 1.3.3 Dielectric flowing system

The dielectric flowing system consists of a dielectric fluid, a pump, a filter, two nozzles and a tank (refer to Fig. 1.4). The dielectric fluid submerges the workpiece and acts as an insulator until the potential difference between the electrode and the workpiece is sufficiently high to produce an electrical spark discharge. The discharge forms a plasma channel in the fluid that removes material particles from the surface of the workpiece by melting and vaporization.

The pump and the maneuverable nozzles, placed on opposite sides of the electrode to minimize pressure induced oscillations, force the dielectric to circulate through the gap between the electrode and the workpiece, directly to the region being machined, in order to wash out the solid metal particles (debris) and to provide a cooling medium (Fig. 1.2).

The filter helps the dielectric to remain clean by retaining debris and contaminants that may cause short-circuits and ensures that electrical properties of the dielectric (e.g. insulation properties) in the gap remain similar to the original values.

The tank is made from glass reinforced with aluminium due to its lack of chemical affinity with the dielectric fluids commonly utilized in the µEDM prototype machine.
1.3.4 Position control devices

The X-Y table is responsible for positioning the workpiece so that μEDM takes place at the proper location. The Z-axis servo head is the machine component that moves the electrode in vertical direction to maintain an adequate electrode-to-workpiece gap distance so that spark discharges will take place. The movement of the X, Y and Z axis is obtained from fine pitch worm gears driven by electric stepper motors.

Fig. 1.6 shows the console panel of the LabView computer based software developed by the authors to monitor and control movement in the X, Y and Z-axis. The console panel is structured into two different modules. The leftmost module allows manual positioning (by means of pushbuttons) of the X-Y table by specifying the displacement and velocity of each individual axis. The display window allows visualizing the position of the electrode in the X,Y coordinate system and helps predefining and storing additional drilling positions.

The rightmost module of the console panel allows monitoring and controlling the vertical position of the electrode. The moving mechanism of the vertical (Z-axis) is made up of an electric stepper motor, driver and loose pulleys (with a transmission ratio of 1:9), a fine pitch worm gear, an elastic stop nut, a timing belt and electric sensors (Fig. 1.4).

Fig. 1.6. Console panel of the XY table and of the servo controlled Z-axis.

The elastic stop nut resists loosening under vibrations and torque and the timing belt prevents slippage during transmission of motion (refer to the schematic detail in Fig. 1.4). The Z-axis positioning mechanism is capable of moving the electrode along its length with an accuracy of 1 µm in 100 mm displacement, under proper alignment and tension applied to the timing belt. The electric sensors consist of a Hameg HZ100 voltage transducer and a Bergoz CTB1.0 current transducer (refer to Fig. 1.3) that monitor the voltage and current between the electrode and workpiece during the electrical spark discharges.

The Z-axis servo head utilizes feedback signals of voltage and current obtained from the previously mentioned sensors to keep the gap constant and prevent the electrode from shorting out against the workpiece. The two display windows included in the rightmost module of the console panel shown in Fig. 1.6 allow monitoring the evolution of voltage and current with time while the available pushbuttons allow changing the gap between the electrode and workpiece in real time.

Table 1.1 resumes the major characteristics of the μEDM prototype machine that was designed and fabricated by the authors.
Table 1.1. Main characteristics of the µEDM prototype machine.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall dimensions</td>
<td>230×450×450 (mm)</td>
</tr>
<tr>
<td>Worktable size (X×Y)</td>
<td>25×25 (mm)</td>
</tr>
<tr>
<td>Worktable travel (X×Y×Z)</td>
<td>25×25×25 mm</td>
</tr>
<tr>
<td>Precision (X,Y-axis)</td>
<td>0.750 µm</td>
</tr>
<tr>
<td>Precision (Z-axis)</td>
<td>0.250 µm</td>
</tr>
<tr>
<td>Maximum velocity (X,Y-axis)</td>
<td>0.35 mm/s</td>
</tr>
<tr>
<td>Maximum velocity (Z-axis)</td>
<td>0.05 mm/s</td>
</tr>
<tr>
<td>Voltage</td>
<td>20 to 330 V</td>
</tr>
<tr>
<td>Maximum output current</td>
<td>4 A</td>
</tr>
<tr>
<td>Maximum frequency</td>
<td>500 kHz</td>
</tr>
<tr>
<td>Dielectric flowing rate</td>
<td>0.75 l/min</td>
</tr>
<tr>
<td>Maximum electrode diameter</td>
<td>2 mm</td>
</tr>
<tr>
<td>Power supply</td>
<td>Single-phase AC, 220 V</td>
</tr>
</tbody>
</table>

1.3.5 Data acquisition

The electric stepper motors utilized in the worm gear position mechanisms produce vibrations that are transmitted to the structure of the µEDM machine. Knowledge of the range of frequencies associated with these vibrations allows users to select operative parameters where the role played by induced vibrations is minimum. In case of the proposed µEDM prototype machine, the identification and quantification of the aforementioned range of frequencies, where the amplitude of vibrations is significant, was performed by means of a Brüel & Kjær’s PULSE platform.

