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ÚSTAV STROJÍRENSKÉ TECHNOLOGIE

MATERIAL OF ELECTRODES FOR ELECTRICAL DISCHARGE MACHINING
MATERIÁL ELEKTROD PRO ELEKTROEROZIVNÍ OBRÁBĚNÍ

MASTER'S THESIS
DIPLOMOVÁ PRÁCE

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ABSTRACT

The diploma thesis deals with problematics of the graphite tool electrode material selection for electrical discharge machining. The thesis is divided into three parts. Theoretical analysis of unconventional technology of EDM based on available sources is summarized at the beggining. A price comparison of graphite materials from present suppliers distributed graphite materials in the Czech republic and Slovakia can be found in the second part. Four different quality grades of graphite and one copper material from a current supplier in GAMARTIS TRADE s.r.o. tool shop are put thru an experiment to find out how much the quality of electrode material influences factors such as the cavity accuracy, wear of a tool electrode, machining time, surface roughness etc.

Keywords

electrical discharge machining, EDM graphite, tool electrode materials, HSC

ABSTRAKT

Diplomová práce se zabývá problematikou volby grafitového materiálu využívaného pro výrobu nástrojových elektrod při elektroerozivní obrábění. Práce je rozdělena do třech částí. Teoretická rešerše nekonvenční technologie elektroerozivního obrábění vypracovaná dle uvedených zdrojů se nachází v první části práce. Dále je v práci proveden cenový průzkum EDM grafitových materiálů nabízených v České republice a na Slovensku. Čtyři odlišné stupně kvality grafitu (od stávajícího dodavatele firmy GAMARTIS TRADE s.r.o.) a jeden měděný materiál byly podrobeny experimentu, jehož účelem bylo zjištění závislosti mezi kvalitou grafitového materiálu (cena) a přesností vyhloubené kavity, opotřebením nástrojové elektrody, časem obrábění nebo také drsností povrchu.

Klíčová slova

elektroerozivní obrábění, EDM grafit, materiály pro nástrojové elektrody, HSC

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DECLARATION

I declare that I have personally compiled the thesis "**Material of electrodes for electrical discharge machining**" according to the instruction of my supervisor, Ing. Karel Osička, Ph.D and with the use of the sources listed in bibliography.

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Datum	Šimon Bednář

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CONTENTS

ABSTRACT 3
DECLARATION..4
ACKNOWLEDGMENT 5
CONTENTS..6
INTRODUCTION 7
1 ANALYSIS OF UNCONVENTIONAL TECHNOLOGY OF EDM 8-24
  1.1 Technological utilization of electro-erosion..8
    1.1.1 Electrical Discharge Machining 8-9
    1.1.2 Electro-Impulsive Machining 9
    1.1.3 Electro-Contact Machining 9
    1.1.4 Anodomechanical Machining 9-10
    1.1.5 Wire Electrical Discharge Machining 10
    1.1.6 Electrical Discharge Drilling 11
    1.1.7 Electrical Discharge Coating 11
  1.2 Physical principle of electrical discharge machining..............................12-20
    1.2.1 Phases of electrical discharge machining process 13-15
    1.2.2 Electric discharge characteristics and working conditions.............15-18
    1.2.3 EDM discharge generators 18-21
  1.3 EDM surface roughness 22-24
2 INDIVIDUAL TYPES OF ELECTRODE MATERIALS 25-27
3 GRAPHITE AND ITS POSSIBILITIES IN EDM..28-35
    3.1 Graphite separation 29-30
    3.2 EDM graphite classification..30-32
    3.3 Key factors in the tool electrode material selection 32-35
4 GRAPHITE CUTTING TECHNOLOGY...36-42
  4.1 High speed cutting of graphite..37-38
  4.2 EDM tool electrode clamping sysstems..38-42
5 GRAPHITE ASSESSMENT FROM INDIVIDUAL SUPPLIERS......................43-47
  5.1 Price comparison of currently used EDM graphite materials......................47
6 RISK AND POSSIBILITIES OF INDIVIDUAL TECH. SOLUTION.......................48
7 EXPERIMENTAL METHOLOGY 49-64
  7.1 Tool electrode preparation 49-51
  7.2 Tool electrode electrode measurement before the EDM 52-53
  7.3 EDM 54-55

7.4 Tool electrode measurement after the EDM..55-57
7.5 Data Collection...58-64
8 EVALUATION OF EXPERIMENT RESULTS...65
9 ECONNOMIC EVALUATION...66-67
CONCLUSION AND DISCUSSION...68
REFERENCES..69-71
SYMBOLS AND ABBREVIATIONS..72
ATTACHMENTS..73

INTRODUCTION

Electrical discharge machining technology has been known for many years now, despite that it still belongs to a group of unconventional machining methods. The EDM is mostly used in the production of injection molds, shearing and press tools etc. Die sinking technology is used to produce complex shapes that are difficult to achieve by other methods of conventional machining techniques (Fig. While the technology itself is mostly used for metal materials, it is also possible to process glass and other materials that have a certain degree of electrical conductivity. Nevertheless, this technology is not intended for machining of polymers and ceramics, even though some of them may exhibit an electrical conductivity.

Currently there are several distributors of graphite materials suitable for the production of EDM tool electrodes on the Czech and Slovak market. The second part of the thesis is dedicated to a price comparison of available materials from present suppliers operating in the Czech Republic and Slovakia. However, it is important to keep in mind that the price should not be the sole criterion when selecting the material of an electrode.

The thesis also examines problematics of the right selection of tool electrode material. Graphite quality grades are put thru an experiment to find out how much the quality of electrode material from a current graphite supplier influences factors such as the cavity accuracy, wear of a tool electrode, machining speed, or surface roughness. These can be used to compare the table's capabilities of an individual material and real results of the spark eroding. The work can also serve to those looking to learn more about the problematics of the right selection of the tool electrode material.

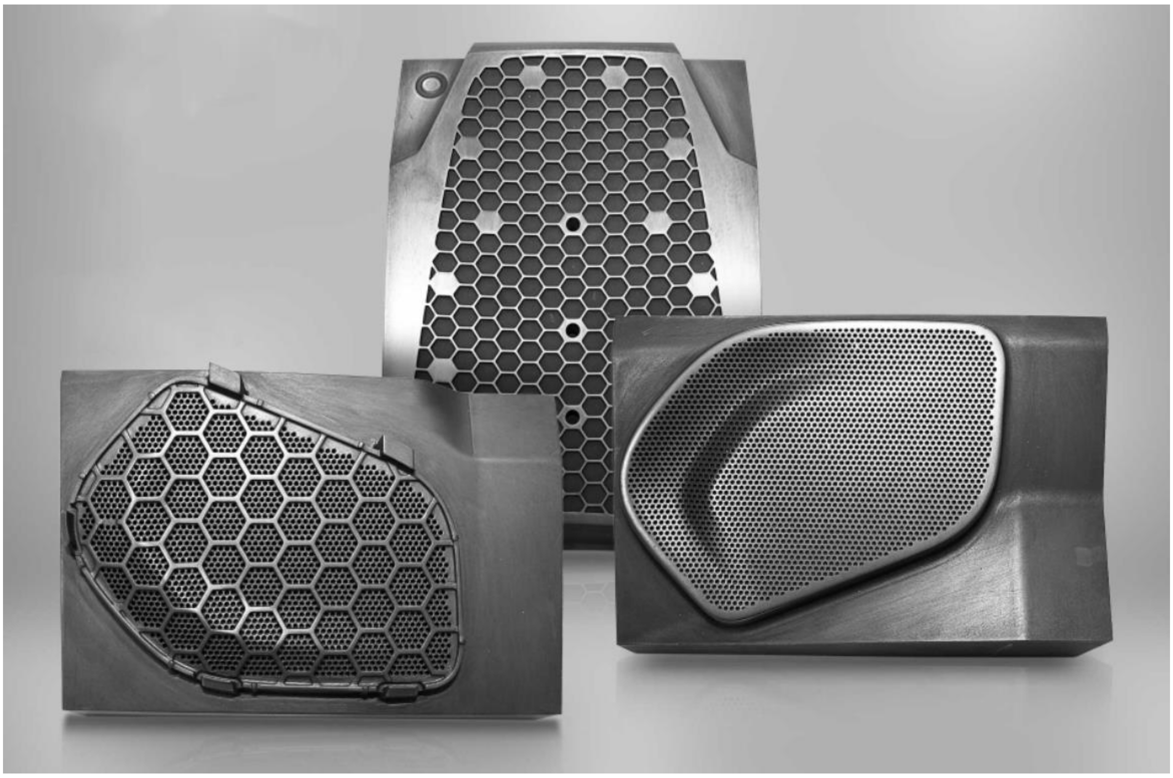


Fig.1 Loudspeaker grids created into a graphite material. [39]

1 ANALYSIS OF UNCONVENTIONAL TECHNOLOGY OF EDM

Spark eroding allows a unique opportunity for machining of complex shapes and cavities in materials with high hardness, fortress, wear resistance etc. The material removal itself does not induce any physical forces into the workpiece material, which is a great advantage over the chip machining. The material removal range ranges from 1 nm to 1 mm per cycle. It is possible to cut, grind, polish, drill, machine and roughen a surface. This technology can be used on both, cylindrical as well as square components, thin or thick parts, hard or soft materials. As there are no convectional cutting tools used in this process, there are no burrs created on the surface. While the technology itself is mostly used for metal materials, it is also possible to process glass and other materials that have a certain degree of electrical conductivity. This process is not intended for machining polymers and ceramics, even though some of them may exhibit some electrical conductivity [1,2,3].

1.1 Technological utilization of electro-erosion

Several methods using the electro-erosion are commonly used in technical practice. These methods can be divided according to the type of electrical discharge, source of impulsive flow and machining parameters [3]:

- electrictrical discharge machining,
- electro-impulsive machining,
- electro-contact machining,
- anodomechanical machining
- wire electrical discharge machining
- electrical discharge coating.

Different methods differentiate from each other by technological characteristics, types of machine-tools and areas of industrial use. As common features may be considered the use of dielectric fluid, generator of electrical impulses and the occurrence of discharge in a machined zone. Methods can be distinguished by:

- the voltage and the type of electrical impulses (symmetrical, asymmetric),
- parameters of an impulse (short, medium, long),
- the method of impulse generation,
- the generator type.

1.1.1 Electrical Discharge Machining

This method is considered as a basic method in electro-erosive processes. It uses short asymmetric pulses which are generated in the unidirectional current generator. The working cycle is consisted of the electrical discharge, thermal effect on the base material and subsequent release of eroded material. The principle of electrical discharge machining is based on the basic principle of electro-erosion, more details in the subchapter 1.2. Electrical discharge machining is classified as a finishing method. It is widely used in the production of small holes, complex cavities and surfaces (external and internal) mainly in the production of injection molds, shearing and forming tools etc. [2,9].

1.1.2 Electro-Impulsive Machining

Electro-impulsive machining is one of the most efficient and cost-effective spark erosion machining technologies. Compared to the electrical discharge machining, it achieves greater material removal, less tool wear and lower energy consumption. The method uses unidirectional arc pulses. The material removal and surface roughness depend on the electrical current and voltage ($I = 80$ to 360 A, $U = 2.5$ to 25 V). The workpiece is mostly connected to the negative pole and the electrode to the positive pole. This causes greater material removal (up to 25,000 mm^{3}·min^{-1}) and the electrode wearance ranges from 1 to 5 %. Compared to the electrical discharge machining, the quality and accuracy of a machined surface is lower [10,11].

1.1.3 Electro-Contact Machining

Electro-contact machining uses the energy of non-stationary arc discharges and heat induced by the passage of electrical charge when there is a contact of electrodes. This contact can be continuous or intermittent. An electrical arc occures when electrodes are approached closer to each other. One of the electrodes must be rotating, othervise there would be a high possibility of weld creation. In addition, the electrodes contain notches for a better removal of melted particles. The electrodes are powered by the AC voltage of 10 to 250 kW and frequency of 50 to 50 Hz. Impulse duration in the discharge channel is 0.01 s. The removal speed can be up to 1 mil · mm^{3} · min^{-1}. Due to very low accuracy, this method is only used for roughing operations and for trimming of sprue and exhaust systems in foundries. The diagram of the method is shown in the Fig. 1.1 [9,10].

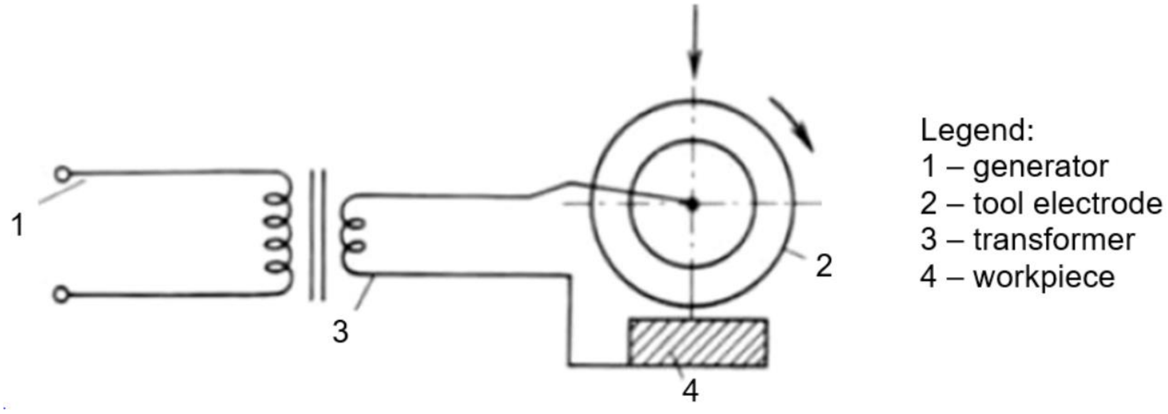


Figure 1.1 Sheme of electro-contact material cutting [7,9].

1.1.4 Anodomechanical Machining

Anodomechanical machining is a combination of electroerosive and electrochemical machining which uses short non-polar pulses. The workpiece is connected to the positive pole of the direct current and it is pressed with a little force against the surface of the rotating electrode (negative pole). The contact area is flooded with an electrolyte which creates a high surface resistence layer on the workpiece surface. This layer prevents the tool from a direct contact with the workpiece. Movement of the tool causes breakage of the layer in the contact area and this leads to a resistence reduction thanks to which electrical discharge may occur. This type of machining is used for cutting poorly machinable materials and sintered carbides. The main disadvantage of this method is low quality and accuracy of the cut. Principle of the method is shown in the Fig. 1.2 [14,15].

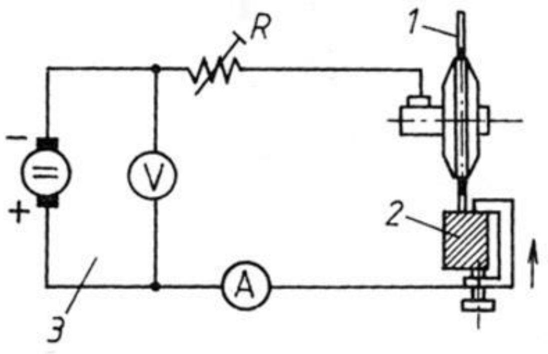
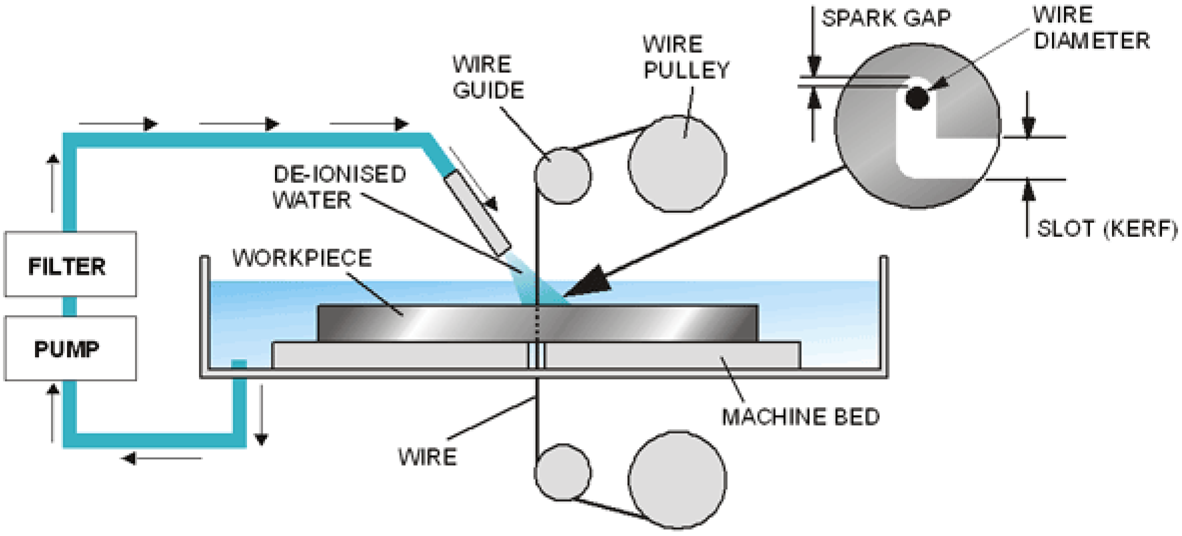


Fig. 1.2 Anodomechanical machining scheme [10].

1.1.5 Wire Electrical Discharge Machining (WEDM)

The tool electrode forms a thin wire which is unwound from one coal to another. This process eliminates excessive wear of the wire in a working process. The wire electrode and workpiece are connected to an electrical circuit by so-called direct polarity (the tool as a cathode and workpiece as an anode). The cutting gap and a subsequent shape is created due to a sprak erosion between the wire and workpiece. The working movement can be performed simultaneously or separately by the upper and lower guide head (according to a programmed path). For multi-axis machines, the workpiece can also make a working movement. The most commonly used wire diameter is 0.2 to 0.33mm.

Wire electrical discharge machining allows to proces complex-shaped shapes with different hardness and sharp edge requirements. Due to the high accuracy and quality of the cut, the method is widely used in the production of injection molds, the production of various shapes of a brake lining, cutting of rotor-stator sheets etc. The principle of the method is shown in the figure 1.3 [12,13].



Obr. 1.3 Wire electrical discharge machining principle [12,13].

1.1.6 Electrical Discharge Drilling

Electrical discharge drilling is a special method of electroerosive machining. It is designed for the production of small holes, carburettor nozzles, starting holes for wire electrical discharge machining etc. It is possible to produce both, circular and non-circular holes with a diameter of 0.02 to 5 mm and length of up to 100 mm. Machines are usually equipped with electrode guiding and optical devices for axis positioning of the holes. Tungsten or copper alloys wires are mainly used as a electrode material. The principle of the method is shown in the figure 1.4 [14,].

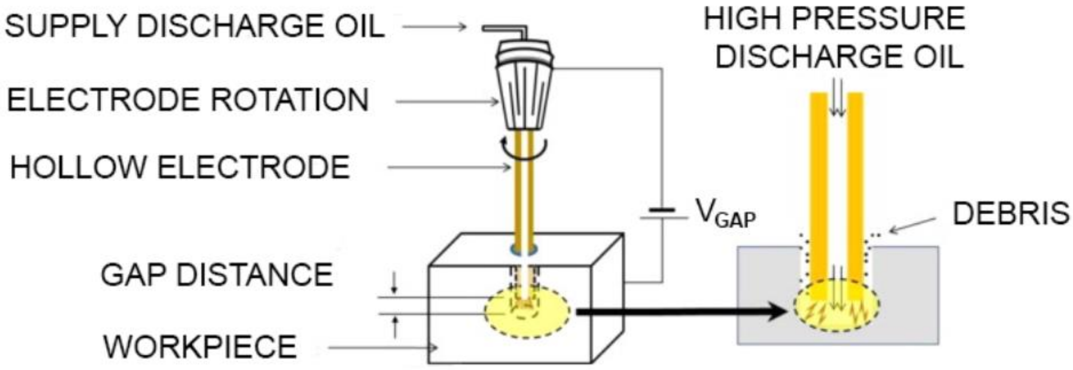


Fig. 1.4 Electrical discharge drilling sheme [18].

1.1.7 Electrical Discharge Coating

The coating electrode, usually made from sintered carbide, is clamped in the coating head and it is than either rotated or vibrated. A workpiece movement is usually hand-operated. A thickness of coating ranges from 2 to 40 μm. The proces itself is very simply and allows an application of coatings on very complicated surfaces. The main disadvantage of this method is a high labor difficulty. Moreover, coatings are unevenly applied to a surface, which is caused by operator’s skills. The technology is used to coat injection molds, bending and extruding tools, as well as coating dril bits, saw blades etc. Scheme of the method shown in the Fig 1.5 [8,19].

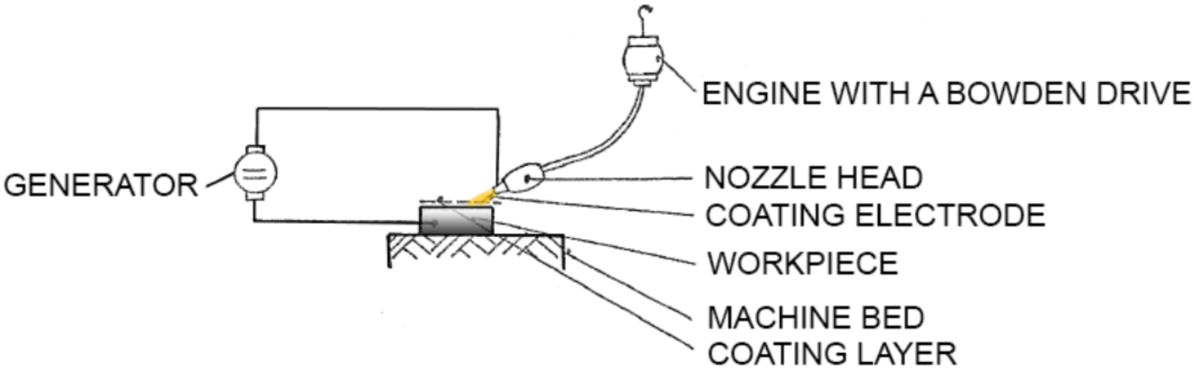


Fig. 1.5 Electrical discharge coatring sheme [4].

1.2 Physical principle of electrical discharge machining

Electric discharge machining is based on the periodical removal of particles in the workpiece surface layer. Material removal is achieved by a thermal and pressure effect of electrical discharges which occur in between the the surface of an electrode and workpiece (see Fig. 1.6).

Machining takes place in between two electrodes (tool electrode and workpiece) which are separated by a spark gap of 0,01 to 0,5 mm. Moreover, they are immersed in a dielectric fluid. Creating of discharges is not efficient in the air or gas atmosphere, therefore it is used a dielectric fluid. The discharge occurs in the area of the highest electrical voltage field which generates an ionized channel allowing the spark to pass between the tool and workpiece. The voltage field value depends primarily on the size of the gap between the workpiece and tool electrode, the conductivity of the dielectric fluid and the dielectric contamination. The ionized channel generates a plasma zone that reaches temperatures of 3000 to 12000 °C. This results in a rapid heating of the workpiece surface, subsequent melting and partial evaporation. Since the dielectric vaporizes at the same time due to the high temperature. A gas bubble, the pressure of which contains high values, is originated. If the current is interrupted, the temperature drops which results in the bubble implosion. The dielectric penetrates into the enclosed space immediately which results in the fling out of melted material from a crater. The melted material solidifies thanks to cooling effect of dielectric fluid and it is discharged from the spark gap in a form of small particles [2,9].

The process also invokes a shape and structural changes on the surface of the electrode. The energy released in the ionized channel affects not only on the workpiece itself but also on the electrode. Effects impacting the electrode:

- bombardment of charged particles, electrons on the anode, ions on the cathode,
- thermal bombardment of channel-forming particles,
- energy exchange through hot vapors and gases flowing from the electrode,
- heat radiation

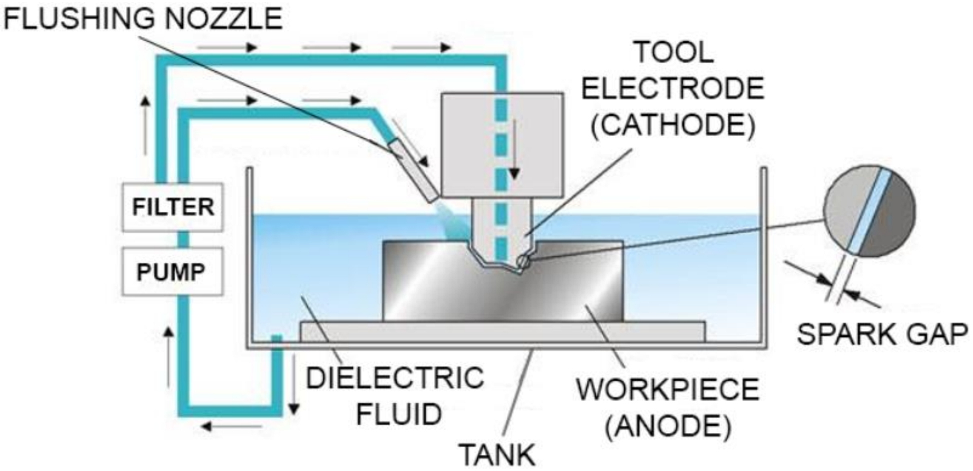


Fig. 1.6 EDM machine layout [15].

1.2.1 Phases of electrical discharge machining process

The process of individual phases induced by a semiconductor generator is characterized as follows [2,6,20].

PHASE 1

An electric field is created by applying voltage to both electrodes. The electrodes do not have an ideally flat surface, therefore an area of maximum gradient is originated in the space of minimal distance of electrodes. Than, conductive particles (impurities) are being pulled into this area. See Fig. 1.7.

PHASE 2

Such electrically conductive particles are considered as the basic condition for the formation of voltage bridges between the electrode and workpiece. These bridges are the basic criterion for discharge ignition. See Fig. 1.7.

PHASE 3

Electrons released from the negative electrode coagulate with neutrally charged particles. This process produces positive and negative ions and it is called the enviroment ionization. See Fig 1.7.

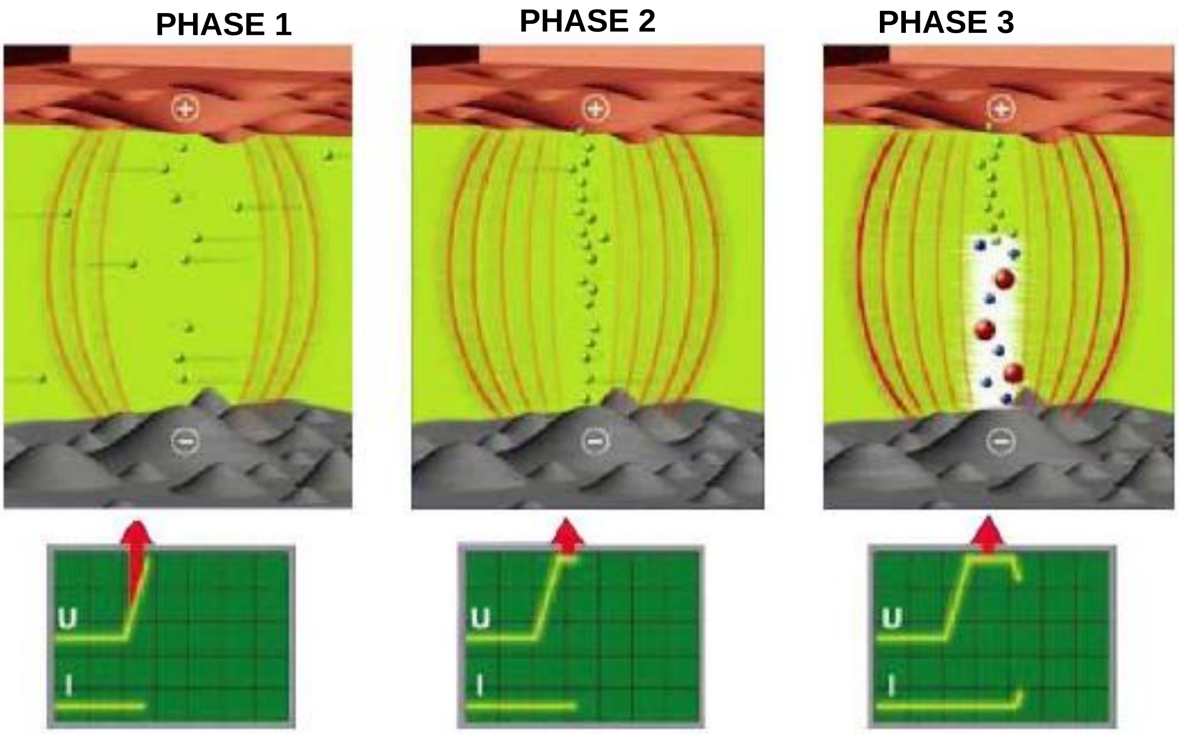


Fig. 1.7 Illustration of the PHASE 1, PHASE 2, PHASE 3 [16].

PHASE 4:

The density of ions increase in the center of a discharge channel which results in a decreasement of electrical resistence. The electric current begins to flow through the spark gap, the current density increases and a plasma channel is formed. The voltage between the electrodes shows a decreasing trend whereas the electric current increasing See Fig 1.8.

PHASE 5

A dielectric evaporation and formation of bubbles occur due to the release of high thermal energy. The voltage is fixed at the ignition value of discharge and the current reaches its maximum value. See Fig 1.8.

PHASE 6

Bubbles‘ expansion, melting and subsequent evaporation of the material. See Fig. 1.8.

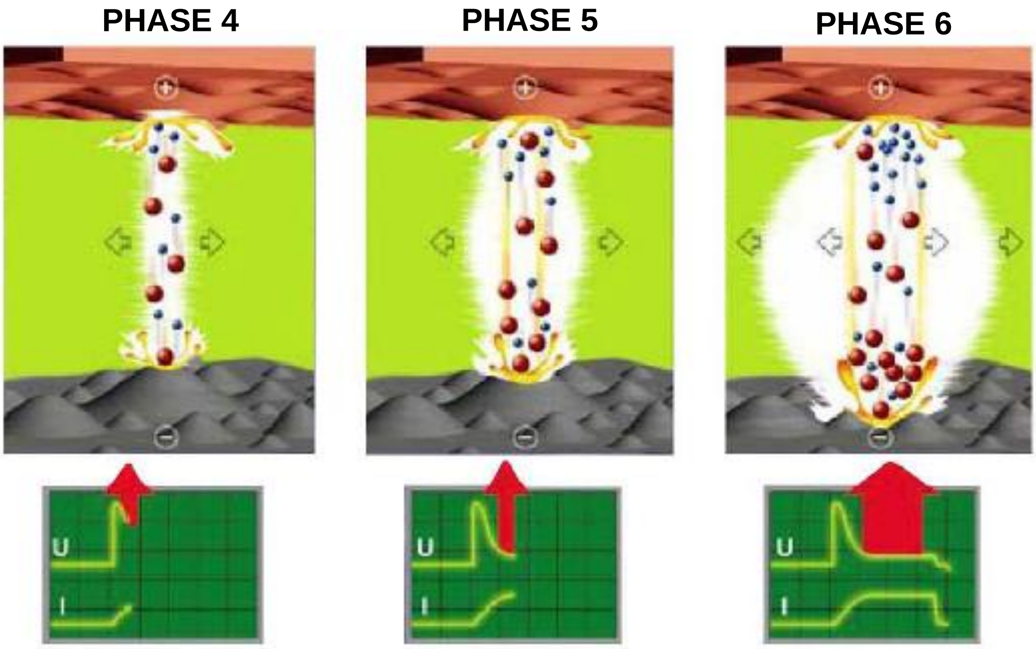


Fig. 1.8 Illustration of the PHASE 4, PHASE 5, PHASE 6 [16].

- **PHASE 7:**

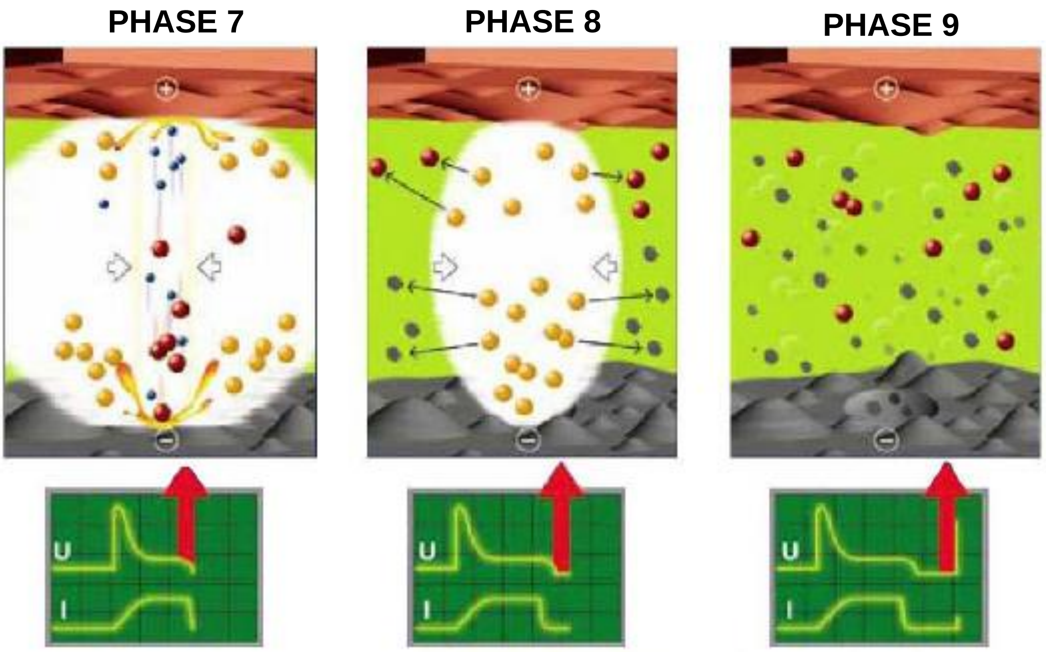
  Power supply is interupted at this point which causes an implosion of gas bubbles. The gas pressure decline causes a disruption of material and following tearing of the melt into a mid-electrode space (a spark gap). See figure 1.9.

- **PHASE 8:**

  Electric discharges and bubbles perish, the electric current and voltage drop to 0 and a dielectric fluid cools the originated craters. Moreover, the dielectric fluid prevents the workpiece from a high thermal impact of electric discharges. Evaporated material is dispersed in the dielectric fluid in a form of flue gases and globuled microparticles. See figure 1.9.

- **PHASE 9:**

  A new cycle start conditions. The dielectric fluid is contaminated with particles of evaporated material and contains the free ions from the previous cycle. See figure 1.9.

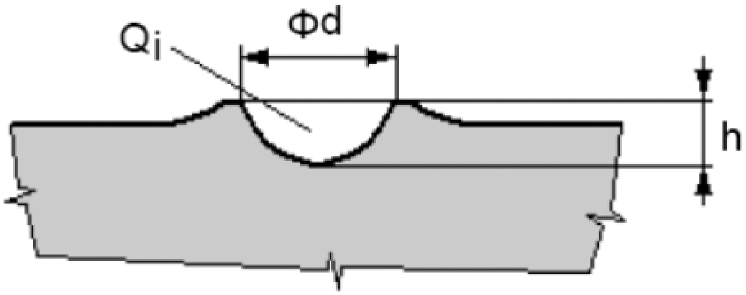


PHASE 7 PHASE 8 PHASE 9

Obr. 1.9 Illustration of the PHASE 7, PHASE 8, PHASE 9 [16].

1.2.2 Electric discharge characteristics and working conditions

The shape and size of craters created by an electrical discharge is depenadent on a discharge energy and discharge duration. The size and shape of craters has a significant effect on the surface roughness, machining accuracy and process efficiency. Representation of such a crater can be seen in the Fig. 1.10 [2.20].



Q_i [mm^3] – volume of removed material
d [mm] – diameter of the crater
h [mm] – depth of the crater

Fig. 1.10 Shape of a crater created by a discharge [2].

The main aim is to achieve the maximum workpiece material removal while minimizing the tool electrode removal (wear of the electrode). The tool electrode wear can be greatly influenced by an appropriate choice of working conditions, namely by:

- an electrical parameters, connection polarity etc.,
- an appropriate choice of the tool electrode material according to the material to be machined.

The time course of a discharge can be evaluated by a number of parameters. Tab. 1.1 describes the course of a discharge using the most commonly used semiconductor generator. Fig. 1.11 shows the shape of such discharge.

The impulse duration is expressed by the equation below:

$$t_i = t_d + t_e \tag{1.1}$$

Tab. 1.1 Time characteristic of a discharge [2].

Discharge duration t_i	The time period between the generator connection and disconnection.
Pause duration t_o	The time period between the generator disconnection and start of new cycle.
Discharge delay duration t_d	The time period between the generator connection and dielectric breakout.
Period duration t_θ	The time period between the discharge ignition and generator disconnection.
Starting voltage U_z	The generator connection voltage (i.e. the ignition voltage)
Discharge working current I	The maximum discharge current flowing between the tool elecrode and workpiece at the time of a discharge.
Mid discharge current I_θ	The middle current value between the moment of a discharge ignition and generator disconnection.
Mid discharge voltage U_θ	The middle voltage value between the moment of a discharge ignition and generator disconnection.
Voltage U_k	The voltage value at the end of the discharge, depending on the material, the dielectric fluid and its pollution value (used to control and optimize the machining proces).

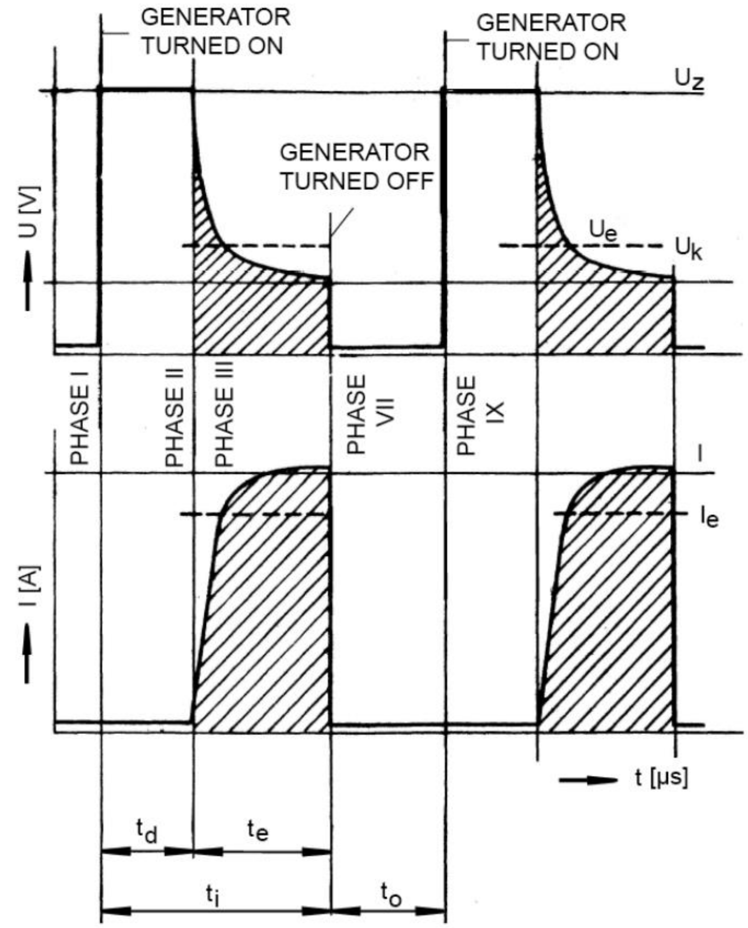


Fig. 1.12 Current and voltage course created by a semiconductor generator [2].

Based on these characteristics it is possible to specify other quantities [2]:

- discharge energy:

$$W_i = \int_0^T u(t) \cdot i(t) dt [J] \tag{2.2}$$

- total amount of removed material per a time unit:

$$Q_i = K \cdot W_i \left[mm^3\right] \tag{2.3}$$

where: W_i [J] – discharge energy

K – coefficient of anode proportionality

There is a considerable influence of the time course on the utilization of discharge. Thus, a variable „q“ is introduced:

$$q = \frac{t_i}{T} = \frac{t_i}{t_i - t_0} [-] \tag{2.4}$$

This variable expresses time utilization of a discharge and it is used to creating a better characteristic when using values of parameters t_i, t_0 and T (see Fig. 1.13).

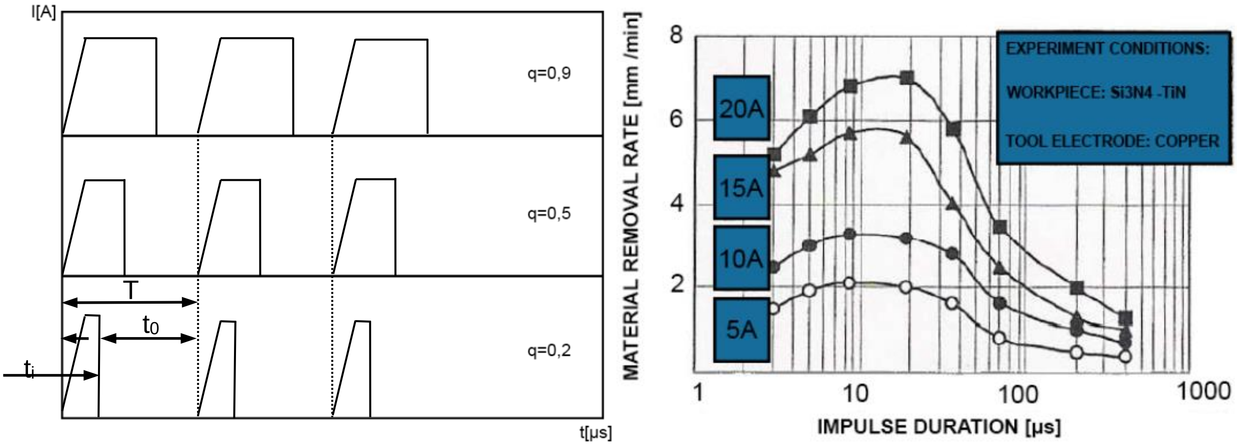


Fig. 1.13 Time period utilization of a discharge (left), A diagram of a material removal rate and impulse duration for different volumes of current [1,2,5].

Electric discharges can be divided further according to the time course of energy delivery into the discharge area as follows: [1,9]:

- an electro-spark discharge,
- a non-stationary short-time arc discharge (arc discharges),

Electro-spark discharges are characterized by a short impulse duration, low utilization of a discharge period and high discharge frequency. The predominant electron conductivity causes a higher loss of anode against the cathode (released electrons have a higher thermal effect on the anode). The energy of a single discharge is low, thus it is mainly used for finishing operations.

On the contrary, short-term non-stationary arc discharges or so-called arc discharges are characterized by a longer impulse time, higher values of utilization of a discharge period and lower discharge frequency. The ionic conductivity prevails in the discharge channel and released particles carry greater thermal energy. This type of discharge is mainly used for roughing operations. The comparison of discharges is shown in the Tab. 1.2.

Tab. 1.2 Time characteristic of discharges [2,8].

Type of discharge	**Electro-spark discharge**	**Arc discharge**
Impulse duration	short $t_i=10^{-4}$ až 10^{-6}s	long $t_i>10^{-4}$s
Utilization of discharge period	q=0,03 až 0,2	q=0,2 až 0,1
Discharge frequency	high	low
Current density in the discharge area	ca. 10^6 A·mm^{-2}	ca. 10^2 až 10^3 A·mm^{-2}
Channel ballance	electron conductivity	ionic conductivity
Discharge channel temperature	up to 12 000°C	3 300 to 3 600°C
Single discharge energy	$W_e=10^{-5}$ až 10^{-1}J	$W_e=10^2$J
Application	finishing operations	roughing operations

The material removal rate „MRR“ (machinability) depends on the material properties, type and quantity of alloying elements and also on the thermal properties of a workpiece material (material temperature, thermal conductivity, specific heat capacity). Mechanical properties of the material (hardness, plasticity etc.) have almost no influence on machinability and that is why EDM machining is widely used for a hard material machining. A tool material properties and discharge duration have also significant effect on machinability [2,9].

1.2.3 EDM discharge generators

Different types of impulses of different frequencies are used in technical practice. The impulses are created by the generator of EDM machine. Generator are characterized by the voltage, current and impulse shape. According to the shape, the impulses can be divided into [1]:

- unipolar impulses – electroimpulsive machining (see Fig. 1.14),
- alternating asymmetrical impulses-EDM machining (see Fig. 1.15),
- bipolar symmetrical impulses-electro-contact machining (see Fig. 1.16).

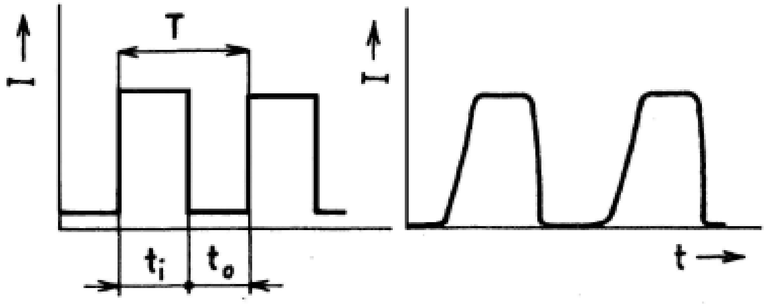


Fig. 1.14 I - t repressentation of unipolar impulses [1]

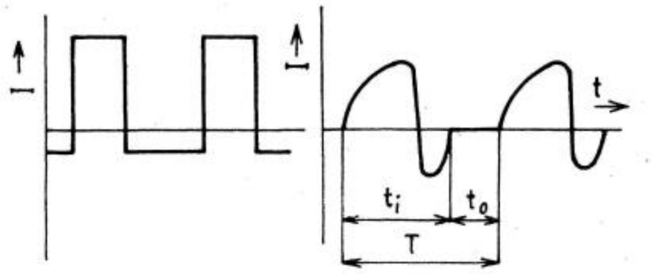


Fig. 1.15 I - t repressentation of alternating asymmetrical impulses [1].

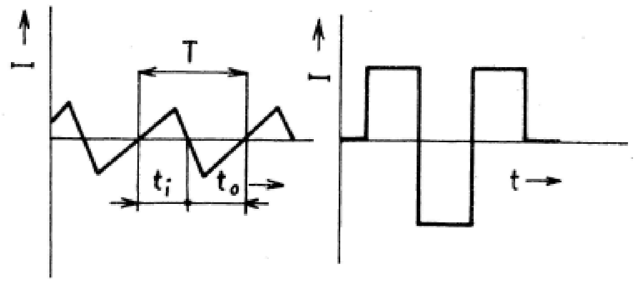


Fig. 1.16 I - t repressentation bipolar symmetrical impulses [1].

The generators itself can be divided by a term of structure and type of connection into [1,2,16]:

- **dependent generators** (electro-spark discharges),
- **semi-dependent generators**,
- **independent impulse generators**.

Dependent generators

This type of generator is considered to be one of the oldest sources of discharges. The function of the generator is based on the periodic charging and discharging of a condenser by a DC power source. Discharging occurs when the breakout value is reached. The magnitude of the breakout voltage is dependent on a dielectric pollution and spark gap size. Frequency and energy of an individual discharge is dependent on the change of ratios in the spark gap, thus dependent generators.

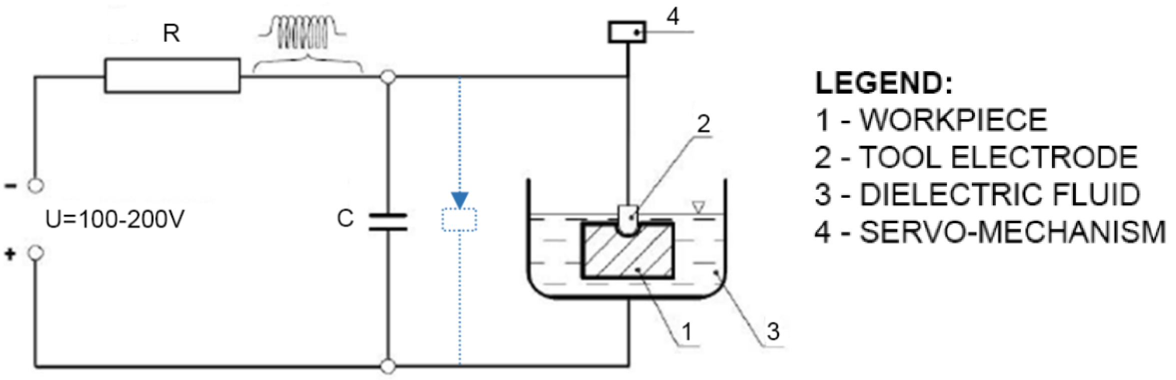


Fig. 1.17 EDM circuit diagram with a RC / RLC elements [11].