The signals of the Hameg HZ100 voltage transducer and of the Bergoz CTB1.0 current transducer utilized in the servo control of the Z-axis are registered in a data acquisition board (National Instruments PCI-6115 with BNC-2120) and can be visualized on a oscilloscope (Tektronix 2004B) for facilitating real-time analysis.

A computer program developed by the authors is used for the treatment of experimental data namely, for performing the recognition and quantification of the different types of electrical spark discharges that are generated during the µEDM process. This is considered one of the most effective procedures for monitoring electrical discharging machining [11].

Fig. 1.7a shows the experimental evolution of voltage and current vs. pulse on time for a real (experimentally acquired) electrical spark discharge.

The computer program works directly with the experimental evolution of voltage vs. pulse on time $V(t_{on})$ and automatically identifies the regions that lie above and below the curve shown in Fig. 1.7b. Region 3A, for example, corresponds to the ionization potential (open circuit voltage $V_{0}$) while regions 2B and 2C correspond to the discharge potential (working voltage $V_{d}$), which varies from approximately 10 to 40 V in the proposed µEDM prototype machine.

The capability of recognizing different types of discharge patterns in the $(A,B,C)\times(1,2,3)$ display window allows the computer program to automatically classify sparks as gap open, normal, arc and short-circuits, to quantify its percentages of occurrence and to determine the values of the pulse on time $t_{on}$, open circuit voltage $V_{0}$ and working voltage $V_{d}$. 
1.4 Results and discussion

This section of the chapter starts by presenting the experimental work plan that was utilized for assessing the performance of µEDM prototype machine for drilling holes with dimensions in the micrometer range and proceeds by analysing how operative parameters such as the electrode diameter, frequency and voltage influence the type of electrical spark discharges and material removal mechanisms namely, material removal rate (MRR) and morphology of the craters.

1.4.1 Experimental work plan

The performance of the µEDM prototype machine was assessed by drilling micro-holes in stainless steel AISI 304 sheets with 1 mm thickness. Electrolytic copper (DIN E-Cu58) wire was utilized as electrode and Shell Macron EDM 110 oil was used as dielectric.

The experimental work plan was designed in order to isolate the influence of four main process parameters that were considered critical for analysing the MRR and the morphology of the craters produced with different types of electrical spark discharges (Table 1.2); (i) the diameter of the electrode, (ii) the frequency of the square pulses of electric current, (iii) the open circuit voltage and (iv) the operating mode (single or multiple spark mode).

The experimental values of the MRR (mm³/h) were obtained from the ratio between the volume removed from the workpiece and the total drilling time.
Table 1.2. Experimental work plan performed in stainless steel AISI 304 sheets with 1 mm thickness.

<table>
<thead>
<tr>
<th>Electrode Diameter D (mm)</th>
<th>Frequency f (kHz)</th>
<th>Open Circuit Voltage $V_0$ (V)</th>
<th>Discharge Circuit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3 and 1</td>
<td>10, 140 and 200</td>
<td>80, 140 and 200</td>
<td>Impulse generator</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>RC relaxation generator</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Electronic pulse generator</td>
</tr>
</tbody>
</table>

By keeping the rest of the parameters at constant value namely, (i) the flow rate of dielectric and (iii) the polarity (reverse polarity) between the electrode and the workpiece, it was possible to reduce the total number of variables that influence the process. Otherwise the number of possible combinations of variables would become quite large.

1.4.2 Vibrations of the servo head

The electric stepper motors utilized in the worm gear position mechanisms produce vibrations that are transmitted to the structure of the µEDM machine. Fig. 1.8 shows the transmissibility of vibrations that are produced under different working frequencies of the motors to the servo head that holds and moves the electrode. As seen, maximum induced vibrations on the electrode holder have amplitudes below 150 nm and the range of frequencies where transmissibility is higher is around 100 Hz.