The source generates very short discharges of $t_i = 10^{-4}$ to 10^{-7} s and there is an electron conductivity. A smaller loss of the tool electrode material predetermines to connect the workpiece to the circuit as an anode and the tool electrode as a cathode (see Fig. 1.17).

The spark gap size is evaluated according to the voltage ratios, by the so-called servomechanism. The value of the charging current varies with the change of resistance R. At the same time, the capacitor is charged. By connecting an inductance (L) to the RLC circuit as shown in Fig. 1.17, the charging current stabilization is achieved, the frequency and power increase, and the charging time is reduced. This results in up to 25% productivity increasement. A diode can be connected in parallel to the circuit to avoid sparking in the opposite direction, see Fig. 1.17 [1,4].

Dependent generators are simple and reliable. The main disadvantage is a heavy wear and tear of tool electrodes (up to 30%) which is cause by the occurrence of AC current with a negative half-wave. Other disadvantages include a limited ability to regulate the shape and frequency of discharges and the low machining efficiency. Thus, it is advisable to use this type of generators for finishing operations.

Semi-dependent generators

Semi-dependent generators have been created by a gradual improvement of relaxation generators by means of an additional device that reduces the dependence of the discharge spark gap. By adding a breaker/blocking element (tyratron), these generators have more regular impulses than relaxation generators. See Fig. 1.18 [2].

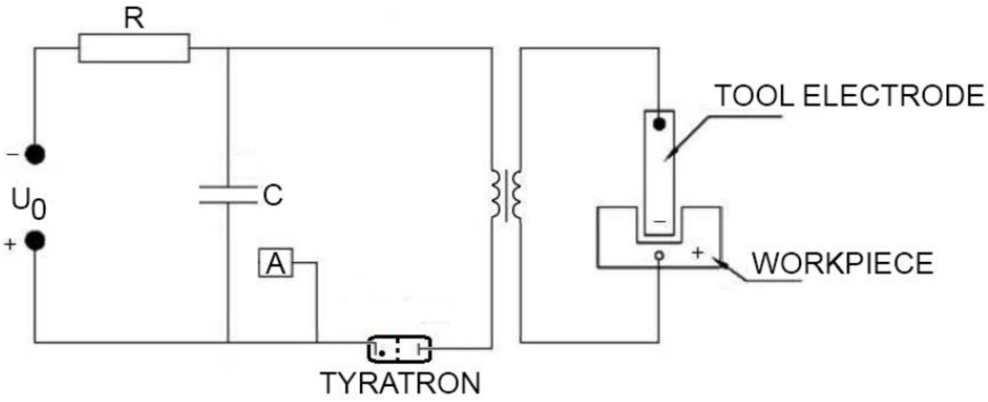


Fig. 1.18 EDM circuit diagram with a semi-dependent generator [2].

Independent impulse generators

Independent generators allow to adjust working conditions regardless a spark-gap ratios. A longer impulse duration, lower working voltage and often the opposite polarity of discharges (workpiece connected as the cathode, tool electrode as the anode) are considered as the main features of this type of generators.

There are two types of independent generators:

- rotary (mechanical generators with collectors and non-collector mechanical generators),
- semiconductor (transistor generators).

Rorary generators

The impulses are generated by rotating a dynamo using an asynchronous motor. Frequency is constant (for instance 400 Hz), which considerably increases material removal (up to 5 $cm^3 \cdot min^{-1}$). Fig. 1.19 shows a diagram of a rotating collector generator. The disadvantages include a high noise level, difficult impulse rate control, and the need to use a finishing generator for the finishing machining [2,10].

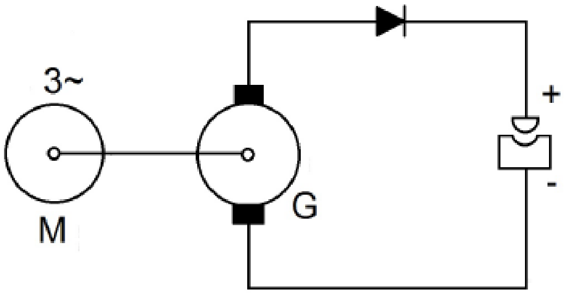


Fig. 1.19 EDM circuit diagram with a rotary generator [2].

Semiconductor (transistor) generators

These generators are considered to be a second-generation generators and allow a wide range of electrical parameter settings. Frequency can be changed in the range of 0.5 to 50 Hz. A transistor is connected in a series circuit with a sparkle generates a voltage on the tool electrode. If the spark gap distance corresponds the breakout distance, the electric current flows through the circuit and discharges occur. Discharges disappear as soon as the transistor is closed. The size of electric current is determined by a number of transistors connected in parallel. Multiple tool electrodes can be machining at the same time if connected appropriately to the transistors. This type of generator allows application of an adaptive control of working conditions using a CNC machine. This guarantees minimal wear and tear of the tool electrode while maintaining a high productivity of the machining process. Fig. 1.20 (see next page) illustrates schematically the circuit connection using a semiconductor generator [11].

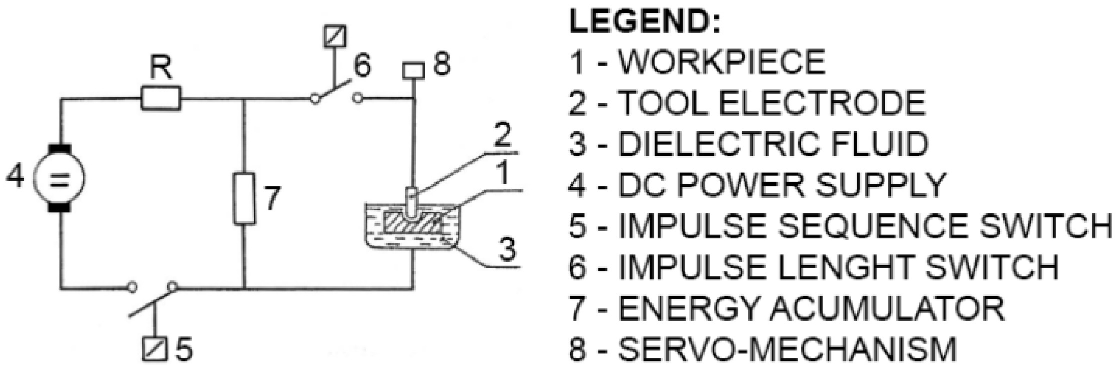


Fig. 1.20 EDM circuit diagram with a semiconductor generator [11].

1.3 Surface rougness for EDM

The surface characteristics of EDM created surface are considerably different than surface characteristics of conventional machining methods. A discharge produces irregular craters of certain dimensions on the surface of a workpiece. The size of a crater depends on the type of dielectric fluid, tool electrode material and setting parameters of the machining process. The difference of an EDM and a milling surface layer is shown in Fig. 1.21.

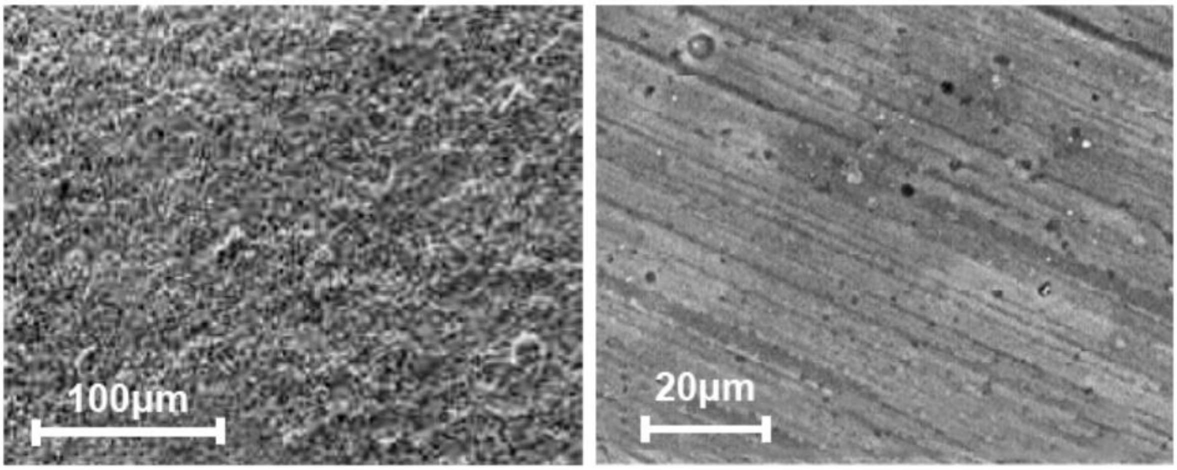
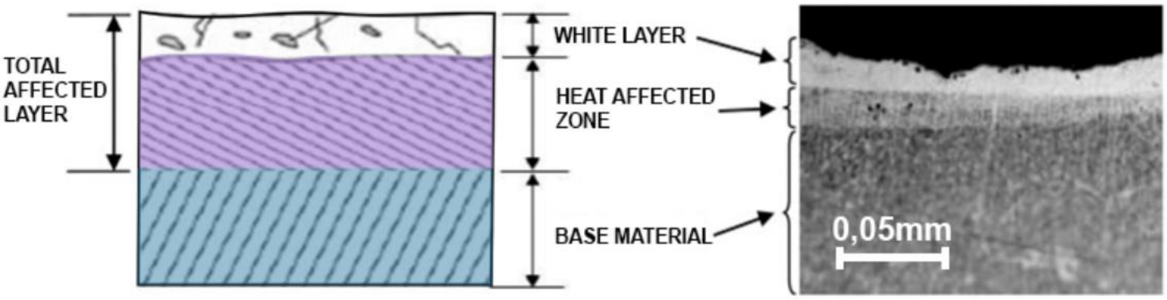


Fig. 1.21 EDM surface layer (left), milling surface layer (right) [16].

A crater formation is accompanied by a local melting of a workpiece surface, formation of a heat-affected layer and plastic deformation of the crater and its surroundings. The melted layer reacts with the tool electrode material and elements of dielectric fluid. This reaction produces a stable austenitic layer. The surface is rapidly cooled due to the dielectric fluid which causes hardening of a certain surface layer. Moreover, the effect of high temperatures (8000 to 12000 °C) causes creation of defects (cracks, twinning). Thus affected area is called the White layer. Hardness of the layer is very high and properties are different than the base material. The depth of layer depends primarily on the discharge energy of impulses. A cross section through an EDM created surface is shown in Fig. 1.22.



Obr. 1.22 Cross section through an EDM machined surface [10,11].

Surface roughness after the electrical discharge machining has its own VDI surface scale. This scale is not based on the arithmetic average Ra (µm). Table 2.2 shows a comparison between Ra and VDI and Fig. 1.23 shows a VDI plate of surface roughness.

Tab. 1.3 Comparison of the VDI and Ra surface roughness.

Ra [µm]	0,4	0,6	0,8	1,1	1,6	2,3	3,1	4,5	6,3	9,0	12,5	18
VDI [-]	12	15	18	21	24	27	30	33	36	39	42	45

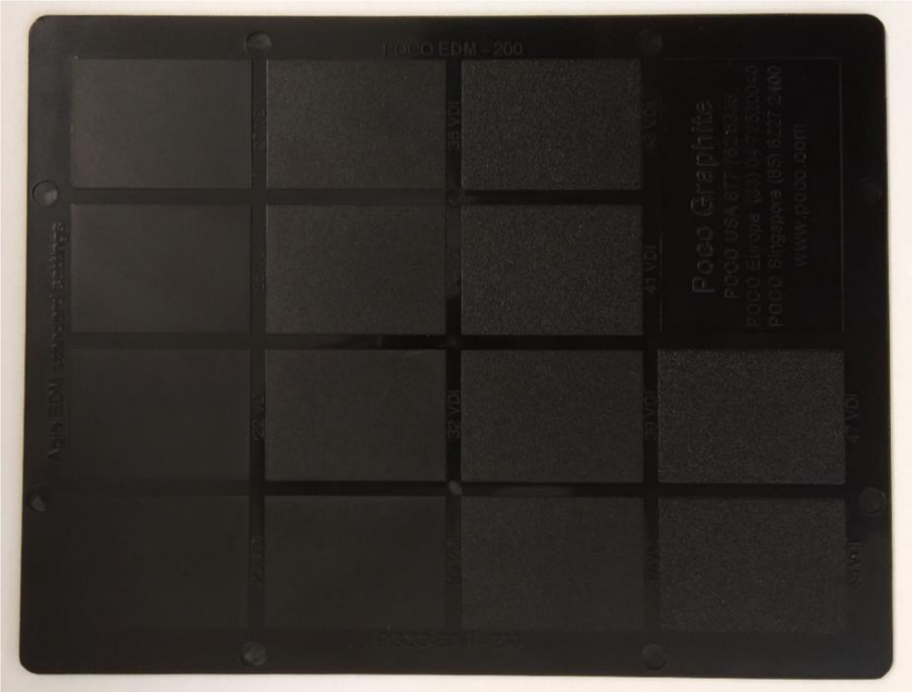


Fig. 1.23 VDI surface roughness plate from graphite supplier POCO graphite

The setting parameters of the machining have a significant influence on the appearance of craters, that is to say on the surface roughness. In general, the best surface quality is achieved when using lower currents, short impulses and high impulse frequencies. Fig. 1.24 shows the effect of the impulse duration on the surface roughness. The quality of the surface is also related to a higher wear of the tool electrode, higher discharge energy and surface layer conditions.

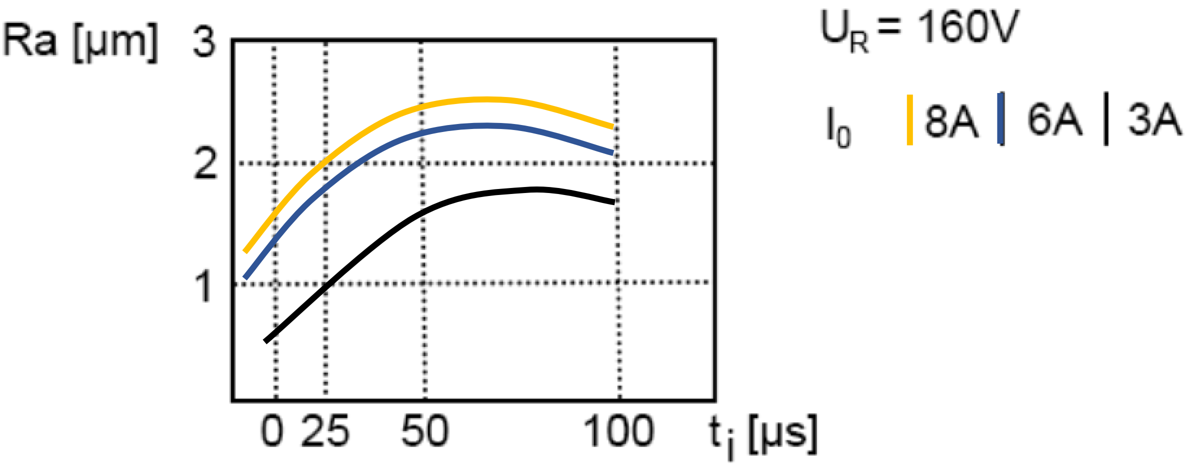


Fig. 1.24 Influence of the impulse duration on the surface roughness when using different machining parameters [16].

Furthermore, higher discharging energy increases the amount of the material removal. Thus, creates are larger and the machining process is faster, however the accuracy and surface roughness decreases significantly. The dependency of the surface roughness, size of electric current and material removal rate is shown in the Fig. 1.25.

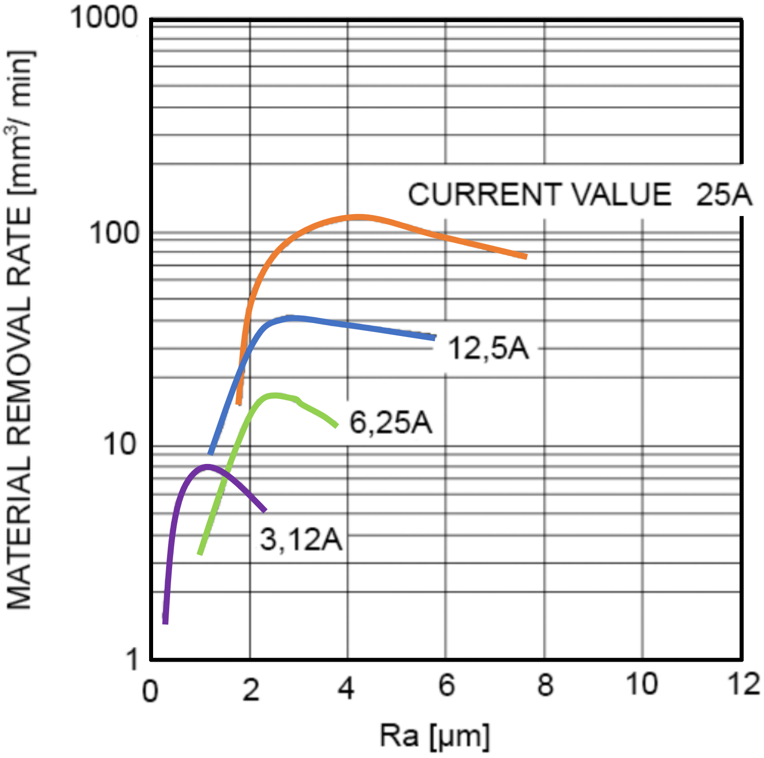


Fig. 1.25 Surface roughness, electric current value and material removal rate dependency [2].

2 INDIVIDUAL TYPES OF ELECTRODE MATERIALS

A tool electrode is very important part in the whole EDM machining process. Tool electrodes determine the machining accuracy, surface quality and machining efficiency. Each tool electrode is designed separately for a certain kind of machining. The production cost of manufacturing of electrodes can be as high as 50 % of the total cost of a cavity production. Hence, it is very important to choose the material, design and manufacturing process correctly [5,6].

The right choice of a tool electrode material depends on the workpiece material, machine type, and relative wear and tear of a tool electrode. It is possible to divide tool electrodes according to the structural composition into [26]:

- metal electrodes (copper, brass, steel, tungsten alloys),
- non-metal electrodes (graphite),
- compound electrodes (graphite-copper compounds).

Machinability when EDM is not dependent on the mechanical properties of material, but it depends primarily on the physical properties of material. The higher the melting point of material, the thermal conductivity, Young‘s modulu, Poisson‘s ratio, the higher the wear and tear resistance. On the contrary, the lower the linear heat conduction coefficient the higher the wear and tear resistence of the material. Furthermore, it was found that the wear and tear resistence is not directly propotional to a melting point temperature of a tool electrode material. Tab 2.1 shows a comparison of physical properties of selected materials [2].

A tool electrode must include following properties:

- high electrical conductivity,
- good thermal conductivity a heat capacity,
- high melting and boiling point,
- high resistence to electric erosion,
- sufficient strenght of materials,
- low thermal expansion,
- good machinability,
- low price.

Tab 2.1 Physical properties of selected materials for a production of tool electrodes.

Material	**Melting point** [°C]	**Boiling point** [°C]	**Thermal conductivity** (Ag = 100%)	**Electrical conductivity** (Ag = 100%)	**Strenght** [N·mm^{-2}]	**Young's modulus** [N·mm^{-2}·10^5]
Graphite	3572	4027	30,3	0,1	34	5,9
Copper	1085	2562	94,3	96,5	241	124
Tungsten	3422	5555	29,6	48,1	41,3	351
Iron	1539	2861	16,2	16,2	275	186

A relative volumetric wear (θ) is introduced to simplify a selection of the tool electrode material. This quantity expresses a ratio of the volumetric wear of the tool electrode (V_N) and workpiece material (V_o) [1].

$$\vartheta = \frac{V_N}{V_0} \cdot 100[\%] \tag{2.5}$$

The wear and tear value of the tool electrode depends, in particular, on [2]:

- polarity,
- tool electrode material and its homogenity,
- thermal conductivity,
- melting temperature of the tool and workpiece material,
- type of generator,
- type of dielectric fluid,
- discharge intensity.

Wear rates range from a tenth of a percent to tens of percents. The wear of a copper tool electrode in a roughing proces of a steel workpiece ranges from 0.5 % to 3 %, while in a finishing process from 2 % to 10 % [11].

Copper (Cu)

Copper has excellent thermal conductivity and good resistance to a spark erosion. The material exhibits very good machinability and material removal rate while maintaining a moderate wear and tear of a tool electrode which results in high process efficiency. Copper as a tool electrodes material were used among the first because of its capability of machining carbide materials.

Copper is widely used for a production of shaped cavities of all kinds made of steel, stainless steels, tungsten carbides, and in a finishing operations with a low roughness requirements (Ra 0.5 and below) [2].

Cu + W, Ag + W compounds

Material compounds are used for special purposes, such as machining of narrow gooves and holes, finishing operations when there is a problematic flow of dielectric fluid. Furthermore, for machining of deep grooves made of steel, sintered carbides and tungsten carbides [2,4].

The price is about 18 to 100 times higher than the price of copper tool electrode. The wear and tear of a tool electrode is about 3 to 5 times lower than when using copper material and it is due to the high content of tungsten in the alloy (50 to 80%) [4].

The tool electrode is produced, according to the shape complexity, by methods of a precise casting or pressure die casting. Turning, milling, grinding etc. is used as a finishing operation in the production of a tool electrode [2].

Brass

Brass is a very cheap material with excellent machinability. Thus, it is suitable for a tool electrode production. Its high wear and tear rate, in comparison with copper and tungsten electrodes, is considered as the greatest disadvantage of this material. Brass electrodes can be used to drill narrow holes when the dimensional inaccuracy caused by wear and tear of the tool electrode is not an issue. Nowadays, brass is replaced by graphite and copper (better dimensional accuracy and more favorable wear and tear of the tool electrode) [2].

Copper-graphite compounds

This material compounds are about 1,5 to 2 times more expensive than graphite itself. Thus, it is ideal to use it for a machining of hard materials, such as tungsten carbide etc.

Graphite

Graphite, with its good machinability, wear characteristics and thermal stability of dimensions, is the most used tool elecrode material. The volumetric wear ϑ in a roughing proces is about 1 % and 5 to 10 % in a finishing process. Due to graphite’s very low weight it is possible to produce tool electrodes of very large dimensions (in the production of injection molds of vehicle bumpers etc.). Tab. 2.2 illustrates a suitable tool electrode and machined material combinations and can be used as a quick guide when selecting a tool electrode material.

Tab. 2.2 Tool electrode and workpiece material combinations [3].

Tool electrode mat.	Workpiece material	Machining type	Surface quality	Note:
Tungsten carbide	Steel	R	Moderate	low material removal
		F	Good	
Brass	Steel	R	Good	suitable for small holes drilling
		F	Good	
BrasS	Titan	R	Good	moderate material removal
		F	Good	
Copper	Al alloy	R	Good	low material removal
		F	Good	
Copper	Cast iron	R	Good	moderate material removal
		F	Good	
Copper	Stainless steel	R	Moderate	discharge instability for some types of steel
		F	Moderate	
Copper	Tungsten carbide	R	Good	moderate material removal
		F	Good	
Cu-W compound	Steel	R	Good	suitable for highly accurate press tools
		F	Good	
Cu-Graphite compound	Tungsten carbide	R	Good	suitable for tungsten carbide products
		F	Good	
Graphite	Cast iron	R	Good	higher material removal at negative polarity
		F	Good	
Graphite	Copper	R	Moderate	low material removal
		F	Moderate	
Graphite	HSS	R	Moderate	moderate material removal
		F	Moderate	
Graphite	Stainless steel	R	Moderate	good material removal
		F	Moderate	
Cu-Graphite compound	Steel	R	Good	high material removal
		F	Good	
Cu-Graphite compound	Tungsten	R	Moderate	moderate material removal
		F	Moderate	

3 GRAPHITE AND ITS POSSIBILITIES IN EDM

Graphite is an excellent material for the tool electrode production, however it is important to note that not all graphite materials are the same. Individual graphite producers use various processing techniques. The basic process may be similar, however the final results are usually very different from each other. Each graphite producer usually produces a certain number of quality grades of graphite which are designed for different purposes [5].

The basic knowledge of graphite structure and its properties can significantly simplify selection of the quality grade. It is a matter of fact that a certain type of the quality grade suitable for a particular type of machining and a particular material may not be suitable for the same type of the operation on a different type of material. The graphite properties and correct utilization of each quality grade have a significant influence on the machining efficiency, production cost of tool electrodes as well as final product. Thus, these knowledges can signiificantly influence, positively or negatively, profitability of the project.

Graphite production

The production of graphite was made possible by the invention of a high-temperature electric furnaces in the 19th century. The raw material for the production is calcined petroleum coke (amorphous carbon). Calcined coke is milled to different grain sizes. The required blends of coke particles are then mixed with coal tar pitch and this kind of mixture is pressed or extruded onto the billets. The billets are baked in an oxygen-free atmosphere, which helps to release volatile sunstances materials from the pitch). The result is a product of an amorphous carbon, which is held together with the rest of carbon pitch residue. The carbon in this form is transformed to graphite (graphitized) by further heat treatment at extremely high temperatures. The production process is illustrated in Fig. 3.1 [5].

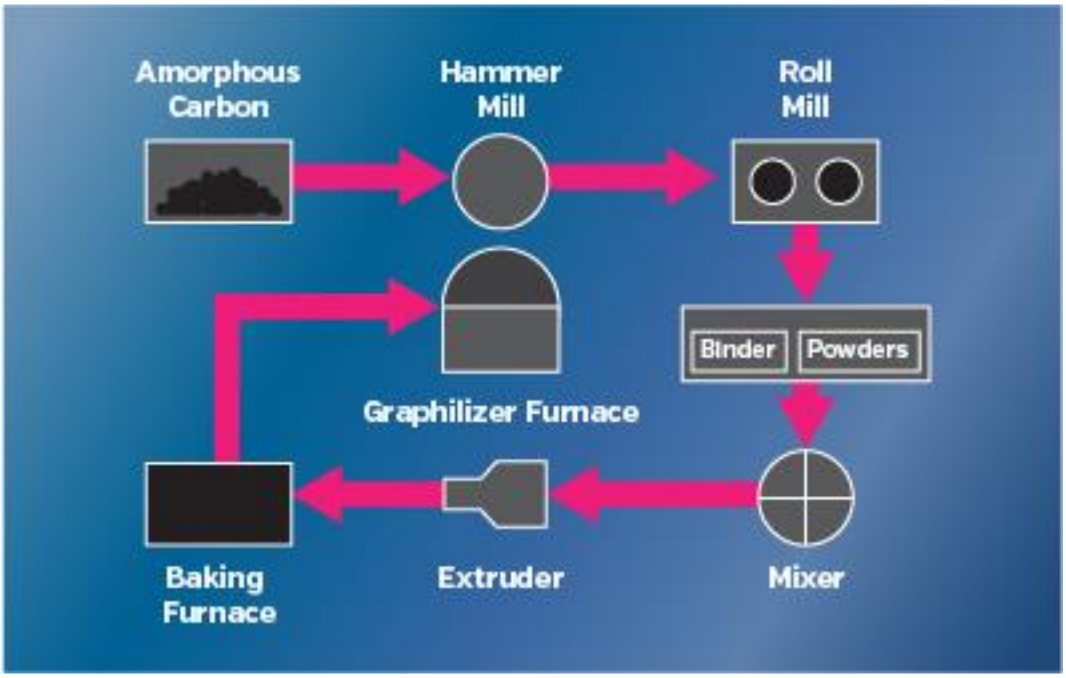


Fig. 3.1 Diagram of typical graphite production process [21].

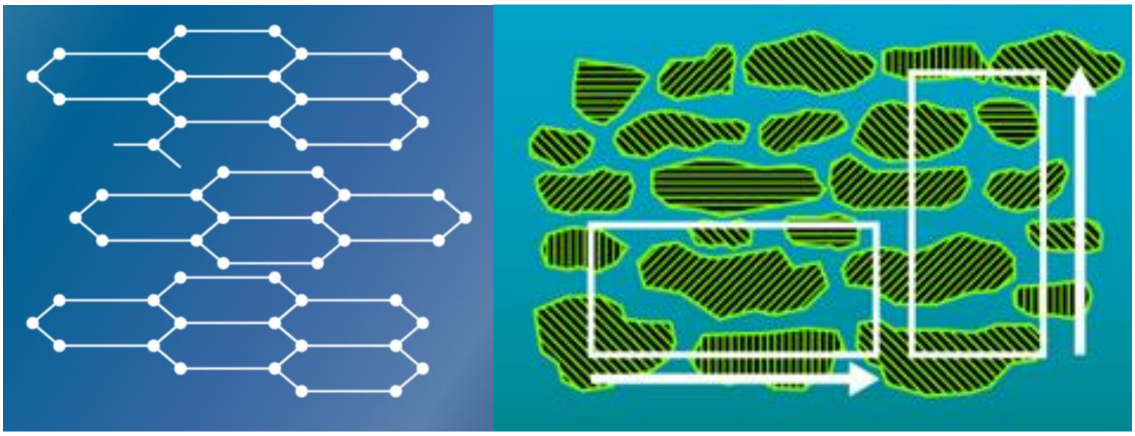
3.1 Graphite classification

Since all graphites seem to look alike, i tis important to understand the importance of the graphite properties and how these properties influence the EDM process.

Ordinary graphite structure

Graphite, as well as wood, has a particular grain orientation. This can be seen in Fig. 3.2. The crystal structure is formed in layers. These crystals form crystallites which form the particles or grain. Strength is greater "with the grain" than it is "across the grain". Also, electrical conductivity and other properties in graphite are usually greater with the grain than across the grain.

The planar structure of ordinary graphite is responsible for its lubricating qualities and differences in strength, electrical resistivity, and other qualities related to grain direction [38].



Obr. 3.2 The planar structure (left), Anisotropic structure (right) [21].

The particles may have a preferred orientation of crystallites within the individual particle, plus the billet may have a preferred orientation of particles within it. These particles may be large and irregular in shape and size, creating a non uniform structure. Unfortunately, the grain in graphite is not visible. Thus, the electrode fabricator cannot take advantage of working with the grain [12].

POCO graphite structure

The special steps in the production of POCO graphite practically eliminate differences between the orientation of grains (see Fig. 3.3). The particles are rounded and are all the same size. The pores are also small, usually less than 1 μm. The particles do not have a major because of its rounded shape. No orientation effects are possible (see Fig. 3.3), thus this kind of graphite does not have a preffered grain orientation and the material is isotropic. Properties such as strength and electrical resistivity are the same in all directions. The isotropic nature of the material means that the tool electrodes machined from any part or orientation of a billet or various billets offer the same performance characteristics [38].

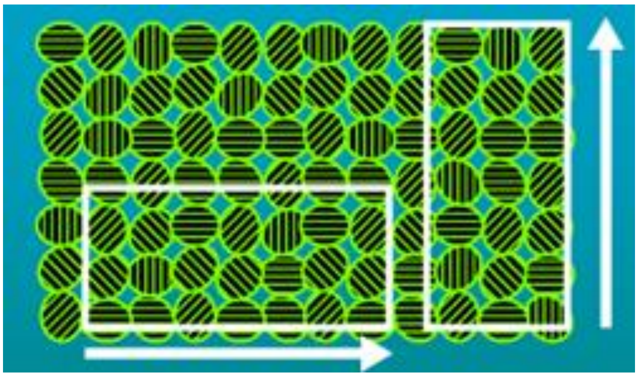


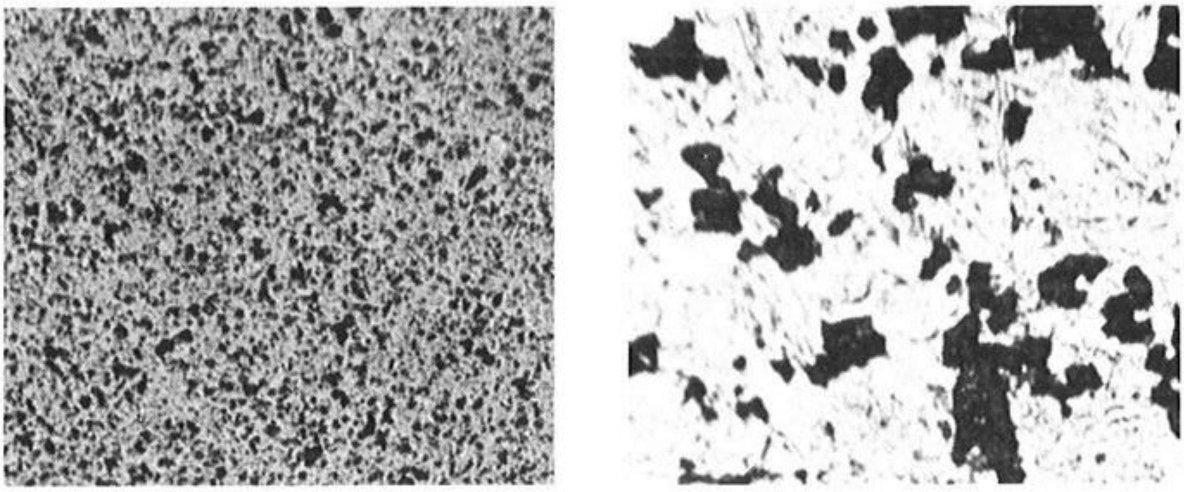
Fig. 3.3 Isotropic structure of POCO graphite [21].

3.2 EDM graphite classifications

EDM graphites are classified by the size of particles. Particle size is used because most of the other properties and characteristics of graphite are related directly or indirectly to particle size and orientation. EDM graphites fall into the following five classifications:

- Angstrofine has a typical particle size of less than 1 μm,
- Ultrafine has a typical particle size of 1-5 μm,
- Superfine has a typical particle size of 6-10 μm,
- Fine has a typical particle size of 11-20 μm,
- Medium graphites have particles that range in size from 21 až 100 μm.

Each manufacturer produces several grades within a given classification. It is important to realize that not all manufacturers make graphites that fall into all classifications. Premium graphites, those with a particle size of 5 microns or less, are difficult to produce [5].



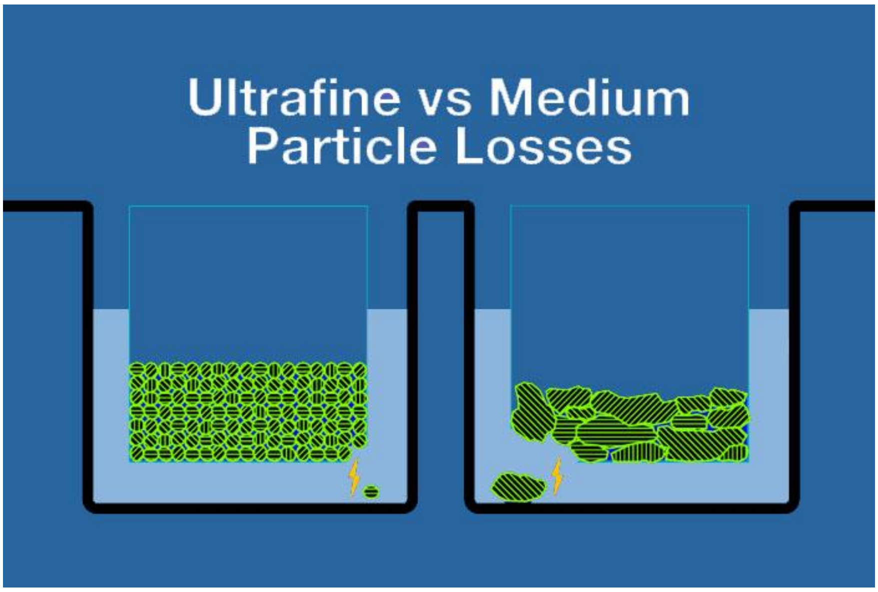
Obr. 3.4 Microstructure of two different grades of graphite [21].

Particle size

Particle size is one of the most important qualities of graphite. Angstrofine class graphites have particle sizes of less than 1 µm in diameter. Many commonly encountered EDM graphites have particle sizes much larger (see Fig. 3.4). The dark areas in the Fig. 3.4 represent the porosity, while the lighter areas represent the graphite particles that are bound together by chemical or mechanical means. The weakest part of any graphite system is the boundary between particles.

The nature of the EDM process causes particles from the tool electrode to be lost (see Fig 3.5). The material loss is more critical with large grain graphites. This effect manifests itself not only in increased wear, but also may contribute to DC arcing. The large particles tend to block the spark gap which could result in reduced cutting speed due to the instability of the cut. This is especially apparent under poor flushing conditions. Even advanced machines with automatic sensing could be slowed down considerably as they try to keep the gap clear.

Particle size also has a relevance the minimum surface roughness value that can be obtained. During finishing operations at low power and a high frequency, the electrode tend to reproduce its structure in the workpiece surface. A coarse grain graphite with large particles and pores will not produce a better finish than the surface of the electrode.



Obr. 3.5 Different particle size in EDM process [21].

Strength

Strenght is also related to particle size. The bonds between individual particles in the Angstrofine and Ultrafine graphites are much stronger than those of coarser classes. POCO graphites have the same strength in all directions due to their isotropic grain structure.

Flexural and compressive strength is important both in and out of the machine. Many electrodes are damaged or destroyed before they reach the machine through rough handling or accidents. Electrodes made of high-strength Angstrofine and Ultrafine graphit withstand much more rough handling without damage. High strength also means better wear resistence and it is mainly because the material with higher strength better resists the damaging effects of electrical discharge machining. In addition, it is possible to machine small free standing ribs and other fine details. Typical effects of low strength materials include chipping when machining of thin walls and fine details. The thin tool electrodes can be deflected by flushing if the material does not have sufficient fluxural strength.

Density

Most of the EDM graphites have an apparent density between 1.55 and 1.85 g / cm^3. When comparing individual materials, it is recommended to take into consideration the density and photomicrograph of the material. Graphites with very large particles and pores can have higher density than some of the best small particles and pore sized materials.

In general, the physical and mechanical properties (such as strength etc.) are improved with increasing graphite density. High density materials along with tightly packed small particles provide better wear and lower surface roughness than high density materials with loosely packed particles.

Hardness

Hardness of graphite depends on a coarse and density of graphite. Hardness can be changed by the graphitization temperature. Most EDM graphites fall within a Shore hardness range of 45 to 85. The most machinable graphites range from 55 to 75 on the Shore scale.

The hardness of the material is especially important in the production of tool electrodes. The harder the material, the more prone to chipping the material is. Hardness of graphite has almost no effect on the performance of EDM process.

Electrical resistivity (ER)

Material density affects electrical resistivity. Since the density of the graphite increases within a given classification of the materials, its electrical resistivity decreases.

The ER value does not affect the EDM machining process. Only exceptions are tool electrodes with thin ribs and rods. Thin ribs are susceptible to overheating if the ER is too high. The energy dissipate in the tool electrode causing it to ack as a heater.

3.3 Key factors in the tool electrode material selection

There is many opinions on how to choose the right tool electrode material for a particular type of work. Each application have different performance requirements which should be considered when selecting a suitable grade of quality. Job factors to be considered are the workpiece material, the shape, size and number of cavities to be cut, and the number of electrodes needed to rough and finish the job.

The basic performance factors to be looked for when choosing the material of the electrode are:

Metal removal rate (MRR)

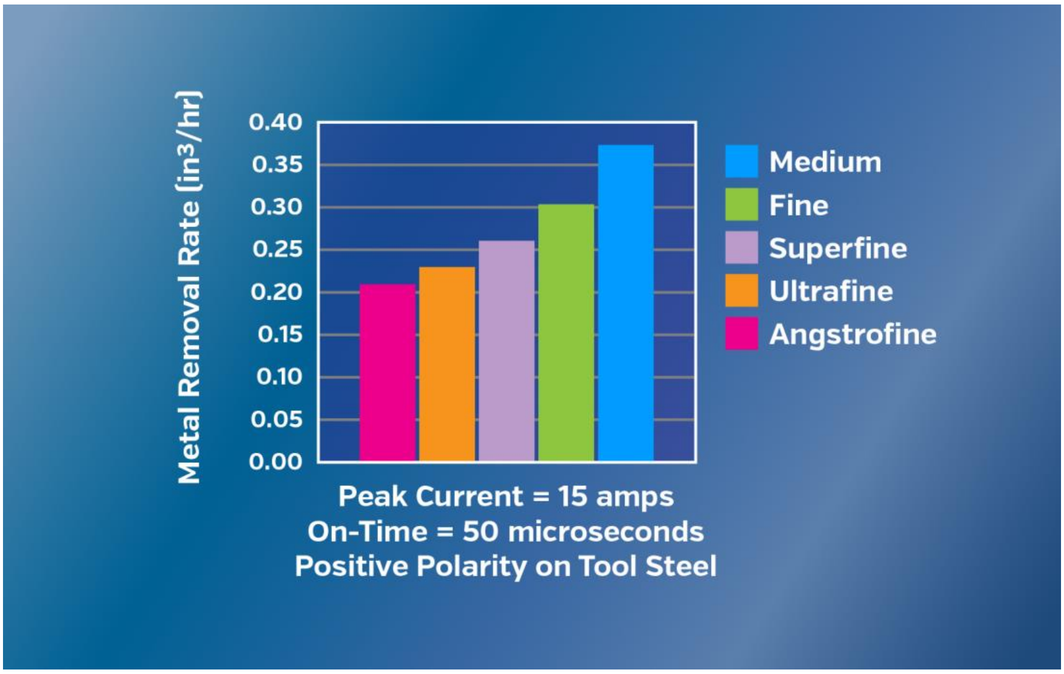
Achieving an efficient MRR is not simply a matter of the right machine settings. It also involves direct energy dissipated in the EDM process. This energy can be dissipated in the workpiece, the spark gap and the tool electrode.

MRR is influenced by the physical properties of the workpiece material. The melting point and the thermal conductivity of the workpiece material are very important properties to consider. Copper, as an example, has a low melting point, however the metal removal is generally low. This is due to copper‘s good thermal conductivity. Thus, the heat is dissipated too quickly, which interferes with efficient material removal. Tool steel, on the other hand, has a higher melting point, but is not a good thermal conductor and therefore has better material removal rates than copper.

The heat disipated in the spark gap is caused by particles of the tool electrode material which resutls in instability and slowdown of the cutting process.

The energy disipated in the tool electrode is the greatest loss and causes a tool electrode erosion. The cutting proces may seem to be running smoothly while the consumption of the tool electrode may be as high as the material removal. Tool electrode erosion cannot be completely eliminated, however it is possible to minimize the value by a correct selection of the machining settings and tool electrode/workpiece material combination.

Generally, when cutting in positive polarity, the larger the particle size of the graphite electrode the higher the MRR. Fig. 4.6 compares the material removal rates of five EDM classifications of graphite under one set of settings. It is also importat to take in consideration that as the number of detail increases, the particle size of the graphite needs to decrease.

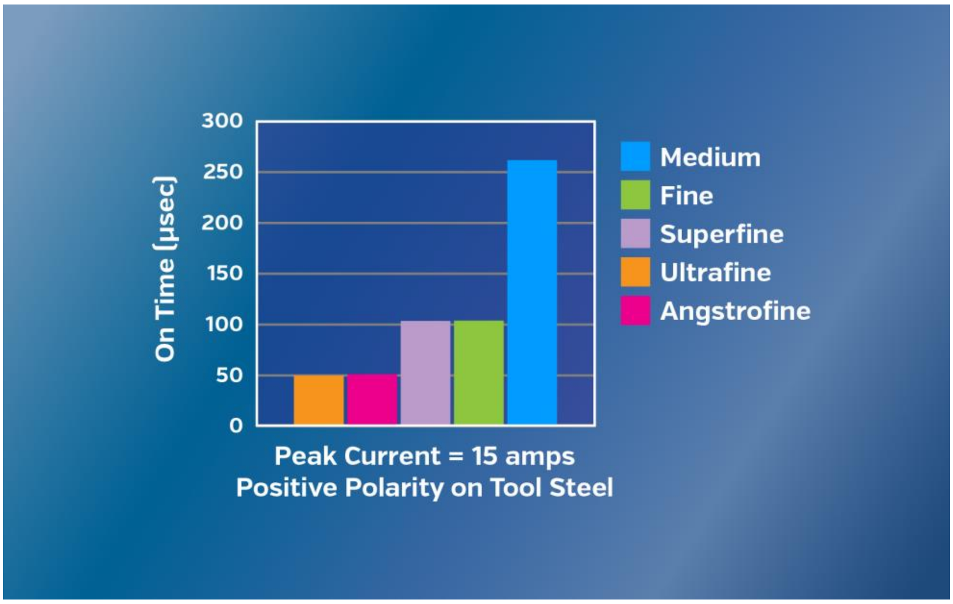


Obr. 4.6 MRR comparison of EDM graphites [21].

2. Wear resistence (WR)

There are four types of wear (volumetric, corner, end and side). Corner wear is the most important as it determines the accuracy of the final cut. The ability of a tool electrode to produce and reproduce detail is directly related to its resistance to wear and its machinability. The better a tool electrode can withstand the erosion at its most vulnerable areas (corners and sharp edges) the longer the lifespan of the electrode. The sharper the angle, the more sparks are generated in this area as well as heat. This causes faster wear in the corner areas of the tool electrode. Blunt corners will wear less than sharp angle corners. Corner wear can be minimized by choosing a small particle size tool electrode material that has high strength and high density.

It is possible to achieve so called "No-wear" machining which means that the tool electrode wear is 1 % or lower. No-wear settings do not produce the fastest material removal rates. It is possible to set no-wear conditions with graphite from any of the five classifications, however not all tool electrode/workpiece material combinations can be put in a no-wear condition. Parameters necessary for a no-wear condition with graphite tool electrodes are positive polarity and long on-times. The off-time is set as short as possible to maintain stable machining conditions. Fig. 4.7 shows the minimum on-time required to achieve a no-wear condition for each class of graphite.



Obr. 4.6 Minimum on-time required to achieve no-wear conditions for different classifications of graphite material [21].

3. Surface quality

Fine finish of the surface is obtained by a correct combination of a tool electrode material, good flushing conditions and settings of the generator (on-time, peak current). Imperfections in the surface of electrode are reproduced in the workpiece surface, thus i tis important to choose a suitable tool electrode production technology. Short on-times and low peak current settings produce the best finish, as these conditions produce smaller craters in the workpiece material.

The smaller the particle size of the tool electrode graphite, the better the final surface. However, it is important to keep in mind that no tool electrode material produce a fine surface finish until the flushing conditions and generator settings are met.

4. Machinability

Good machinability does not necessarily mean the best tool electrode material option. The tool electrode material should be strong enough to resist possible handling damages and must also withstand the spark erosion. Strength and small particle size are important to achieve minimum diameters and high accuracy of the process. Hardness of the material is an important factor when fabricating. The higher the hardness, the greater the propensity to chipping.

5. Material cost

The actual material cost generally represents only a small portion of the total EDM job cost and it is often overlooked that the cost of material should not be the only material selection feature. Fabrication time, tool electrode wear, and cutting time are closely connected with the tool electrode material and should all be weighed to determine the best electrode material and machining settings. That is why it is critical to understand the properties and characteristics of the graphite grades and how they perform with a workmetal to be machined. Only with this data it is possible to make a cost/performance analysis to determine the actual cost of an EDM job.

4 GRAPHITE CUTTING TECHNOLOGY

Graphite is standardly used tool electrode material in most EDM applications and it is mainly because its lower roughing cycle time and lower initial costs than copper tool electrodes.

Graphite has specific properties that make machining a challenge. It is high strength as well as fragile material and this results in a high probability of splitting during the fabrication process. Moreover, graphite is highly abrasive, which causes unusually high tool wear. In fact, the machinability is way better, in terms of spindle load, than steel machining. EDM-type graphite is much softer than steel, which allows for higher feed rates. The material changes to powder or dust when machining, therefore the machine must be provided with a special exhaustion dust collecting system. Graphite cutting suffers from following problems.

Tool wear

Since the graphite materials used for EDM work are very abrasive, tool wears out very quickly. While even standard HSS plate can handle the fabrication of graphite materials, it exhibits a high sign of wear which makes it difficult to maintain a high dimensional accuracy and good surface quality. Most of the graphite materials are now machined either with a carbide or diamond coated plate tools which shows way better resistance to abrasive effects of graphite.