Fig. 1.8 Experimental displacements of the servo head due to transmissibility of vibrations that are produced under different working frequencies of the electric stepper motors.
1.4.3 Material removal rate

Fig. 1.9 shows MRR as a function of the frequency of the pulses and of the open circuit voltage, for two different electrode diameters. Results were obtained with the impulse generator discharge circuit and show that MRR decreases as the diameter of the electrode decreases. However, the variation of results with frequency and open circuit voltage requires further analysis.

In case of electrodes with 1 mm diameter, MRR is graphically illustrated as a concave function which increases and then decreases with higher levels of frequency, over a constant duty cycle $D = 0.5$ (Fig. 1.9a). The leftmost region of the graphic (where MRR increases with frequency) is attributed to higher values of current density inside the plasma that is formed in the dielectric. This is because the smallest frequencies give rise to durations of the pulse on time $t_{on}$ large enough to cause a significant drop in the efficiency of the plasma due to greater losses of thermal energy to the dielectric fluid and to the workpiece.

Fig. 1.9 (a) Influence of the frequency of electric current pulses and of (b) open circuit voltage in material removal rate (amplitude of current 1.5 A and diameters of the electrodes (0.3 and 1 mm).

The rightmost region of the graphic in Fig. 1.9a (where MRR decreases at higher frequencies) is attributed to smaller gaps between the electrode and the workpiece and to smaller durations of the pulse off time $t_{off}$. Smaller gaps create difficulties in washing out the debris by the flowing dielectric fluid whereas small
durations of the pulse off time $t_{off}$ cause difficulties in ensuring that properties of the dielectric fluid in the gap recover the original values. The risk of debris being trapped in the gap between the electrode and workpiece does not ensure the electrical insulation properties that are required for a dielectric fluid and gives rise to short-circuiting that significantly decreases the overall surface quality of the micro-holes.

The MRR’s of the electrodes with 0.3 mm diameter are practically insensitive to frequency and up to 10 times smaller than those obtained with the electrodes of 1.0 mm diameter (Fig. 1.9a). The overall decrease in MRR is explained by the increase in the percentage of short-circuits and by the decrease in the percentage of effective electrical spark discharges (refer to Fig. 1.10a).

Data in Fig. 1.10 was automatically collected by the computer software that is capable of recognizing different types of discharge patterns (refer to Section 1.3.5 and Fig. 1.7). The increase in short-circuits for the electrodes with smaller diameters is attributed to its higher aspect ratio and to lack of rigidity, which create difficulties in keeping the gap and preventing the electrodes from shorting out against the workpiece as a result of vibrations induced by spark discharges and position devices (i.e. motion of the electrode holder). This will additionally create difficulties in the position control of the electrode.

Fig. 1.9b allows concluding that MRR’s of both electrodes increase with the increase of the open circuit voltage and that MRR’s of the electrodes with 1 mm diameter are up to 10 times higher than those obtained with electrodes of 0.3 mm diameter. A possible explanation for the increase of MMR with open circuit voltage is related to the larger gap between the electrode and workpiece, which improves wash out by the flowing dielectric fluid and increases the overall efficiency of the electrical spark discharges. Larger gaps also facilitate the servo-control to adjust the position of the Z-axis in order to obtain better and more efficient discharges.

### 1.4.4 Types of electrical spark discharge

Fig. 1.10a shows that the percentage of effective electrical spark discharges (i.e. normal, arc and other sparks that efficiently remove material from the workpiece surface) diminishes as frequency increases for both 0.3 mm and 1 mm electrode diameters. This is attributed to smaller gaps between the electrode and workpiece and to difficulties in washing out debris and contaminants during shorter duration of the pulse off times $t_{off}$.

The remaining discharges correspond to gap open and short-circuits that are unable to create a plasma in the dielectric fluid. The percentage of occurrence of short-circuits is compatible with results presented by other researchers [12].

The percentage of the different types of effective electrical spark discharges as a function of the open circuit voltage (Fig. 1.10b) shows a trend similar to that obtained with frequency. In fact, normal, arc and other sparks that effectively remove material from the workpiece surface increase with open circuit voltage in case of electrodes with 1 mm diameter whereas material removal mechanism for the electrodes with 0.3 mm diameter are basically due to, less effective, short-circuits.