Tool electrode geometry

Most of the EDM tool electrodes are complicated components with features that are not easily created by conventional tools and standard milling machines. In fact, a large number of these electrodes contain small, deep and fragile elements that are very difficult to create. Combination of both small and deep elements on the electrode geometry require using smaller cutting tools. The high feed rate, small diameter of cutting tool and difficult graphite machinability result in a very high spindle speed of the milling machine (20,000 to 40,000 RPM). Milling machines designed for machining of graphite materials differ in several key factors, from typical machining centers, including high speed spindle, dust collecting systems and more powerful CNC). Such a machine is shown in the Fig. 5.1.

Fig. 4.1 Fanuc TrodeMaster graphite machining center and its dust collecting system [17,18].

Dust collection system

The dust generated by the milling is also very abrasive. It is a danger to the machine and the production environment. If the graphite dust is not collected properly, it may pose a health risk to an operator and can also resuts in a damage of critical mechanical parts of the milling machine, such as spindle, covers and ball screws. The dust arising during the tool electrode production process is usually dense enough that there is no risk of a combustible dust explosion, thus the machine does not require to contain an explosion-proof collector system. Proper handling and disposal of graphite waste should be refered by individual suppliers.

Humidity:

Graphite is a porous material that absorbs moisture. This causes problems during the EDM process. If the moisture is not removed from the material before the EDM proces itself, a tool electrode may overheat and expand during the machining process, which may lead to the breakage of the tool electrode. Removal of moisture can be achieved by drying of graphite in furnaces.

4.1 High speed cutting of graphite

Milling machines specially intended for the production of graphite tool electrodes are designed with several key differences. These include:

- **higher spindle speed** (higher spindle speeds are needed due to the use of high feeds and small diameter cutters),
- **dust collection system** (it is important to control and collect graphite dust produced during the milling process, all graphite milling machines are completely enclosed, and many machines offer high capacity dust filtering and dust collector systems that evacuate graphite dust from the workspace area and collect it in a dust collector),
- **special covers and seals** (majority of graphite milling machines is designed with additional seals and special covers that prevent graphite dust from escaping the working area),
- **CNC performance** (graphite milling centers need control systems that are powerful enough to handle a large amount of data which is characteristic for highly complex programs),
- **high dynamic stiffness** (some of the graphite milling machines can perform both, the machining of graphite and maching of steel and can be changed from one to another relatively quickly. This increases flexibility).

Productivity of finishing is very high. Finishing achieves very good surface quality (up to Ra = 0.2 μm) and it is also very accurate.

The radial forces, acting on the tool and spindle, decrease due to the shallow cuts that are characteristic in high-speed machining and this positively affects a service life of the spindle. Machining is combined with axial milling due to low bearing loads and the possibility of using longer tools with lower risk of vibration [2,6].

Spindle speed ranges in the range of 10,000 to 30,000 per minute. The high speed spindle is designed to ensure the maximum accuracy, high temperature stability and long service life. See Fig. 4.2, an example of such a spindle.

Graphite dust collection system consists of a powerful suction device with a filter. The dust is collected in a collector tank and the filtered air is returned to the workshop area. Moreover, the clean air is used to create overpressure in the area of ball screws, linear rolling lines and motors due to a telescopic coverage so that these components are effectively protected from the penetration of abrasive graphite into these areas and possible damage.

Increased feed and rapid traverse rates contribute to reduction of the secondary machining times. On the other hand, the control system speed of a HSC machine can significantly affect the main machining times (a powerful control system can lead to a reduction of the main working time). The control system provides permanent calculation of coordinates with up to 80 program sentences ahead. Using the "acceleration before interpolation" motion algorithm, the control system allows the use of the feed rate up to 21 $m \cdot min^{-1}$ for a track interpolation of complex shapes without the risk of crossing contour shapes. This leads to shortening of the cycle times while increasing the dimensional accuracy and surface quality.

By implementation of high-speed machining, the production costs is reduced while the work productivity is increased. Both, in finishing and roughing operations of graphite materials and hard steels. Moreover, a low cutting tool temperature and short times of the tool in a cut result in an increased tool service life.

Obr. 4.2 High-speed spindle in a cutting process [8,10].

4.2 EDM tool electrode clamping systems

Each company has its own way of attaching a tool electrode to the holder and then into the machine itself. There are many ways of technical attachment and clamping systems. The most suitable and powerful systems are those where it is possible to remove the tool electrode from the holder and repeatedly return it back to the holder while maintaining the same position.

These clamping interfaces between machine and workpiece help to increase productive time on machines substantially. Set-up times are eliminated, because the palletized workpiece is moved from machine to machine very quickly and with top precision and stability. All these are improving the productivity and the rentabiltity of the production equipment. List of such systems offered in the Czech republic are described below.

3R Macro Junior (Fig. 4.3)

This type of a holders are among the less expensive holders and are used for clamping of small electrodes. It is a system that increases flexibility and profitability. The tool electrode holder is attached to the body of the electrode by a portative pin and a desired shape of the tool electrode is machined afterwards. The clamping force is 5000 N and the repeatable clamping accuracy is 2 μm [24].

Fig. 4.3 3R Macro Junior clamping systém [8,22].

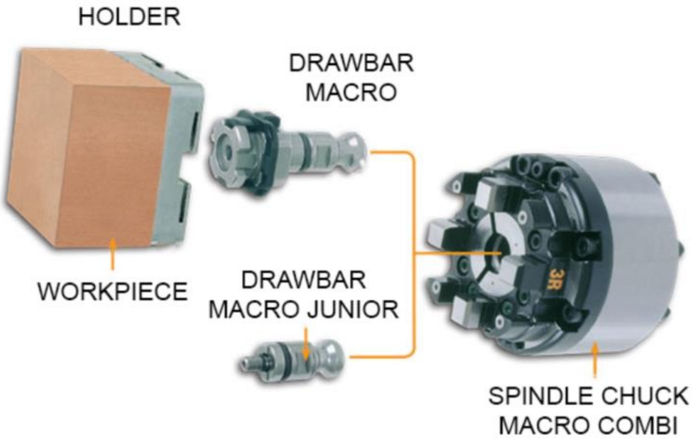
3R Macro (Fig. 4.4)

The principle of the system is based on production of precise threaded holes with precise coordinates in the upper clamping surface of the tool electrode. By inserting the electrode on the expansion pins on the holder and pulling the screw or bolts, the repeatable clamping capability is achieved in the same position. The clamping force is 6000 N, reccommended max. worpiece weight is 50 kg and the repeatable clamping accuracy is 2 μm [7].

Fig. 4.4 3R Macro system (left), 3R Macro clamping kit from GF Machining solution (right) [24,26].

3R MacroCombi (Fig. 4.5)

The MacroCombi system offers extreme flexibility both in electrode production and in die-sinking EDM. Small and large electrodes can be clamped in the same chuck without any adapter elements. The MacroCombi chucks accept two completely different types of electrode holder. Both Macro with its immovable stability and precision, and MacroJunior with its highly economical holders. The clamping force is 5000 N and the repeatable clamping accuracy is 2 μm [25].



Obr. 4.5 3R MacroCombi systém [25,26].

Mounting system Hirschmann (Fig. 5.6)

The Hirschmann system is a versatile device used for clamping tool electrodes. It is suitable for EDM machines, HSC milling machines, lathes, drills, grinders, measuring machines etc. The system can be either operated manually or for automatically via an exchanger or a robotic workstation. The clamping of the individual brackets with the machine is done through a hardened centering prismatic tool. The centering is automatic. The repeatable clamping accuracy is 0.002 mm When rotation of the electrode holder in the prism lined by 4 x 90 °, the axial position can be deflected by a maximum of 4 μm. It must be taken into account that offset errors can be added when using, for example, a collet holder. The error of the bracket and the collet is added here. [35].

Obr. 4.6 User kit, Systém 3R Macro from GF Machining solution [28].

Clamping journals (Fig. 4.6)

Very inexpensive solution for mounting of electrode and workpiece blanks. The components are screwed directly to the tool electrode body, pallet or workpiece using threaded and drilled holes. Clamping journals can be used for both manual and automatic type of loading of electrodes and workpieces. Magazine forks allow the use of journals from other manufacturers as well. It can also be fitted to "Pick-up" magazines as well as linear and disc tool changer [11].

Fig. 4.6 Clamping journals [11].

Minifix, Minifix Plus mounting system (Fig. 4.7)

Suitable for precision clamping of small copper electrodes up to 30 mm in diameter and up to 40 mm in diameter for graphite electrodes. The high precision of the mounting is secured by a centering prism. Tool electrodes can be secured to the pallets and holders via screws, clamps, glue etc.

MINIFIX copper electrode blanks and aluminium pallets are equipped with pre-milled centering prism slots and mounting holes. The slots in the blanks or pallets are first „coined“ by griping them in the milling adapter assuring a high degree of repeatability. They are than put in a holder and ready for machining.

MINIFIXplus copper electrode blanks are equipped with a slot allowing for automatic changing in machines with magazine fork type linear or disk tool changers. Minifixplus blanks can be automatically or manuály exchanged in an EDM machine equipped with clampers with or without P-Holders [12].

Fig. 4.7 MINIFIX clampers and holders (left), holder in a disc type magazine (right) [32].

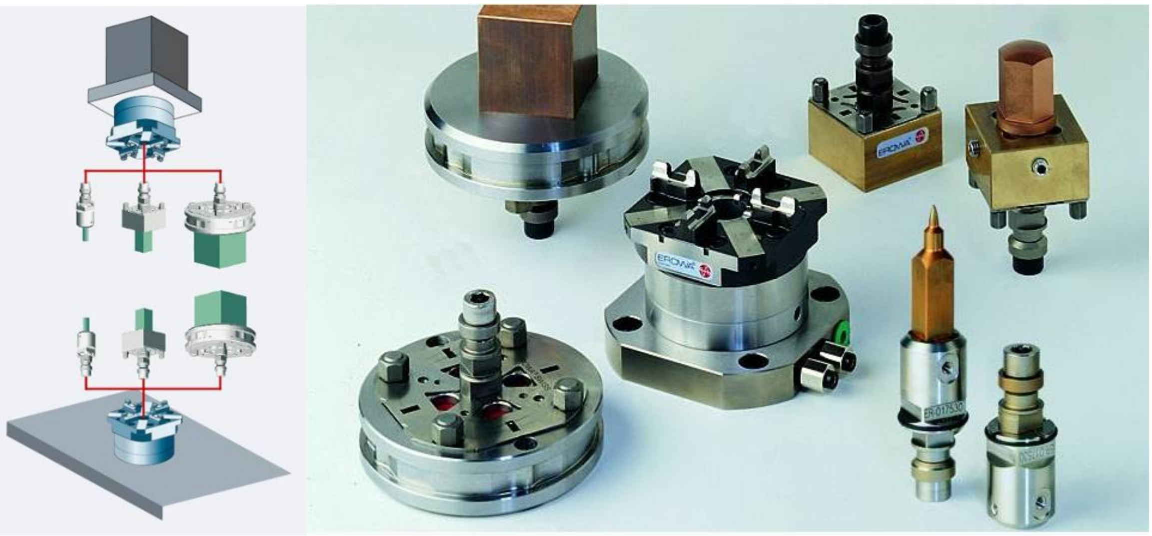
EROWA mounting systems [14]

Mounting system EROWA is an universal clamping device for electrodes. It can be used on EDM, HSC milling machines, lathes, drills, grinders, measuring machines etc.

EROWA’S chuck operates with guaranteed 2 µm accuracy. It holds both tools and workpieces with equal precision and with a high degree of repeatability. Its applications are so numerous that it forms the basis for a well thought-out modular.

After a rough precentering proces, the reference position is reached when the centering plate is fixed. Together with the contact points, this flexing action creates the stability of the frictional connection. This i show positioning accuracy is created between the flexible centeering plate and the rigid centering prisms.

The clamping mechanism with the self-locking ball lock generates a clamping power of up to 7,000 N and does not inlock even if the pressure fails [35].



Obr. 4.8 Clamping system EROWA (left), selection of EROWA chucks and holders (right) [29].

5 GRAPHITE ASSESSMENT FROM INDIVIDUAL SUPPLIERS

As mentioned before, the type and quality of graphite material significantly influences the result of the entire EDM machining proces. Thus, it is important to pay very close attention to the choice of a supplier of graphite materials. Distributors of graphite materials on the Czech and Slovak market are specified below.

Penta Trading s.r.o. [31]

Penta Trading is a representative of SGL Carbon for the Czech Republic and Slovakia. Graphite can be ordered not only in blocks, but also in cutout blanks in sizes according to a customer's request. The company offers the express delivery within 24 hours. The company also offers a tool electrode machining services based on the 3D model data and trainings which cover the whole unconventional technology of EDM, from the tool electrode production to die sinking process itself.

The company offers 6 grades of graphite quality:

- **R8340** – roughing grade (max. finish **33 VDI / Ra 4,5**),
- **R8500** – universal grade (max. finish **27 VDI / Ra 2,24**),
- **R8510** – universal grade, R8500 successor, it has a higher density, higher flexural strength and better machinability (max. finish **24 VDI / Ra 1,6**),
- **R8650** – fine grade, suitable for milling of complexly shaped electrodes and ribs (max. finish **21 VDI / Ra 1,12**),
- **R8710** – ultra-fine grade, suitable for milling of complexly shaped electrodes and ribs (max. finish **12 VDI / Ra 0,4**).
- **R8650cu** a **R8710cu** – special types of graphite mixed with copper, shows very low tool electrode wear in sharp edges and radiuses.

The Fig. 5.1 shows a surface micrograph of each graphite grade. Complete specifications of the graphite classes can be found in the appendix section.

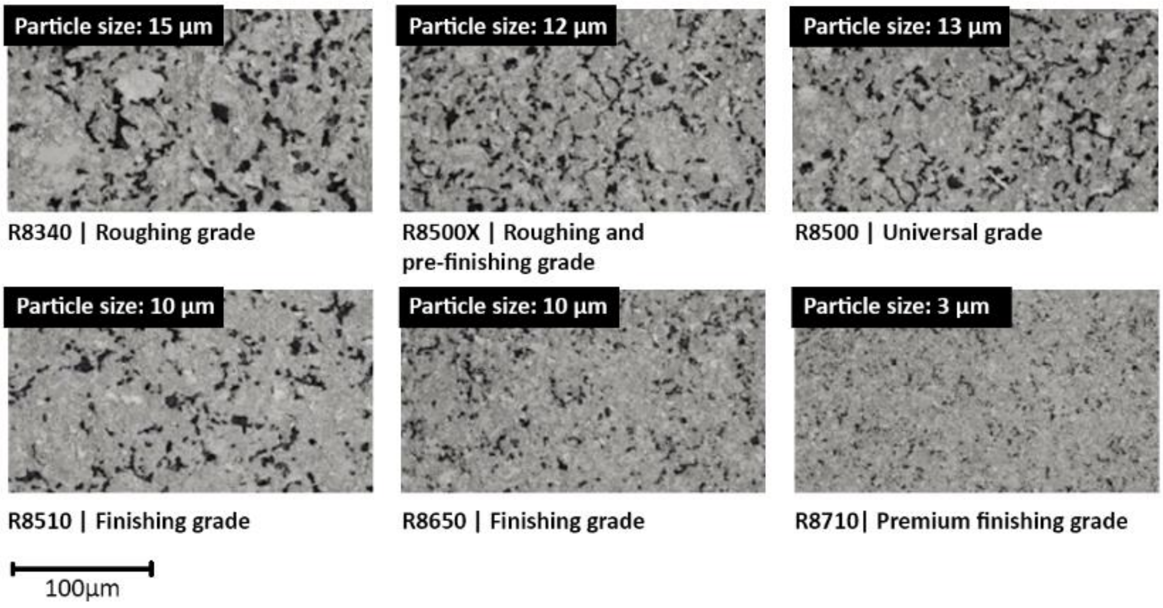


Fig. 5.1 Micrographs of electrode graphites offered by Penta Trading s.r.o. [31].

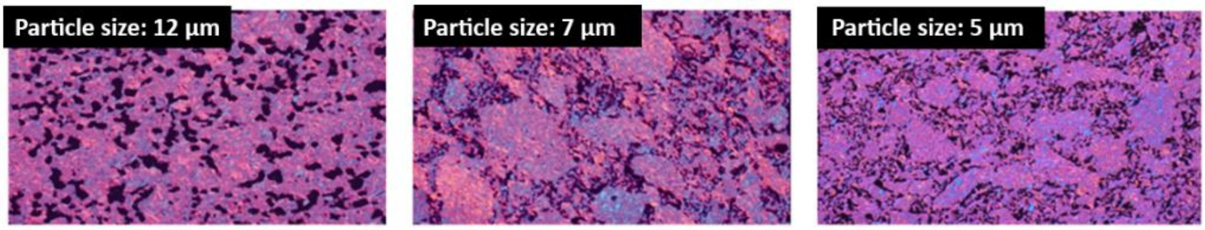
Interspark Praha s.r.o. [38]

Interspark Praha s.r.o. is focused on all consumables connected with EDM and WEDM technology. The company offers graphite materials produced by the German company CP GRAPHITPRODUTE GMBH. It is possible to order graphite blocks, cutout blanks, bars and foils.

The company offers 6 grades of graphite quality:

- **CP-1000** – roughing grade (max. finish **30 VDI / Ra 3,15**),
- **CP-1100** – universal grade (max. finish **24 VD I/ Ra 1,6**),
- **CP-1250** – universal grade (max. finish **18 VDI / Ra 0,8**),
- **CP-1300** – fine grade (max. finish **15 VDI / Ra 0,56**),
- **CP-1400** – fine grade (max. finish **15 VDI / Ra 0,56**),
- **CP-1500** – superfine grade (max. finish **12 VDI / Ra 0,4**).

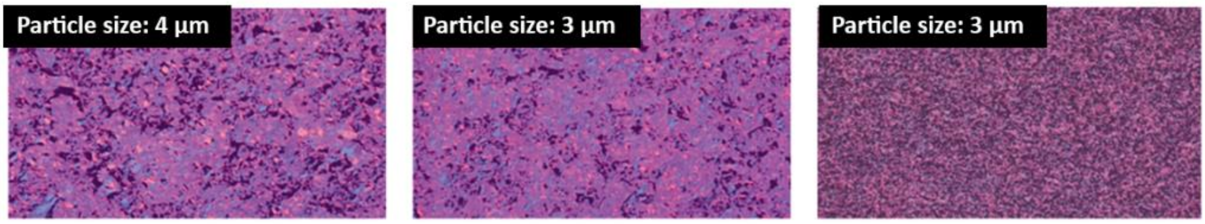
The Fig. 5.2 shows a surface micrograph of each graphite grade. Complete specifications of the graphite classes can be found in the appendix section.



CP-1000 | Roughing grade

CP-1100 | Universal grade

CP-1250 | Universal grade



CP-1300 | Ultrafine finishing grade

CP-1400 | Premium vFinishing grade

HK-2| Premium finishing grade

Fig. 5.2 Micrographs of electrode graphites offered by Interspark Praha s.r.o. [38].

Pfingstner s.r.o. [33]

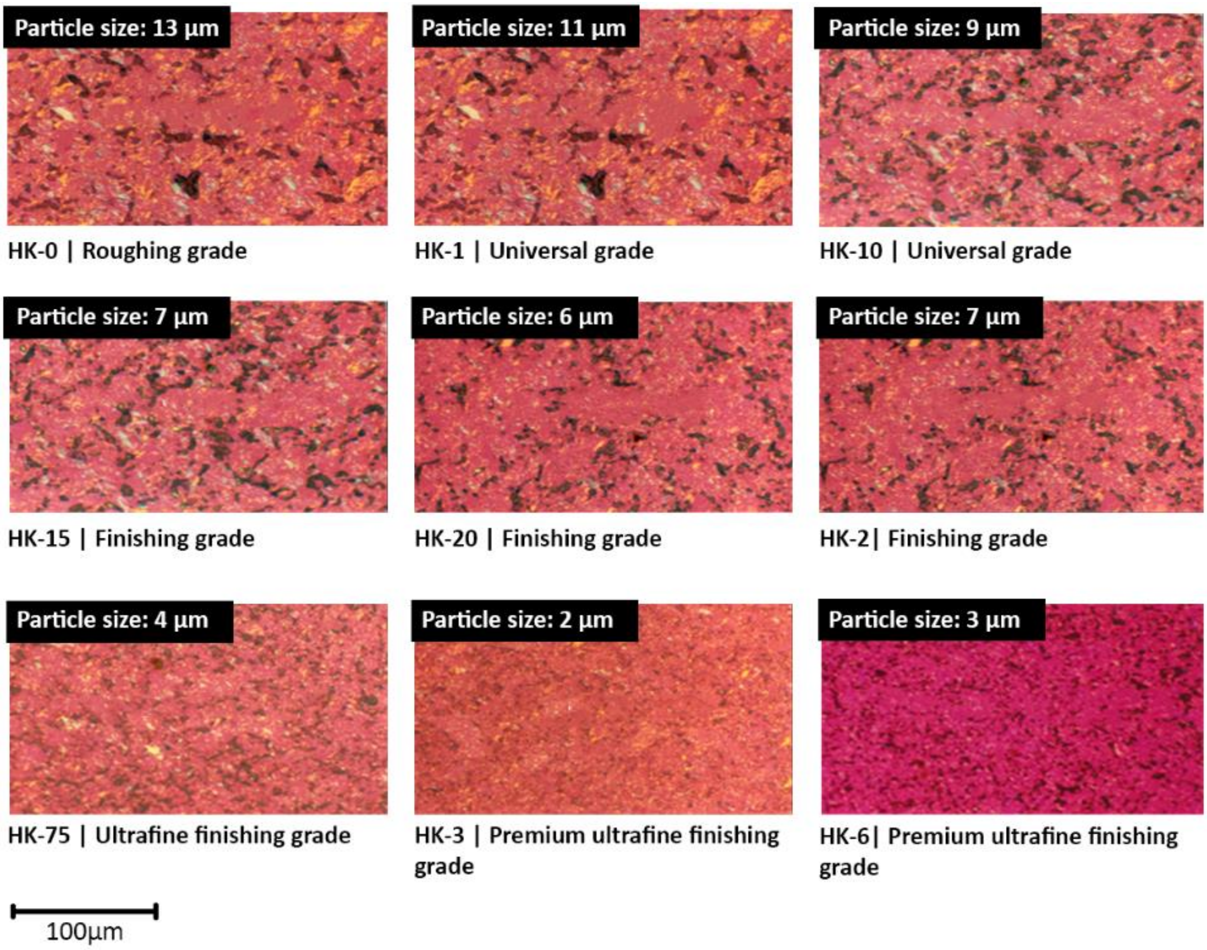
Pfingstner s.r.o. is focused on selling all consumables connected EDM and WEDM technology. The company offers graphite material from one of the world's largest graphite manufacturers, Japanese company Tocai Carbon Ltd and is its exclusive representative in the Czech Republic. In addition, it is possible to purchase whole blocks of circular and square profiles as well as cutouts of specific dimensions. Additionally, the company offers free technical support, consultations and trainings.

The company offers 9 grades of graphite quality:

- **HK-0** – roughing (max. finish **33 VDI / Ra 4,5**),
- **HK-1** – roughing + finishing (max. finish **30 VDI / Ra 3,15**),
- **HK-10** – roughing of large surf. areas (max. finish **30 VDI / Ra 3,15**),

- **HK-15** – roughing; good accuracy and finish (max. finish **27 VDI / Ra 2,24**),
- **HK-20** – finishing; high density, low resistancematerial for low wear and high speed EDM (max. finish **24 VD I/ Ra 1,6**),
- **HK-2** – finishing; low wear high definition and good surf. quality (max. finish **21 VDI / Ra 1,12**),
- **HK-75** – ultra-fine grade of graphite material; high surf. finishes and good edge wear resistance (max. finish **21 VDI / Ra 1,12**),
- **HK-3, HK-6** – premium grade of ultra-fine graphite; good MRR rate and excellent edge wear resistance (max. finish **15 VDI / Ra 0,4**),

The Fig. 5.3 shows a surface micrograph of each graphite grade. Complete specifications of the graphite classes can be found in the appendix section.



HK-0 | Roughing grade

HK-1 | Universal grade

HK-10 | Universal grade

HK-15 | Finishing grade

HK-20 | Finishing grade

HK-2| Finishing grade

HK-75 | Ultrafine finishing grade

HK-3 | Premium ultrafine finishing grade

HK-6| Premium ultrafine finishing grade

Fig. 5.3 Micrographs of electrode graphites offered by Pfingstner s.r.o. [37].

Tedok spol s.r.o. [34,35,36]

Tedok spol s.r.o. focuses on a distribution of EDM grapfite materials. The company is the only official dealer of POCO graphite materials in the Czech republic and Slovakia. The material can be odered in blocks as well as cutouts of specific dimensions, foils and plates. The company, the same as its competition, offers professional training, fine-tuning of EDM machines and technical support.

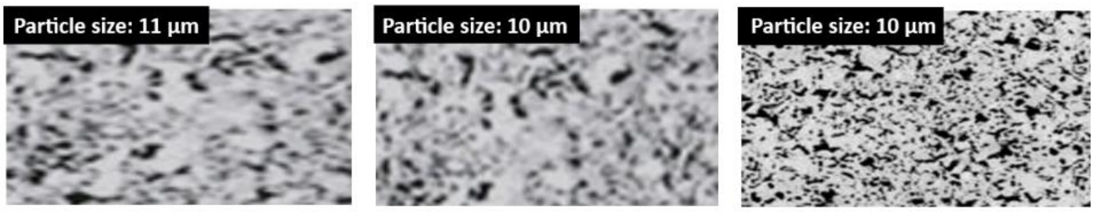
POCO EDM graphite materials are generally considered to be the world‘s industry leader in the graphite material production field. The poco structure of graphite is specially developed for EDM tool electrode production.

Each quality class of POCO graphite is customized to a specific range of applications with given performance characteristics. This guarantees the best balance between the material removal rate (machining time), tool electrode wear and surface quality while maintaining high efficiency.

The company offers 9 grades of graphite quality:

• **EDM-160**	fine grade,
• **EDM-180**	superfine grade,
• **EDM-200**	
• **EDM-1**	ultra-fine grade,
• **EDM-3**	
• **EDM-4**	
• **EDM-C3**	copper superfine grade,
• **EDM-C200**	
• **EDM-AF5**	angstrofine grade.

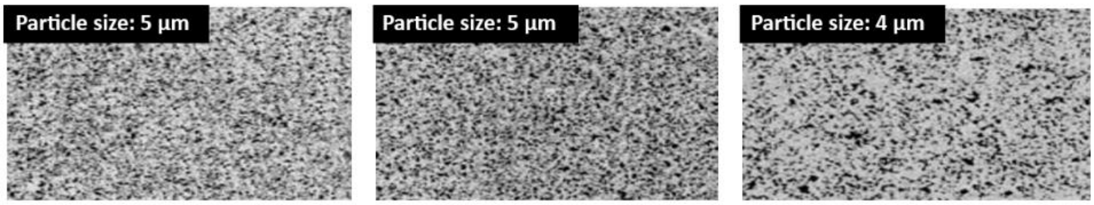
The Fib 5.4 shows a surface micrograph of each graphite grade. Complete specifications of the graphite classes can be found in the appendix section.



EDM-160 | Roughing grade

EDM-180 | Universal grade

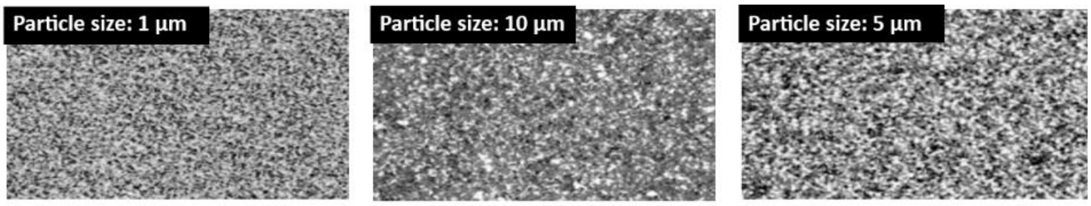
EDM-200 | Universal grade



EDM-1 | Finishing grade

EDM-3 | Finishing grade

EDM-4| Finishing grade



EDM-AF5 | Premium finishing grade

EDM-C200 | Copper infiltered finishing grade

EDM-C3| Copper infiltered finishing grade

100µm

Fig. 5.4 Micrographs of electrode graphites offered by Tedok spol s.r.o. [36].

5.1 Price comparison of currently used EDM graphite materials

Current supplier of graphite materials in Gamartis Trade s.r.o. is the company Tedok spol s.r.o. Thus, the following materials were used in an experiment (described in Chapter 7). These are commonly used graphite materials in injection molds manufacturing.

- EDM-160,
- EDM-180,
- EDM-200,
- EDM-1.

The tables 5.2, 5.3, 5.4, 5.5 compare individual tool electrode graphites from other suppliers, with their properties matched as closest to the above mentioned quality classes which were used for the experiment. The comparisons of these materials were made according to the properties of each material (such as grain size, density, hardness, elect. resistivity, compres. strength etc.).

Tab. 5.2 Price comparison of FINE grade graphites from other suppliers matched to EDM-160 POCO graphite.

SUPPLIER	TEDOK spol. s.r.o.	PFINGSTNER s.r.o.	INTERSPARK s.r.o.	PENTA s.r.o.
MAT. MARKING	EDM-160	HK-1	CP-1000	R8500
PRICE [Kč/dm^3]	965	890	880	750

Tab. 5.3 Price comparison of SUPER-FINE grade graphites from other suppliers matched to EDM-180 POCO gragphite.

SUPPLIER	TEDOK spol. s.r.o.	PFINGSTNER s.r.o.	INTERSPARK s.r.o.	PENTA s.r.o.
MAT. MARKING	EDM-180	HK-1	CP-1000	R8500
PRICE [Kč/dm^3]	965	890	880	750

Tab. 5.4 Price comparison of SUPER-FINE grade graphites from other suppliers matched to EDM-200 POCO graphite.

SUPPLIER	TEDOK spol. s.r.o.	PFINGSTNER s.r.o.	INTERSPARK s.r.o.	PENTA s.r.o.
MAT. MARKING	EDM-200	HK-2	CP-1100	R8510
PRICE [Kč/dm^3]	1550	1030	950	990

Tab. 5.5 Price comparison of ULTRA-FINE grade graphites from other suppliers matched to EDM-1 POCO graphite.

SUPPLIER	TEDOK spol. s.r.o.	PFINGSTNER s.r.o.	INTERSPARK s.r.o.	PENTA s.r.o.
MAT. MARKING	EDM-1	HK-75	CP-1250	R8650
PRICE [Kč/dm^3]	2900	1280	1440	1345

6 RISKS AND POSSIBILITIES OF INDIVIDUAL TECHNOLOGICAL SOLUTION

Graphite is the predominantly used tool electrode material in unconventional technology of EDM, where at least 75 percent of electrodes in the Europe are produced from this material. Asia follows with estimations of 45 percent and the United States with almost 95 percent (see Fig. 6.1).

However, what is too often overlooked is that tool electrode material considered outside the job cannot be taken as the only parameter when selecting a material. Transition to a new supplier could be linked to following risks, however could also bring new opportunities.

Risks:

- it would be necessary to test new EDMing parameters for each quality grade in order to be to be entirely sure of achievable VDI structure, these parameters can be differenet even though the particle size could look alike to another graphite from a different supplier,
- extra cost associated with material behaviour research in the EDM process,
- unknown wear of the tool electrode, which could result in a possible time increasement of the whole EDM process.

Possibilities:

- lower particle size of graphite material ought to result in better surface finish,
- great opportunity to establish a new partnership with another supplier, long term suppliers tend to offer way better prices,
- lower grain sized material, used for finishing operations, are able to perform much better surface roughness/graining patterns; great utilization in the automotive industy, therefore a big advantage for GAMARTIS TRADE as it is its main targeted industry,
- parameter research for new graphite materials may show that roughing could be eleiminated, which would result in machining time savings, thus lower EDM proces cost.

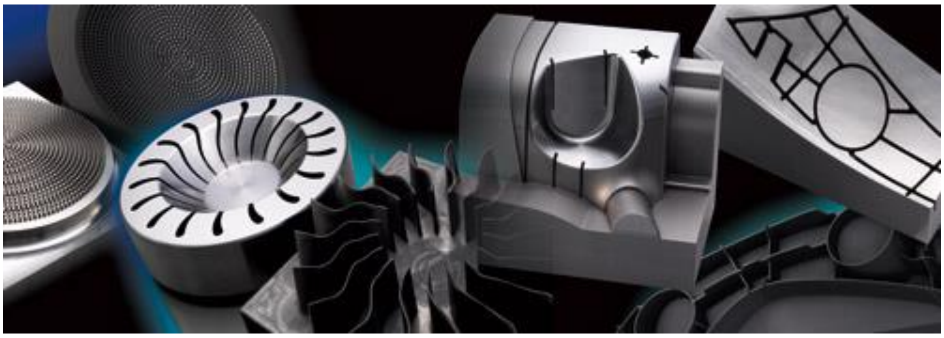


Fig. 6.1 High precision graphite electrodes and EDMed cavities [41].

7 EXPERIMENTAL METHOLOGY

Four different quality grades of graphite and one copper material from a current supplier in GAMARTIS TRADE s.r.o. tool shop are put thru an experiment to find out how much the quality of electrode material impact the EDM proces. Factors being tested are the cavity accuracy, wear of the tool electrode, machining time, surface roughness etc. Subchapters below specifically describes each step of the experiment.

The methology of the experiment is shown in the Fig. 7.1.

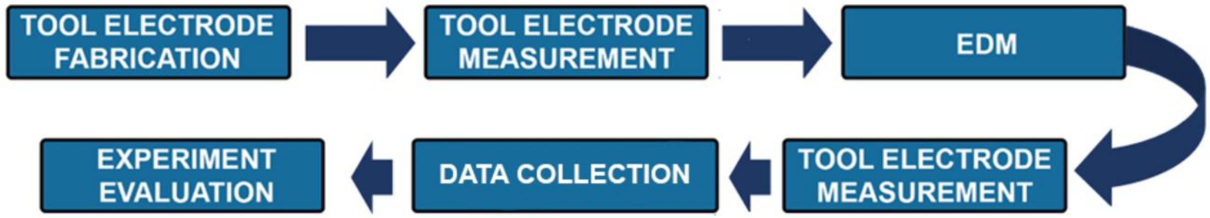


Fig. 7.1 Experimental procedure.

The following quality grades of POCO graphite, shown in the Tab 7.1, are tested in the experiment below. Moreover, a copper material was added to the experiment and compared with graphite electrodes. Tested graphite materials and their specific properties are presented in the Tab 7.1.

Tab. 7.1 Graphite materials used for the experiment.

Quality Class	**Particle Size** [μm]	**Flux. Strength** [kg·cm^{-2}]	**Compress. Strength** [kg·cm^{-2}]	**Hardness** [Shore]	**El. Resistivity** [μ·Ω·m]
EDM-160	11	550	1020	68	14,5
EDM-180	10	590	1060	66	13,0
EDM-200	10	635	1075	68	14,7
EDM-1	5	682	998	69	19,3

7.1 Tool electrode preparation

First, the data is processed in the designing department, where a designer models the shape of the cavity. The CAD part of an experimental workpiece designed using the software PTC Creo is shown in the Fig 7.1 on the next page.

Consequently, the CAD data is converted into the CAM. Electrodes are created at such workpiece locations as a negative shape to the shape of the cavity. The shape of the cavity is going to be created by using 3 different electrodes. These are shown in the Fig. 7.2, next page. Specifically, there are going to be used square shaped electrodes, rib shaped electrodes and spherical shaped electrode.

A sample of such CAM process for an extracted electrode created using software Rhinoceros 5.0 is shown in the Fig. 7.3. This proces of creating electrodes is repeated for each shape of the cavity.

Powermill 2017 software was used for creating programs (text files) in such a way that the Fagor software system, used on the Graphite mill CT-600, is able to read, decode it. An example of such program is shown in the Fig. 8.4 on the next page. All program lists can be found in the attachment section.

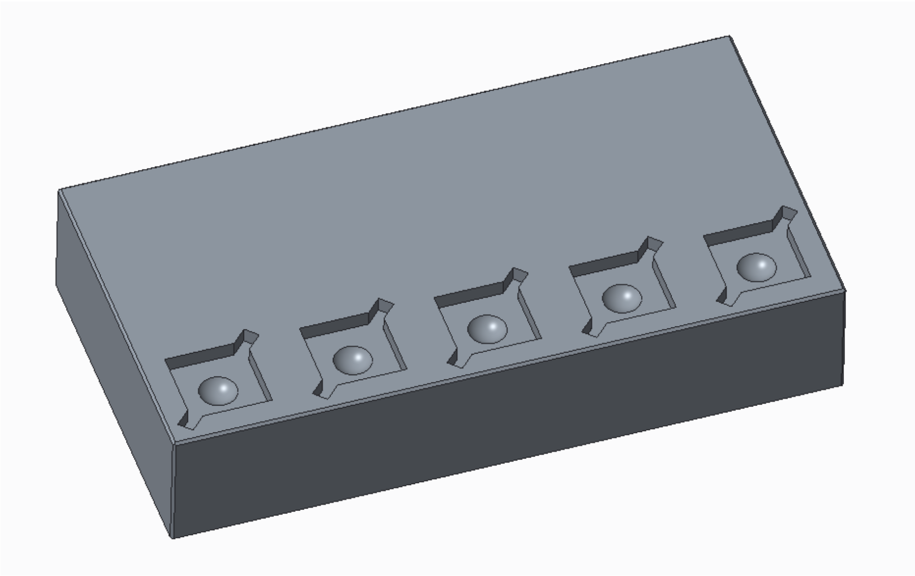


Fig. 7.1 Workpiece 3D part of cavities.

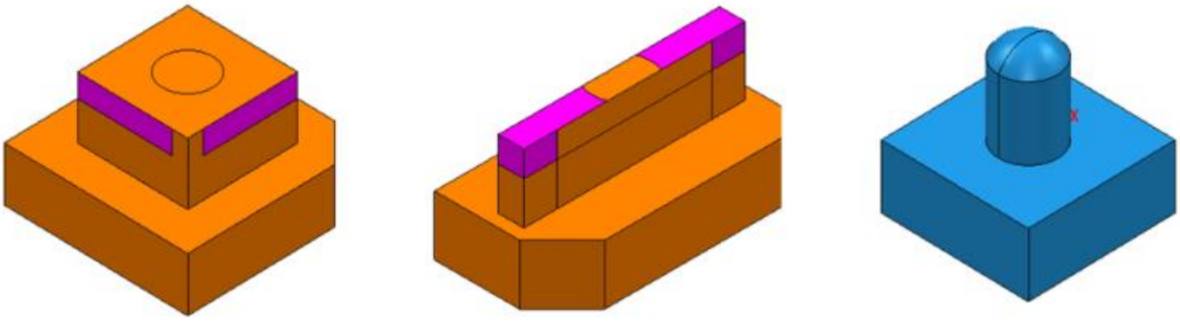


Fig. 7.2 Three different shapes of the electrode used for maching the shape of the cavity.

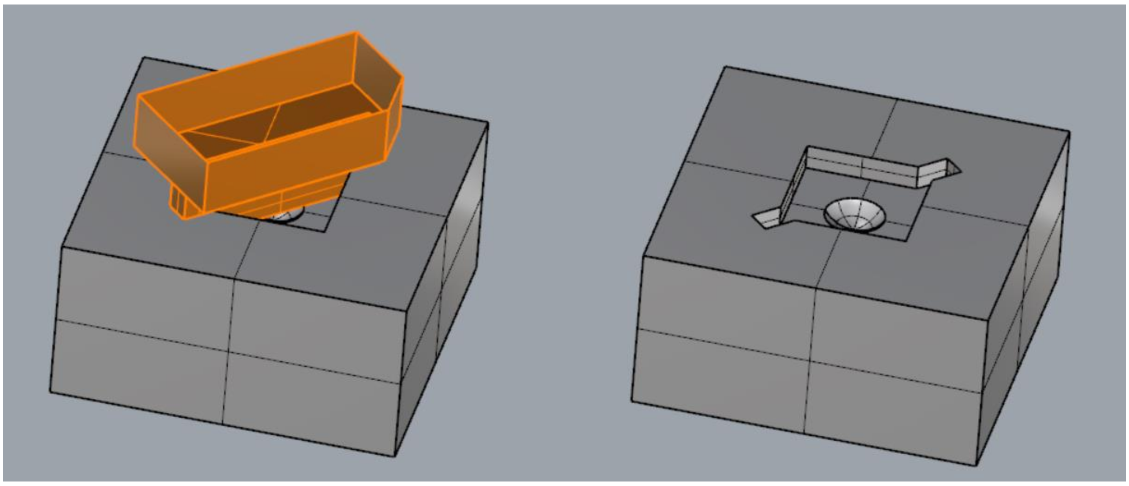
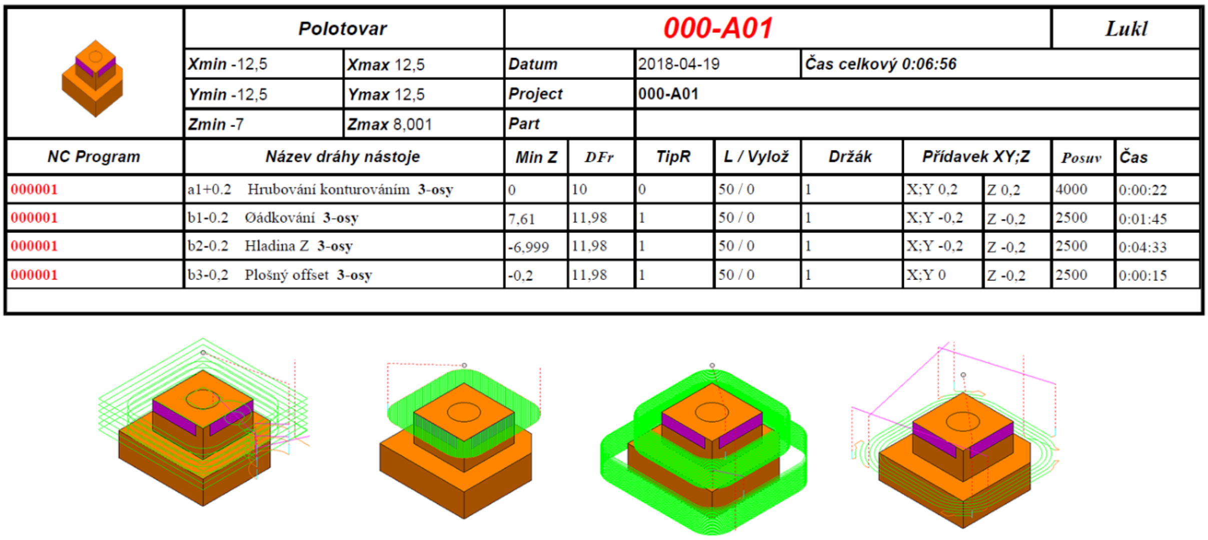


Fig. 7.3 Extraction of an electrode from a model of the cavity by using Rhinocerros 5.0.



	Polotovar		**000-A01**		**Lukl**
	Xmin -12,5	**Xmax** 12,5	**Datum**	2018-04-19	**Čas celkový 0:06:56**
	Ymin -12,5	**Ymax** 12,5	**Project**	**000-A01**	
	Zmin -7	**Zmax** 8,001	**Part**		

NC Program	Název dráhy nástoje	Min Z	DFr	TipR	L / Vylož	Držák	Přídavek XY;Z		Posuv	Čas
000001	a1+0.2 Hrubování konturováním **3-osy**	0	10	0	50 / 0	1	X;Y 0,2	Z 0,2	4000	0:00:22
000001	b1-0.2 Øádkování **3-osy**	7,61	11,98	1	50 / 0	1	X;Y -0,2	Z -0,2	2500	0:01:45
000001	b2-0.2 Hladina Z **3-osy**	-6,999	11,98	1	50 / 0	1	X;Y -0,2	Z -0,2	2500	0:04:33
000001	b3-0.2 Plošný offset **3-osy**	-0,2	11,98	1	50 / 0	1	X;Y 0	Z -0,2	2500	0:00:15

Fig. 7.4 Program protocol generated by Powermill 2017 for the squre shaped electrode.

For this experiment it was necessary to fabricate 5 sets of tool electrode (4 quality grades of graphite and 1 set of copper electrodes). Tool electrodes used in the experiment are shown in the Fig. 7.5.

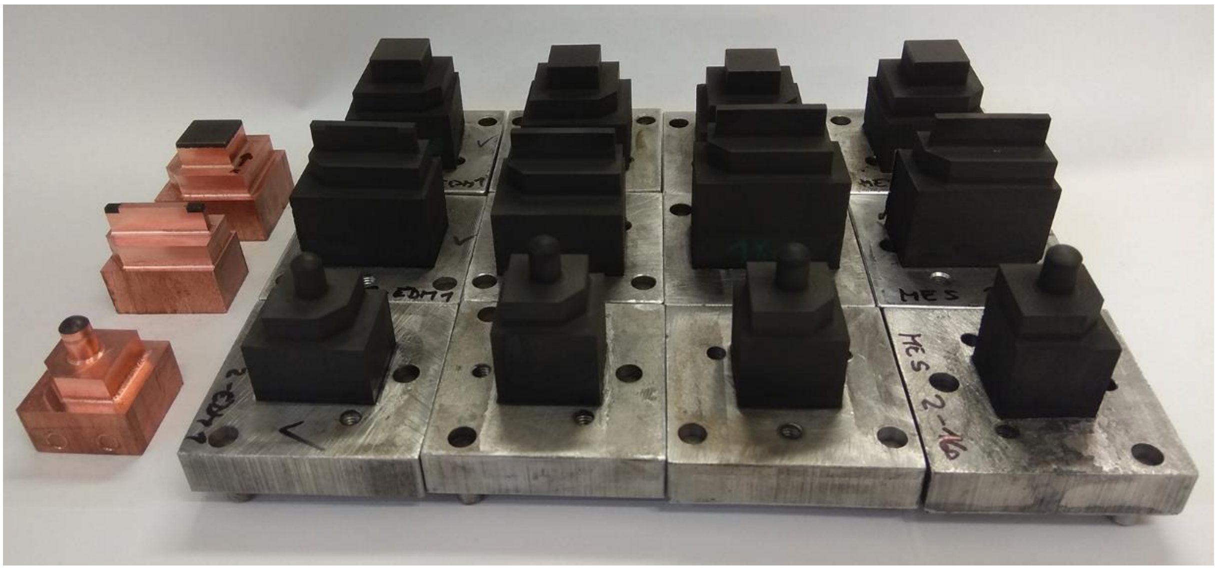


Fig. 7.5 Tool electrode used for the experiment.

7.2 Tool electrode measurement before the EDM

All electrodes were mesured before EDM machining proces. This measurement was taken by Aberlink – Axiom too CNC coordinate measuring machine (shown in the Fig. 7.6). The measurement of a tool electrode is shown in the Fig. 7.6.

Measurement protocols of EDM-1 elecrodes are shown in figures 7.7, 7.8, 7.9. The rest of measurement values of tool electrodes are processed into the spreadsheet which is used further to evaluate a wear of each tool electrode.