### 1.4.5 Single spark discharges and material removal mechanisms

The proposed µEDM prototype machine is capable of operating under single electrical spark discharge mode. This hardware feature is not commonly found in commercial equipment and allowed investigating the influence of each type of sparking discharge in the material removal mechanisms and morphology of the craters.
Fig. 1.10 (a) Influence of the frequency of electric current pulses and of (b) open circuit voltage in the type and percentage of electrical spark discharges (amplitude of current 1.5 A and diameters of the electrodes equal to 0.3 and 1 mm).

The electrical spark discharges generated by the circuit shown in Fig. 1.5b (‘impulse generator’) under reverse polarity were analysed by the computer program described in Section 1.3.5 and classified into three main groups (Fig. 1.11).

The first group corresponds to open circuits and therefore to absence of sparking discharge, plasma formation and material removal. The second group includes three different types of electrical spark discharges (delayed, normal and arc...
sparks), which effectively remove material from the surface of the workpiece. The third group includes complex discharges and short-circuits that are much less effective than those belonging to the second group in removing material from the surface of the workpiece.

The difference between the classification of sparks given in Fig. 1.11 and that available in one of the very few available research publications in the field [13] is the introduction of two additional types of sparks. The new sparks are named as ‘delayed sparks’ and ‘complex sparks’ and had been previously classified as ‘other sparks’ (refer to Fig. 1.10).

Delayed and complex sparks correspond to discharge patterns that were not automatically recognized by the aforementioned computer program (Section 1.3.5) due to significant deviations from standard voltage vs. pulse on time evolutions. Delayed electrical sparks, for instance, present very large ionization times while complex electrical sparks show evidence of ionization and short-circuiting. Both types of sparks give rise to material removal but complex sparks are included in the third group for being less effective.

A possible reason for the lack of publications relating the type of electrical spark discharge with material removal mechanisms and morphology of craters can be the aforementioned limitations of commercial µEDM machines to operate under single spark mode. In fact, operation in single electrical spark discharge mode allows investigating how duration of pulse on time \( t_{on} \) influences the size of the craters (Figs. 1.12 and 1.13).

In general terms, the size of the craters increases as the duration of pulse on time increases because the plasma channel formed in the dielectric enlarges and the energy is transmitted to a larger surface of the workpiece (Fig. 1.12). Because transmission to larger surfaces implies smaller energy densities, the resulting craters are less well defined than those generated with smaller duration of the pulse on time (please refer to the left and rightmost pictures in Fig. 1.12).

![Fig. 1.12](image)

**Fig. 1.12** Influence of pulse on time on the morphology of the craters. (Single electrical spark discharge mode with an amplitude of current of 2 A and electrode diameter of 1 mm).

The decrease in definition of the craters that is observed for larger pulse on times \( t_{on} \) is attributed to the formation of multiple small craters during an electrical spark discharge as a consequence of secondary streamers that are formed at the vicinity of the main plasma channel. The result of multiple plasma streamers on the surface of the workpiece can be observed in Fig. 1.12 by referring to the photographs corresponding to pulse on times equal and above 25 \( \mu s \).

From an energy point of view, formation of secondary streamers is associated with instability of the primary plasma channel as pulse on time increases, due to increasing of size and diminishing of energy density.
Fig. 1.13 shows the average diameter of craters formed in single electrical spark discharge mode as a function of the pulse on time. There are two quite distinct trends: a leftmost trend where average diameter grows progressively with the pulse on time and a subsequent trend where the rate of growth is exponential. The change in trend occurs for a pulse on time around 10 µs and is physically attributed to the formation of multi craters (over a larger surface of the workpiece) instead of single craters. Similar evolution of the average diameter of craters with the pulse on time was reported by other researchers [14, 15].

The overall morphology of craters resulting from electrical spark discharges that produce single or multiple craters is shown in Fig. 1.14. The number of craters, geometry, area, aspect ratio (between crater depth and average diameter), borders, spatter and formation of black layers are comprehensively systematized and the work illustrates the potential of the µEDM prototype machine, operating under single electrical spark discharge mode, for investigating material removal mechanisms.

![Fig. 1.14 Morphology of craters produced with the µEDM prototype machine operating under single electrical spark discharge mode (normal type of sparks).](image)

The overall characterization of the morphology of the craters that are produced by a single electrical spark discharge (Fig. 1.14) is not commonly found in the re-
search literature and, as far as authors are aware, only the works by Schulze et al. [16] and Rehbein et al. [17] briefly addresses this topic.

Although the investigation has been mainly performed with reverse polarity (that is, the workpiece connected to negative terminal of power) it was decided to check the combined effects of polarity and pulse on time on the morphology of the craters. As shown in Fig. 1.15, direct polarity always produce a single, well defined, crater per electrical spark discharge whereas reverse polarity changes material removal mechanisms from single to multiple craters per electrical spark discharge when the pulse on time increases.