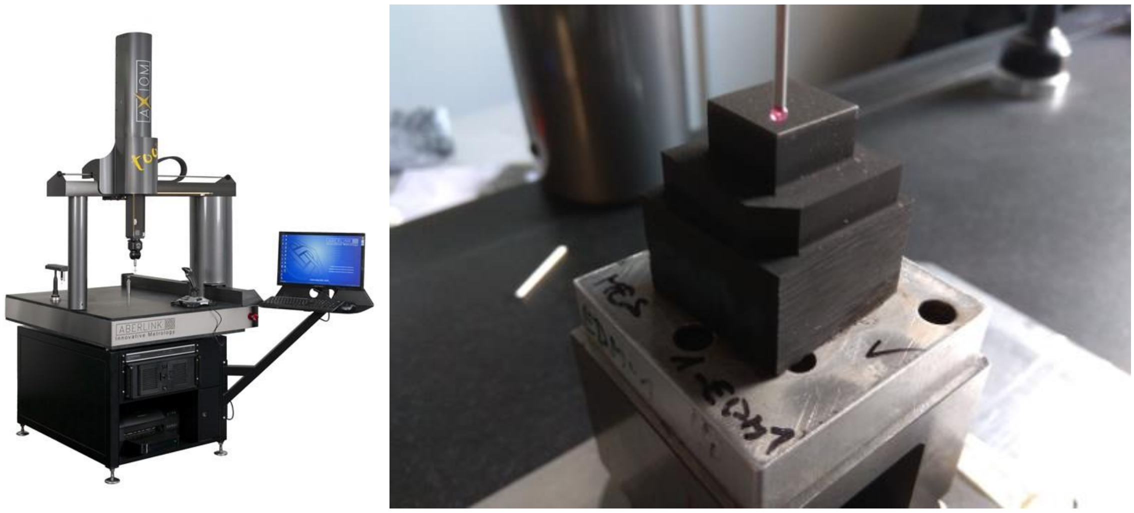
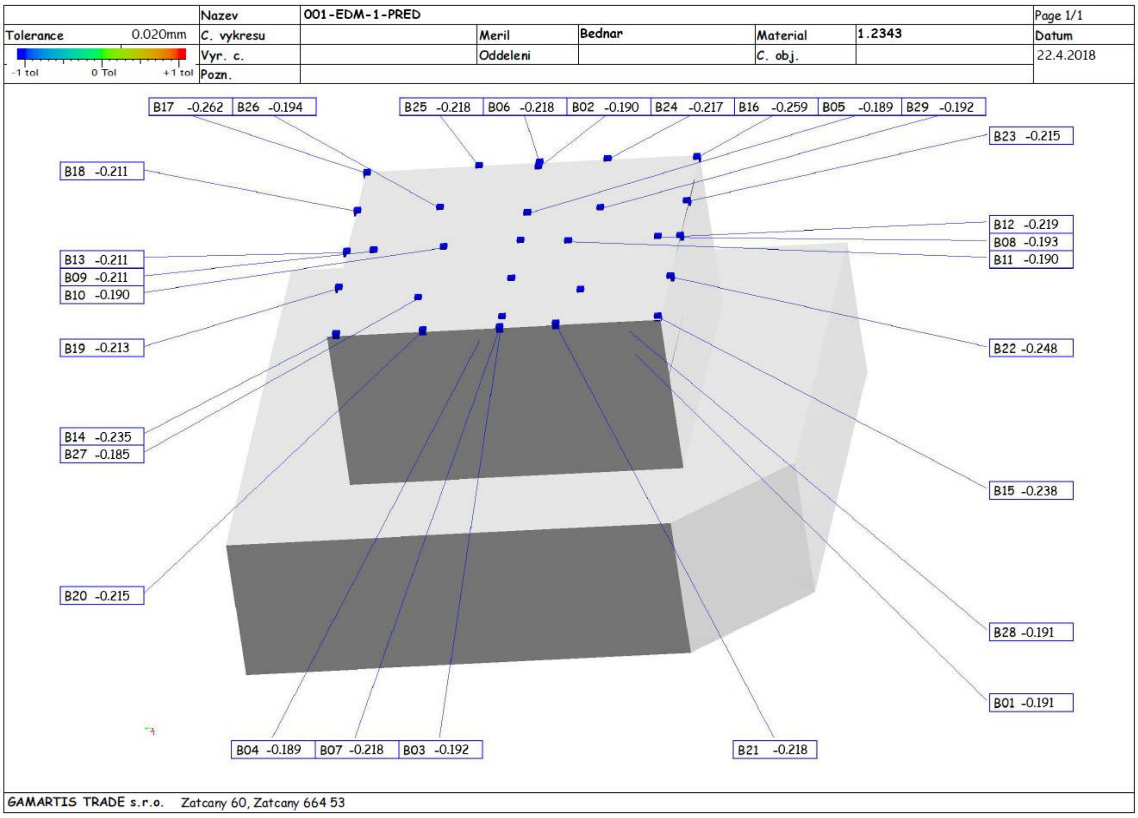


Fig. 7.6 Aberlink – Axiom too CNC CMM used for measuring (left), measurement of a tool electrode (right).



	Nazev	001-EDM-1-PRED					Page 1/1
Tolerance 0.020mm	C. vykresu		Meril	Bednar	Material	1.2343	Datum
	Vyr. c.		Oddeleni		C. obj.		22.4.2018
	Pozn.						

B17 -0.262
B26 -0.194
B25 -0.218
B06 -0.218
B02 -0.190
B24 -0.217
B16 -0.259
B05 -0.189
B29 -0.192
B23 -0.215
B18 -0.211
B12 -0.219
B08 -0.193
B11 -0.190
B13 -0.211
B09 -0.211
B10 -0.190
B19 -0.213
B22 -0.248
B14 -0.235
B27 -0.185
B15 -0.238
B20 -0.215
B28 -0.191
B01 -0.191
B04 -0.189
B07 -0.218
B03 -0.192
B21 -0.218

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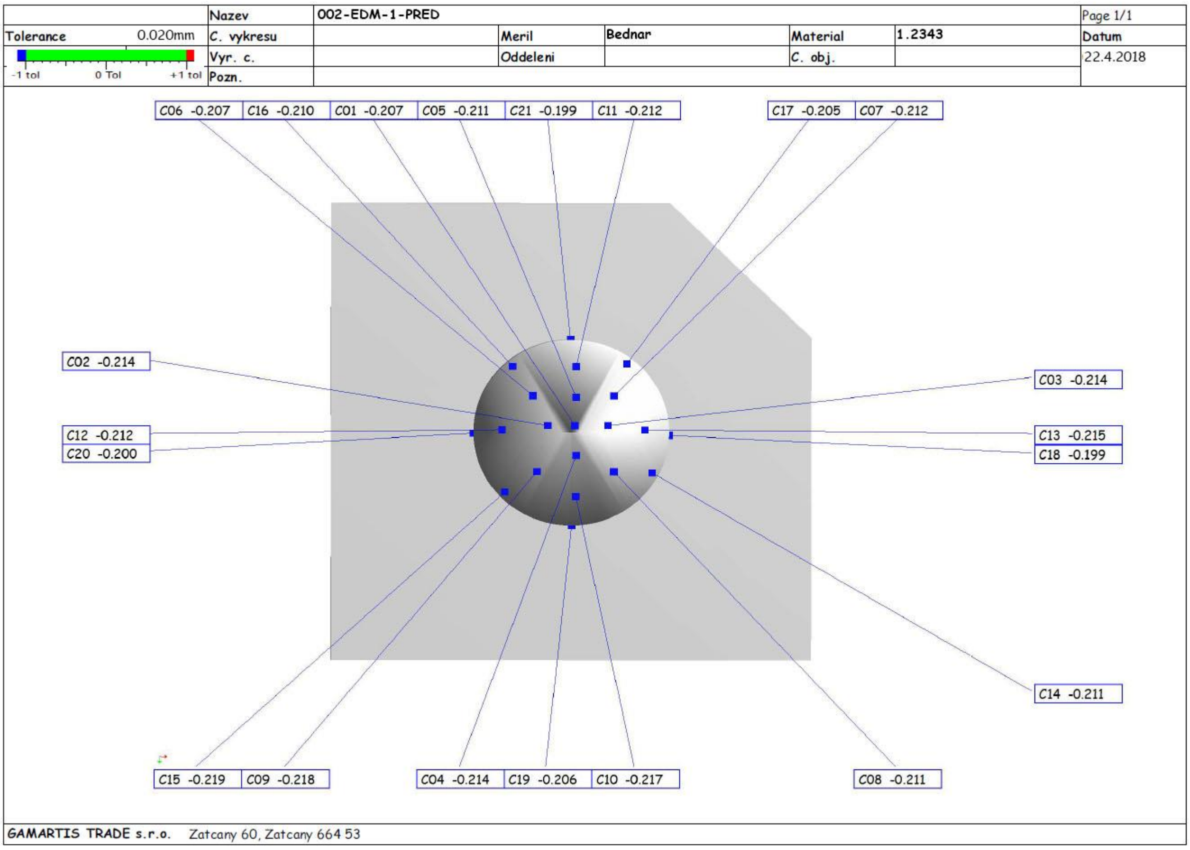
Fig. 7.7 EDM-1 square shaped tool electrode measurement protocol.



	Nazev	002-EDM-1-PRED					Page 1/1
Tolerance 0.020mm	C. vykresu		Meril	Bednar	Material	1.2343	Datum
	Vyr. c.		Oddeleni		C. obj.		22.4.2018
	Pozn.						

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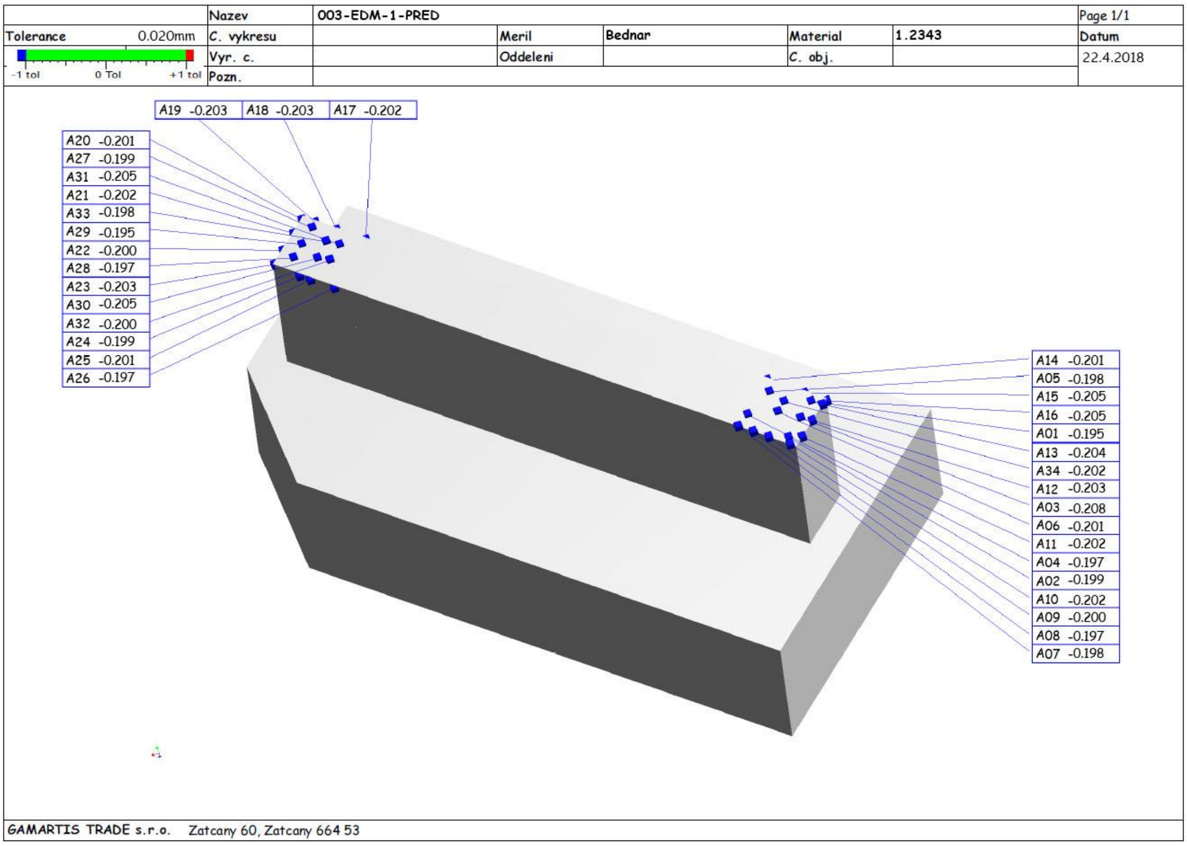
Fig. 7.8 EDM-1 spherical shaped tool electrode measurement protocol.



	Nazev	003-EDM-1-PRED					Page 1/1
Tolerance 0.020mm	C. vykresu		Meril	Bednar	Material	1.2343	Datum
	Vyr. c.		Oddeleni		C. obj.		22.4.2018
	Pozn.						

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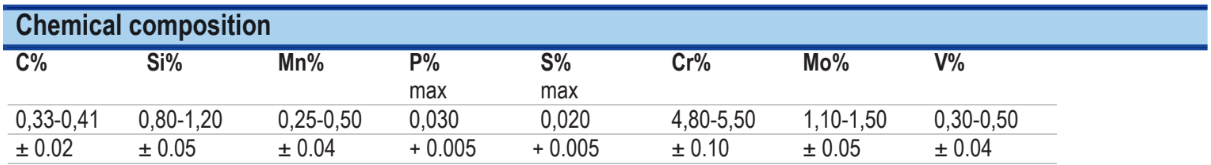
Fig. 7.9 EDM-1 rib shaped tool electrode measurement protocol.

7.3 EDM

As a workpiece material was used material 1.2343 which is frequently used as a material for inserts of plastic injection molds. The chemical composition of the steel is shown in the Tab 7.2.

Tab. 7.2 The chemical composition of 1.2343



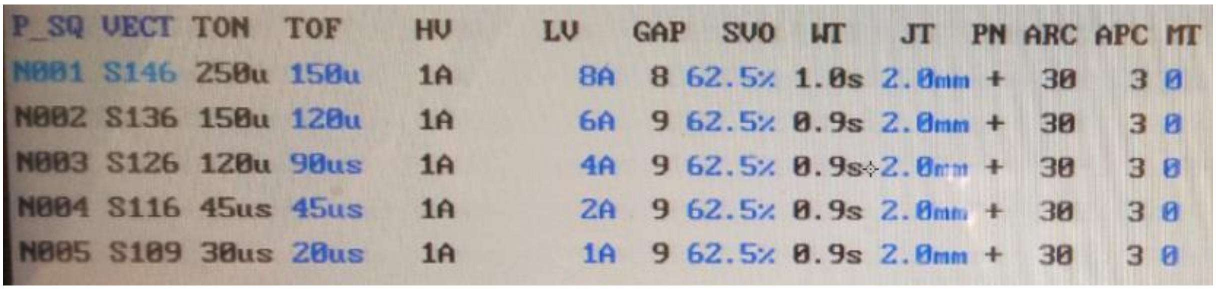
Chemical composition

C%	Si%	Mn%	P% max	S% max	Cr%	Mo%	V%
0,33-0,41	0,80-1,20	0,25-0,50	0,030	0,020	4,80-5,50	1,10-1,50	0,30-0,50
± 0.02	± 0.05	± 0.04	+ 0.005	+ 0.005	± 0.10	± 0.05	± 0.04

Material 1.2343 fits perfectly for the production of injection mold parts and is prefered prior to the 1.2738 (formerly very commonly used) primarily because of its good traceability. Material 1.2343 can be easily hardened (without the risk of cracking) to the 52 HRC. On the other hand, material 1.2738 or 1.2738HH is not suitable for hardening. High lifetime span of an injection mold is required in the production of injection molds for the automotive industry (usually 1 million and more strokes). As GAMARTIS TRADE is mainly focused on the injection mould production in the automotive industry, it is going to be a perfect sample. Thus, this material was choosen to for the experiment.

Fig. 7.10 Workpiece material used for the experiment.

The same EDM parameters were used for all tool electrodes. These parameters are illustrated in the Fig. 7.11. Roughing parameters were used for squre shaped tool electrodes (line N001 in the Fig 7.11) and finishing parameters for rib shaped and spherical shaped electrodes (line N001, N002, N003, N004, N005 in the Fig 8.11).



```
P_SQ VECT TON   TOF    HV      LV   GAP  SVO   WT    JT     PN ARC APC MT
N001 S146 250u  150u   1A      8A   8 62.5% 1.0s 2.0mm  +   30   3 0
N002 S136 150u  120u   1A      6A   9 62.5% 0.9s 2.0mm  +   30   3 0
N003 S126 120u  90us   1A      4A   9 62.5% 0.9s 2.0mm  +   30   3 0
N004 S116 45us  45us   1A      2A   9 62.5% 0.9s 2.0mm  +   30   3 0
N005 S109 30us  20us   1A      1A   9 62.5% 0.9s 2.0mm  +   30   3 0
```

Fig. 7.11 EDMing parameters.

There has been used roughing and finishing parameters in order to see the difference between the differences in between these two processess (VDI, wear of electrodes, accuracy, machining times etc.).

The machining process itself is illustrated in the Fig.7.12. Cavities for each quality grade of the graphite and copper is shown in the Fig. 7.13. These cavities are investigated further in the subchapter 7.4.

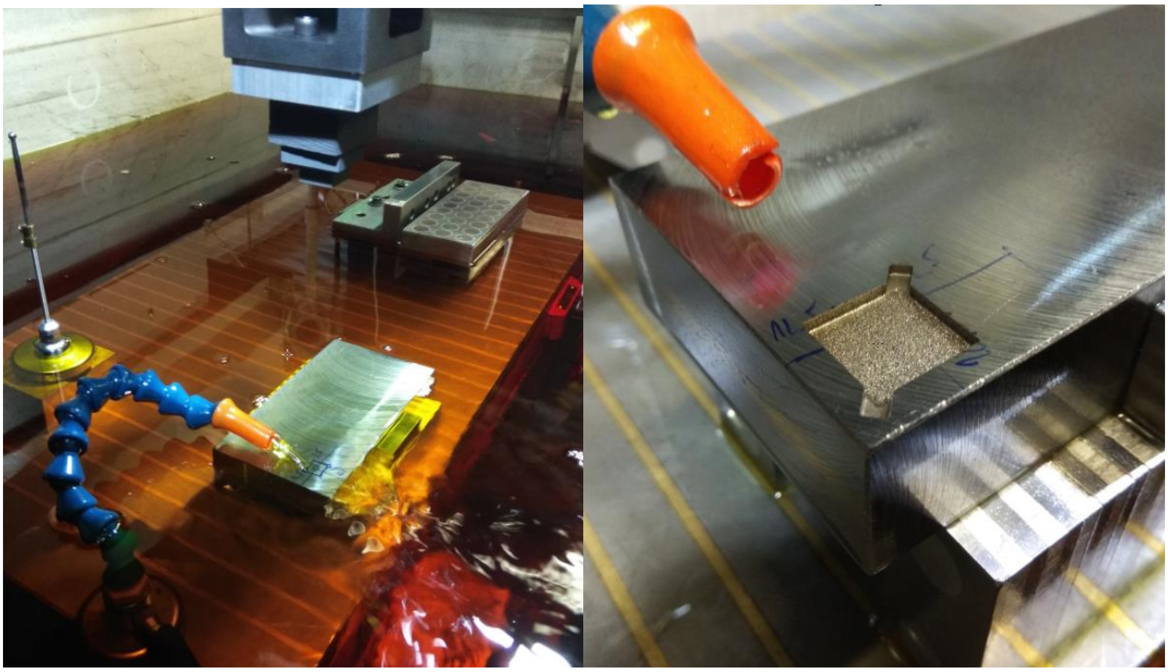


Fig. 7.12 EDM proces of the experiment.

Fig. 7.13 EDMed cavities ready for another measuring process.

7.4 Tool electrode measurement after the EDM

All electrodes were mesured again after the EDM machining proces to determine the amount of wear during the burn. This measurement was taken by Aberlink – Axiom too CNC coordinate measuring machine by the same program as they were done before the EDM. This results in the most precise measuring as the points of the measuring are the same.

Figure 7.14 shows the measurement of a copper tool electrode after the EDM. Measurement protocols of EDM-1 elecrodes after the EDM process are shown in figures 7.15, 7.16, 7.17. The rest of measurement values of tool electrodes are processed into the spreadsheet which is used further to evaluate a wear of each tool electrode.

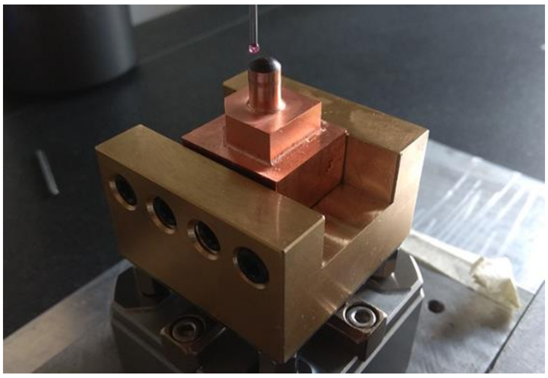
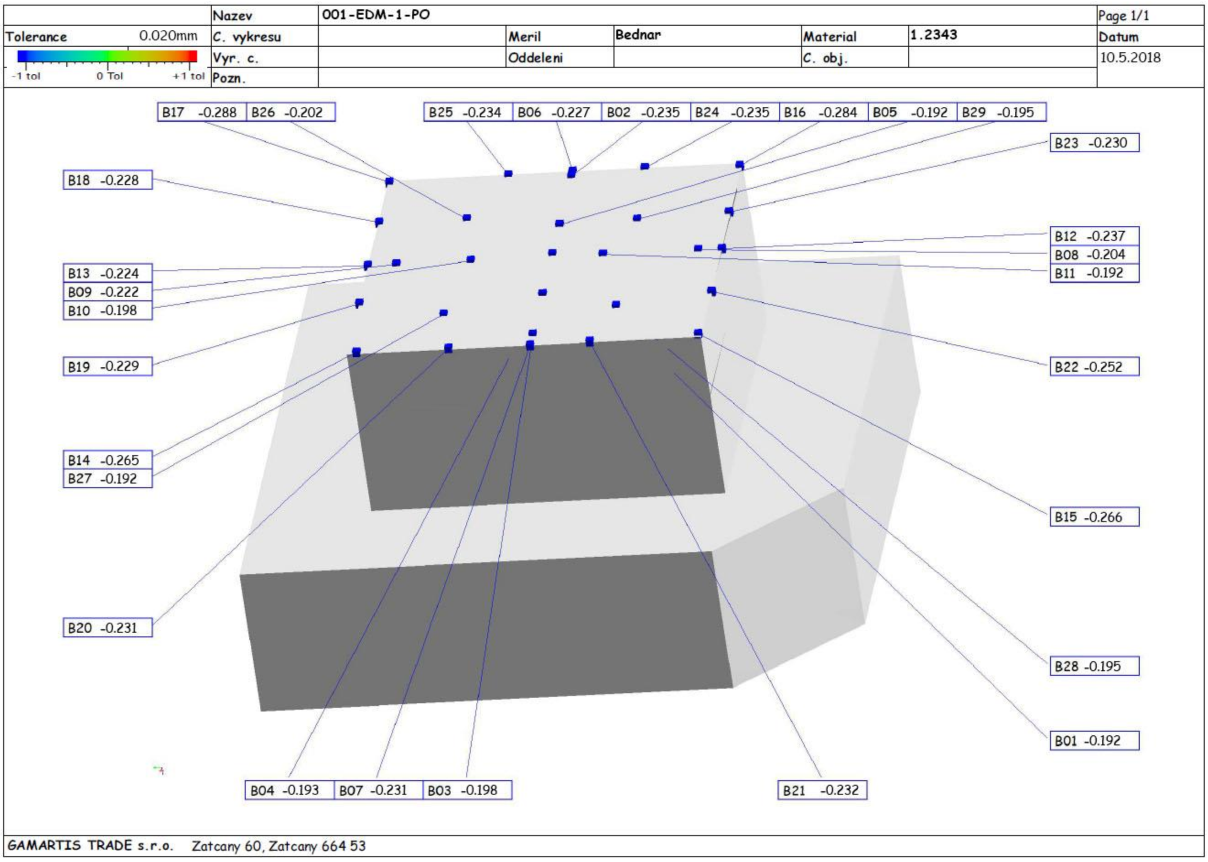


Fig. 7.14 Measuring of the Copper spherical shaped tool electrode after EDM.



	Nazev	001-EDM-1-PO					Page 1/1
Tolerance 0.020mm	C. vykresu		Meril	Bednar	Material	1.2343	Datum
-1 tol 0 Tol +1 tol	Vyr. c.		Oddeleni		C. obj.		10.5.2018
	Pozn.						