The reason why direct polarity was not utilised throughout the investigation was due to larger electrode wear resulting from collisions of positive ions against the electrode surface and to lower stability of process control compared with that obtained by reverse polarity. The flow of electrically charged particles is schematically depicted in Fig. 1.15.

![Fig. 1.15 Combined influence of polarity and pulse on time on the morphology of craters produced with the µEDM prototype machine operating under single electrical spark discharge mode (normal type of sparks).](image)

**1.4.6 Electrical discharge circuits and material removal mechanisms**

Fig. 1.16 shows the influence of the three different interchangeable discharge circuits of the µEDM prototype machine (Fig. 1.5b to 1.5d) on the morphology of the craters.

Observation of the craters shown in Fig. 1.16 combined with measurements of their depth reveal that craters produced by the RC type relaxation circuit present the highest ratios between depth and average diameter (Fig. 1.16b). This is because craters produced by the RC type relaxation circuit are deeper than the others as a result of the discharge energy being instantly transferred without enough time for the plasma channel to increase its diameter and enlarge its working area on the workpiece surface.

The remaining two types of circuits produce similar craters (Fig. 1.16a and 1.16c). The influence of current flow with time, which is feasible to study with electronic pulse discharge circuit, is globally negligible although the overall morphology of the craters shows signs of slightly larger edges and spatters as well as black layer deposits.

The utilization of RC type relaxation circuits quite often leads to the formation of two craters (one much smaller than the other) during a single electrical spark discharge (Fig. 1.17a). This phenomenon is due to reverse of current flow between the capacitor and µEDM process and gives rise to a second plasma channel, which corresponds to negative peaks of voltage and current that are clearly seen in the evolutions of voltage and current with pulse on time (Fig. 1.17a). Similar negative
peaks of voltage and current with pulse on time have been observed by other researchers [18].

![Diagram of different discharge circuits](image)

**Fig. 1.16** Normal craters produced by the µEDM prototype machine operating under single electrical spark discharge mode with: (a) the impulse discharge circuit (open circuit voltage 200 V, peak current 2 A, pulse on time 10 µs), (b) the RC type relaxation discharge circuit (open circuit voltage 200 V, peak current 10 A, capacitor of 27 mF) and (c) the electronic pulse discharge circuit (open circuit voltage 200 V, peak current 2 A, pulse on time 10 µs).

By modifying the RC type relaxation circuit to include two diodes that allow current to pass in one direction, while blocking current in the opposite (reverse) direction there is only a plasma channel and only one crater (Fig. 1.17b). This additional control avoids reversing polarity during each sparking discharge and, therefore, helps diminishing the overall wear of the electrodes.

![Graph of voltage and current evolution](image)

**Fig. 1.17** Evolution of voltage and current with pulse on time and photographs of craters obtained by the µEDM prototype machine operating under single electrical spark discharge mode with (a) a conventional RC type relaxation discharge circuit and (b) a modified RC type relaxation circuit that includes two diodes.
1.5 Conclusions

The chapter presents a prototype machine for micro-electrical discharge machining (µEDM) capable of operating across a broad range of operative conditions that are suitable for educational and research purposes.

The design of the machine to incorporate easily interchangeable discharge circuits that quickly adapt the hardware to meet specific requirements of investigation allowed authors to test single and multiple electrical spark discharge mode and to better analyse and quantify the physical mechanisms behind material removal.

The computer program that automatically performs the recognition of the different types of electrical spark discharges that are generated during the µEDM process proved to be efficient in determining the percentage of the each type of discharge that occurred during the experiments. The program revealed crucial to investigate the physical mechanisms behind material removal.

Variations in the electrode diameter, frequency and open circuit voltage give rise to significant differences in material removal rate (MRR), effectiveness of electrical spark discharges and morphology of the craters. It was found that MRR increases with open circuit voltage and that there is an optimum frequency that ensures the best MRR. This was attributed to competing effects of plasma efficiency, type of electrical spark discharges, adaptivity and reaction of the electrode position control, and effectiveness of flushing out debris and contaminants from the gap between the electrode and workpiece.

In addition it was found that morphology of the craters is significantly influence by polarity and by the pulse on time. In case of reverse polarity, multiple craters produced by secondary streamers of the plasma channel are likely to be observed when the pulse on time is higher than 10 µs.

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