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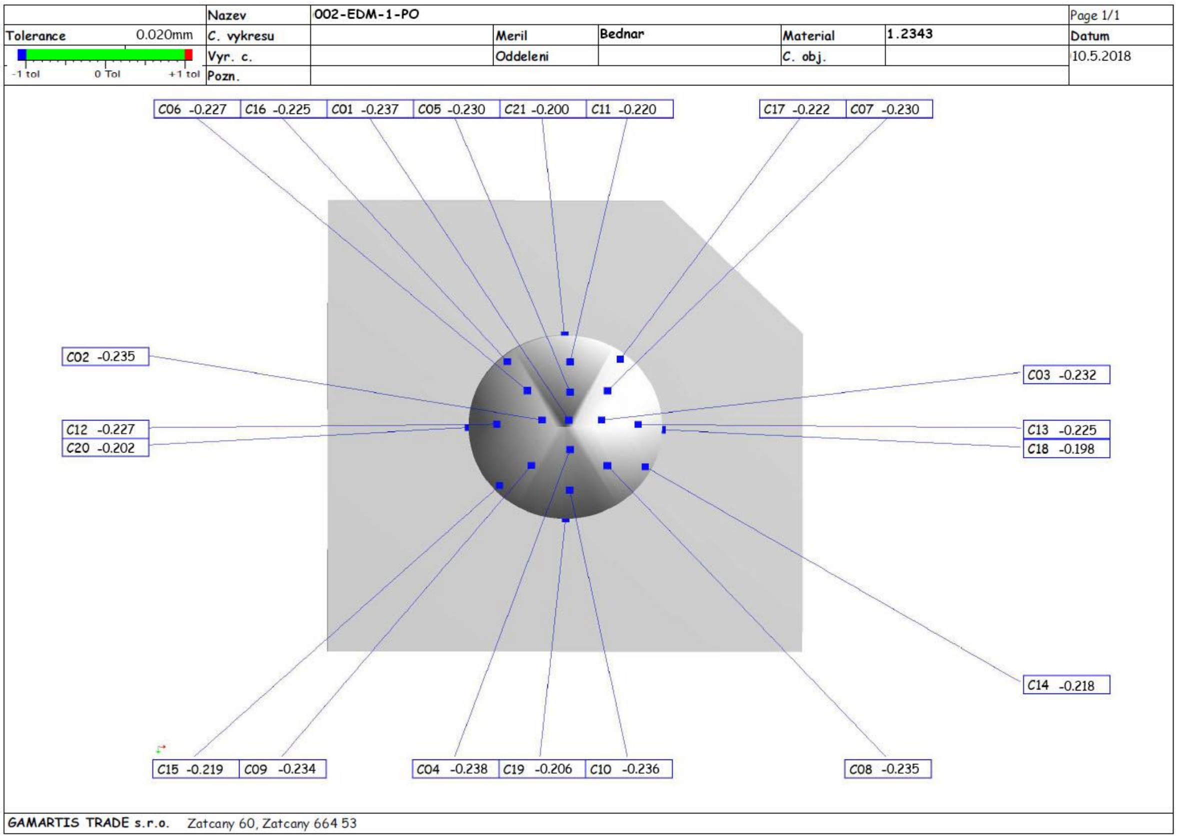
Fig. 7.15 EDM-1 square shaped tool electrode measurement protocol after the EDM.



	Nazev	002-EDM-1-PO				Page 1/1
Tolerance 0.020mm	C. vykresu		Meril	Bednar	Material	1.2343	Datum
-1 tol 0 Tol +1 tol	Vyr. c.		Oddeleni		C. obj.		10.5.2018
	Pozn.					

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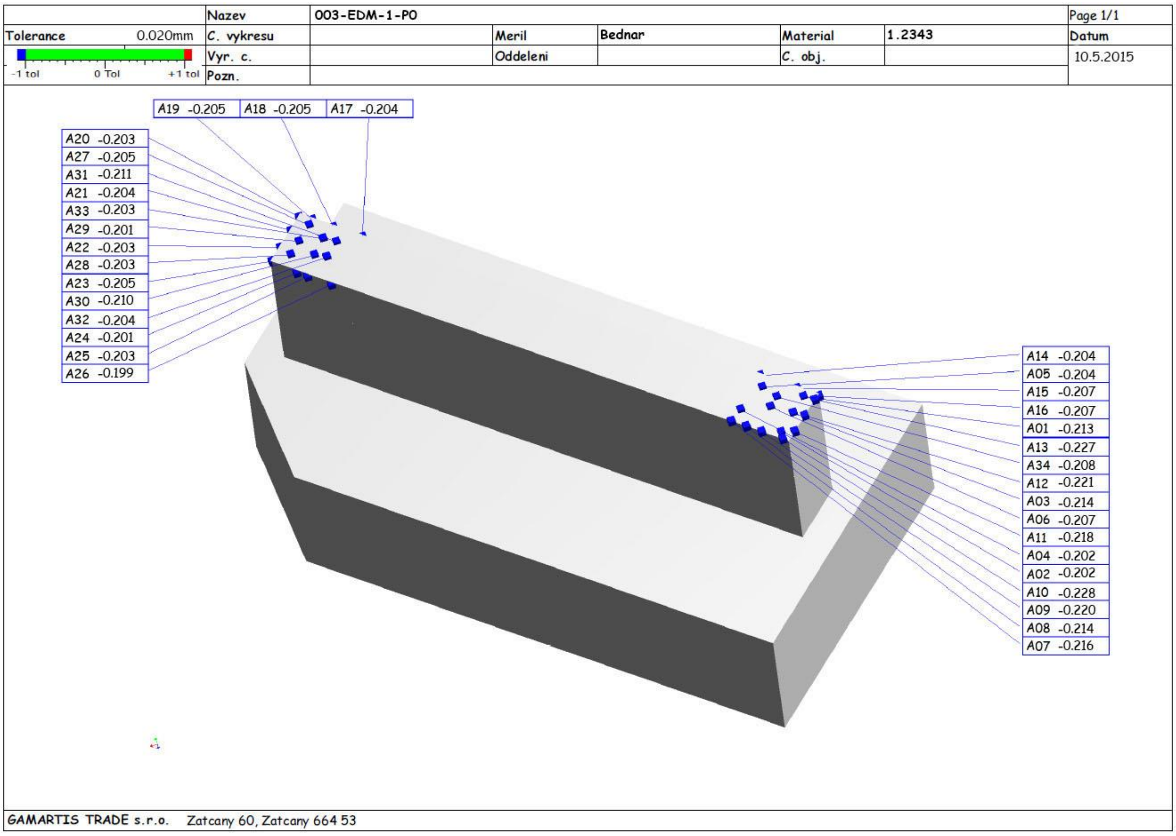
Fig. 7.16 EDM-1 spherical shaped tool electrode measurement protocol after the EDM.



	Nazev	003-EDM-1-PO					Page 1/1
Tolerance 0.020mm	C. vykresu		Meril	Bednar	Material	1.2343	Datum
-1 tol 0 Tol +1 tol	Vyr. c.		Oddeleni		C. obj.		10.5.2015
	Pozn.						

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Fig. 7.17 EDM-1 rib shaped tool electrode measurement protocol after the EDM.

7.5 Data Collection

The following aspects were considered during the experiment:

- wear of electrodes after the EDM compared to electrodes measured before the EDM process,
- quality of tool electrode material compared to time of the EDM,
- quality of tool electrode material compared to surface roughness.

Electrode wear

The wear of all electrodes was determined using a 3D measuring center as described in subchapters 7.2 and 7.4. Tables 7.3, 7.4 and 7.5 contain the measured values of the individual measurement points. By comparing these two values (before and after), the electrode wear can be determined depending on the type of graphite.

Tab. 7.3 Wear of the square shaped tool electrodes for each material before and after EDM, all dimension stated in μm.

MAT. / POINT	Cu		EDM 1		EDM 200		EDM 180		EDM 160	
	Before EDM	After EDM	Before EDM	After EDM	Before EDM	After EDM	Before EDM	After EDM	Before EDM	After EDM
B1	-205	-208	-191	-192	-202	204	-192	-195	-195	-198
B2	-206	-223	-218	-235	-216	-238	-214	-238	-204	-229
B3	-207	-214	-192	-198	-218	-223	-231	-236	-225	-232
B4	-193	-198	-189	-193	-237	-245	-187	-196	-205	-216
B5	-199	-201	-189	-192	-220	-224	-217	-225	-212	-221
B6	-205	-215	-218	-227	-227	-237	-195	-204	-221	-234
B7	-209	-223	-218	-231	-221	-237	-219	-236	-208	-226
B8	-201	-208	-193	-204	-191	-202	-214	-220	-222	-229
B9	-203	-211	-211	-222	-198	208	-229	-240	-218	-230
B10	-205	-213	-190	-198	-212	-217	-202	-206	-194	-199
B11	-206	-208	-190	-192	-195	-200	-205	-211	-198	-205
B12	-205	-225	-219	-237	-196	-213	-205	-214	-214	-222
B13	-194	-209	-211	-224	-224	-241	-216	-234	-218	-238
B14	-205	-240	-235	-265	-225	-265	-238	-281	-256	-294
B15	-214	-247	-238	-266	-236	-277	-225	-267	-238	-279
B16	-215	-246	-259	-284	-231	-271	-245	-281	-217	-268
B17	-218	-248	-262	-288	-244	-280	-257	-294	-242	-287
B18	-200	-219	-211	-228	-222	-240	-215	-234	-225	-248
B19	-206	-224	-213	-229	-218	-240	-228	-251	-218	-243
B20	-193	-212	-215	-231	-186	-200	-219	-234	-215	-232
B21	-202	-218	-218	-232	-220	-235	-213	-229	-217	-236
B22	-198	-210	-238	-252	-188	-205	-203	-221	-209	-227
B23	-200	-214	-215	-230	-217	-234	-210	-230	-215	-236
B24	-198	-217	-217	-235	-193	-216	-197	-221	-206	-232
B25	-200	-217	-218	-234	-213	-231	-186	-202	-215	-233
B26	-204	-214	-194	-202	-246	-254	-233	-242	-225	-233
B27	-196	-203	-185	-192	-208	-211	-219	-223	-205	-222
B28	-197	-204	-191	-195	-220	-225	-212	-218	-218	-227
B29	-193	-198	-192	-195	-219	-222	-218	-225	-209	-214

Tab. 7.3 Wear of the spherical shaped tool electrodes for each material before and after EDM, all dimension stated in μm.

MAT. / POINT	Cu		EDM 1		EDM 200		EDM 180		EDM 160	
	Before EDM	After EDM	Before EDM	After EDM	Before EDM	After EDM	Before EDM	After EDM	Before EDM	After EDM
C1	-202	-228	-207	-229	-205	-233	-210	-241	-208	-243
C2	-188	-195	-214	-220	-202	-208	-207	-215	-199	-209
C3	-211	-223	-214	-232	-210	-228	-212	-239	-189	-220
C4	-202	-210	-214	-219	-222	-228	-202	-208	-209	-216
C5	-194	-198	-211	-213	-199	-201	-218	-222	-215	-218
C6	-217	-238	-207	-235	-208	-225	-197	-224	-209	-238
C7	-202	-224	-212	-226	-209	-218	-212	-226	-191	-209
C8	-217	-230	-211	-224	-206	-217	-212	-228	-217	-236
C9	-211	-217	-218	-222	-214	-219	-210	-216	-216	-222
C10	-209	-230	-217	-236	-200	-219	-213	-239	-216	-244
C11	-219	-239	-212	-230	-211	-230	-216	-242	-187	-215
C12	-200	-214	-212	-225	-218	-228	-214	-230	-204	-225
C13	-217	-222	-215	-219	-219	-224	-194	-201	-214	-223
C14	-214	-219	-211	-215	-222	-227	-192	198	-208	-218
C15	-217	-218	-219	-221	-213	-217	-206	-211	-214	-223
C16	-196	-218	-210	-229	-221	-239	-197	-223	-190	-219
C17	-192	-206	-205	-222	-196	-205	-199	-213	-209	-229
C18	-200	-216	-199	-209	-200	-209	-205	-219	-202	222
C19	-204	-209	-206	-208	-218	-220	-203	-204	-190	-194
C20	-204	-207	-200	-202	-205	-207	-212	-212	-206	-209
C21	-215	-215	-199	-201	-212	-212	-196	-197	-196	-196

By subtracting the values from the tables, the greatest wear can be found on materials with a larger particle size. The greatest wear of any electrode can be found in its the corners. When the corners are compared, the wear results of individual electrode materials correspond to the wear on the sides, fronts, edges.

.

The wear at the corners of the roughing parameters of the square shaped electrodes result as follows:

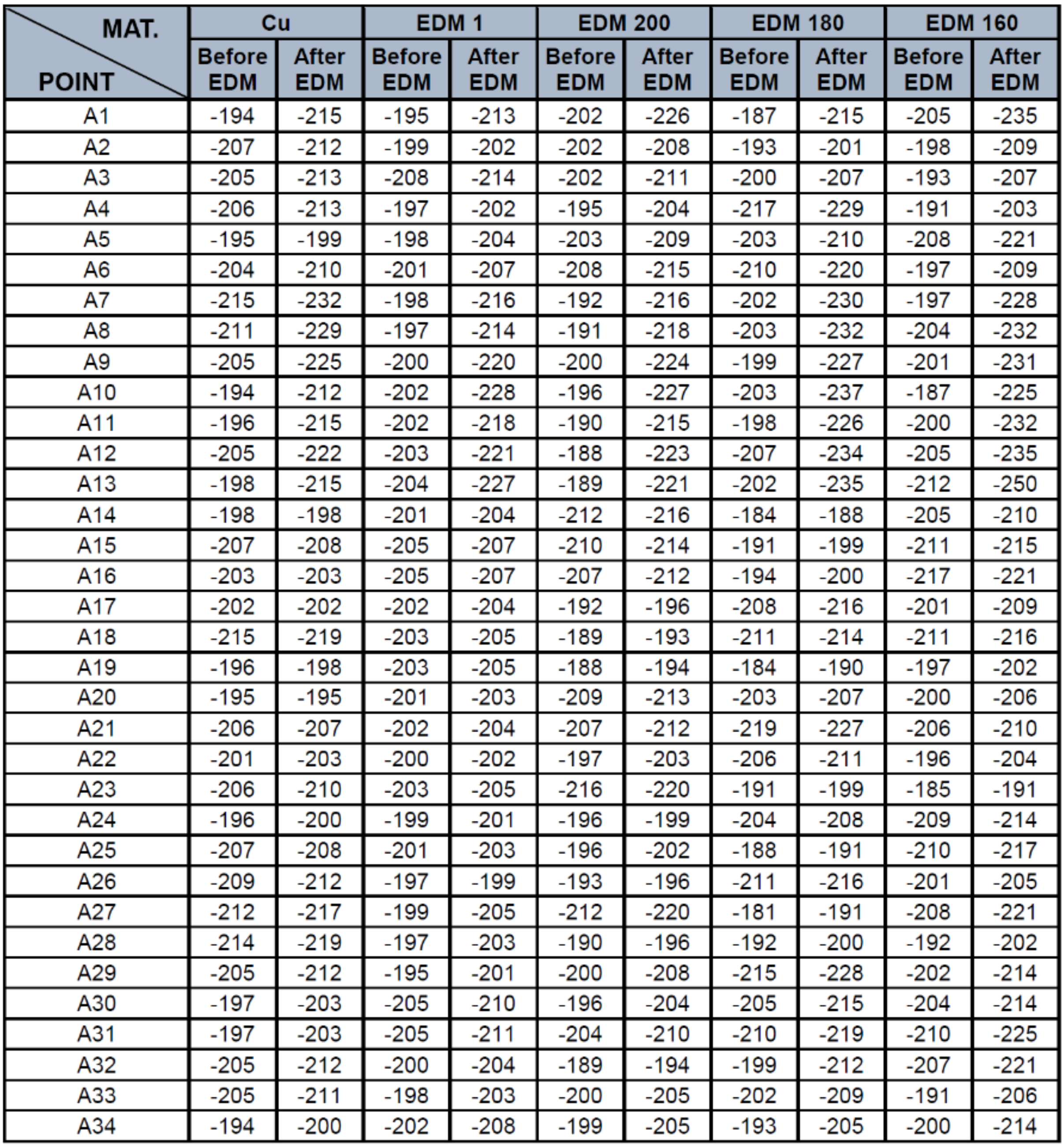
- EDM-1 ranges in 25 – 30 μm,
- EDM-200 ranges in 36 - 41 μm,
- EDM-180 ranges in 36 – 43 μm,
- EDM-160 ranges in 38 – 51 μm.

Wear of edges is not as big as corner wear. The wear ratio is approximately 50 to 60%.

There is minimal, almost negligible wear on the front and side faces. This characteristic corresponds across all tested graphite classes.

Copper itself exhibits lower electrode wear but is unable to achieve the required surface quality after machining.

Tab. 7.3 Wear of the rib shaped tool electrodes for each material before and after EDM, all dimension stated in μm.



MAT. POINT	Cu		EDM 1		EDM 200		EDM 180		EDM 160	
	Before EDM	After EDM	Before EDM	After EDM	Before EDM	After EDM	Before EDM	After EDM	Before EDM	After EDM
A1	-194	-215	-195	-213	-202	-226	-187	-215	-205	-235
A2	-207	-212	-199	-202	-202	-208	-193	-201	-198	-209
A3	-205	-213	-208	-214	-202	-211	-200	-207	-193	-207
A4	-206	-213	-197	-202	-195	-204	-217	-229	-191	-203
A5	-195	-199	-198	-204	-203	-209	-203	-210	-208	-221
A6	-204	-210	-201	-207	-208	-215	-210	-220	-197	-209
A7	-215	-232	-198	-216	-192	-216	-202	-230	-197	-228
A8	-211	-229	-197	-214	-191	-218	-203	-232	-204	-232
A9	-205	-225	-200	-220	-200	-224	-199	-227	-201	-231
A10	-194	-212	-202	-228	-196	-227	-203	-237	-187	-225
A11	-196	-215	-202	-218	-190	-215	-198	-226	-200	-232
A12	-205	-222	-203	-221	-188	-223	-207	-234	-205	-235
A13	-198	-215	-204	-227	-189	-221	-202	-235	-212	-250
A14	-198	-198	-201	-204	-212	-216	-184	-188	-205	-210
A15	-207	-208	-205	-207	-210	-214	-191	-199	-211	-215
A16	-203	-203	-205	-207	-207	-212	-194	-200	-217	-221
A17	-202	-202	-202	-204	-192	-196	-208	-216	-201	-209
A18	-215	-219	-203	-205	-189	-193	-211	-214	-211	-216
A19	-196	-198	-203	-205	-188	-194	-184	-190	-197	-202
A20	-195	-195	-201	-203	-209	-213	-203	-207	-200	-206
A21	-206	-207	-202	-204	-207	-212	-219	-227	-206	-210
A22	-201	-203	-200	-202	-197	-203	-206	-211	-196	-204
A23	-206	-210	-203	-205	-216	-220	-191	-199	-185	-191
A24	-196	-200	-199	-201	-196	-199	-204	-208	-209	-214
A25	-207	-208	-201	-203	-196	-202	-188	-191	-210	-217
A26	-209	-212	-197	-199	-193	-196	-211	-216	-201	-205
A27	-212	-217	-199	-205	-212	-220	-181	-191	-208	-221
A28	-214	-219	-197	-203	-190	-196	-192	-200	-192	-202
A29	-205	-212	-195	-201	-200	-208	-215	-228	-202	-214
A30	-197	-203	-205	-210	-196	-204	-205	-215	-204	-214
A31	-197	-203	-205	-211	-204	-210	-210	-219	-210	-225
A32	-205	-212	-200	-204	-189	-194	-199	-212	-207	-221
A33	-205	-211	-198	-203	-200	-205	-202	-209	-191	-206
A34	-194	-200	-202	-208	-199	-205	-193	-205	-200	-214

The visual assessment of the wear of the corners and edges of the square electrodes is shown in Figure 7.18 on the next page. In the visual comparison, the AN-E500 eScope Handheld Digital Microscope was used to evaluate the results. Visual wear was evaluated at 5 times higher magnification.

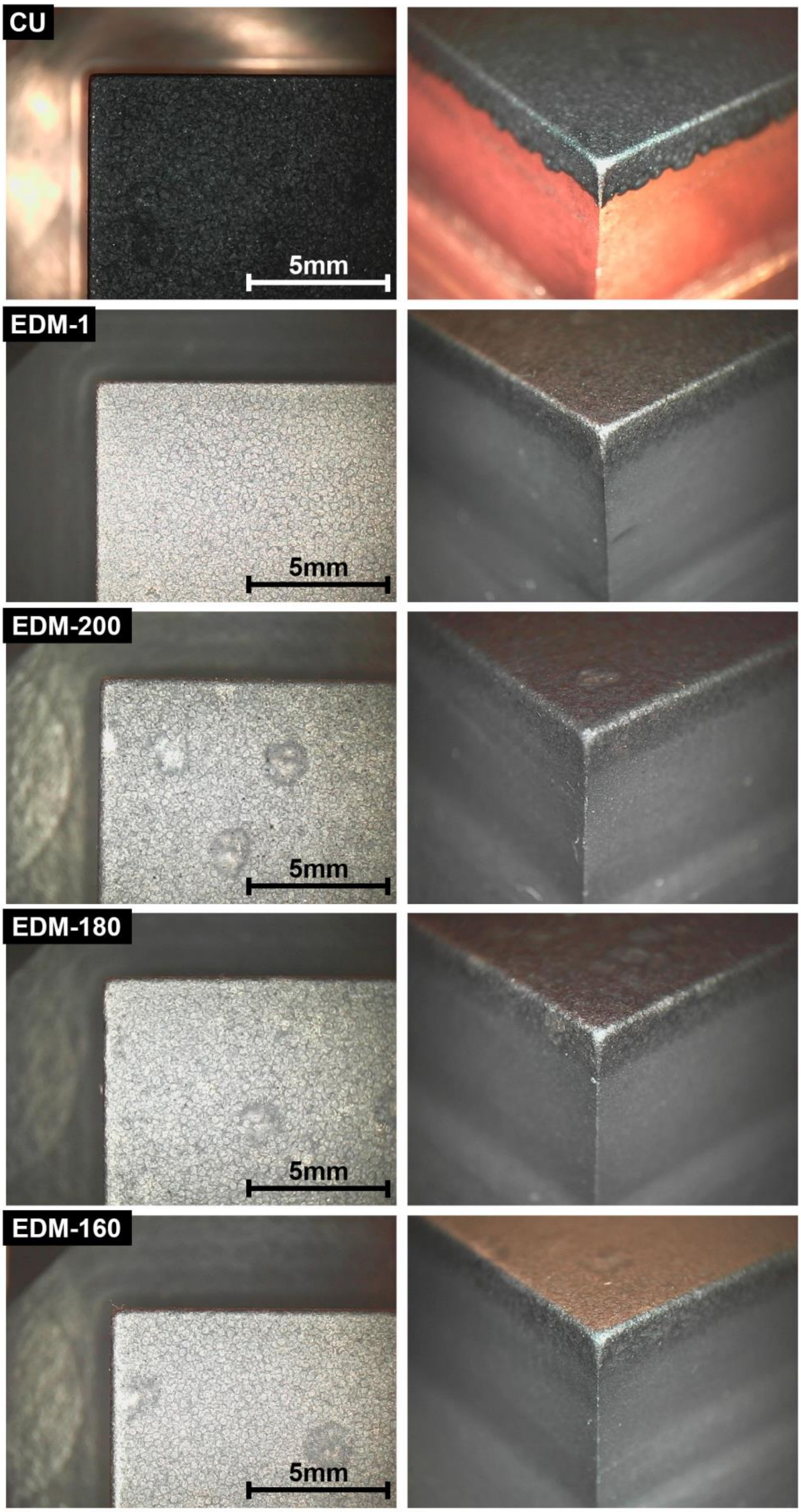


Fig. 7.18 Corner wear comparison for each quality grade.

EDM machining time

The considerable part of the total EDM production cost is the machining time. Machining time is significantly affected by the size of the grain. The lower the grain, the longer the EDM machining time. This time, however, is significantly associated with the quality of the machined surface. The EDM machining time itself is summarized in Tab. 7.6 and production time on the Graphite Mill CT-600 in the Tab. 7.7.

The result of the EDM for square shaped elecrode was surprising in terms of the EDM-180. The material showed irregular machining time. The remaining materials correspond to the following:

- higher wear = lower machining time (can be used in roughing operations).

Spherical electrodes follow the same characteristic. On the other hand, the machining time for machining the rib shaped cavity does not follow this hypothesis. This could be caused by an orbit motion movement, which is comonly used when finishing. When making a rib, impurities evolving into the spark gap by the wear of the electrode may be large enough to stop dielectric fluid to flow properly. These impurities cause that a discharge is not efficient enough and this leads to a machining time increasement.

This knowledge is very important when selecting a material for machining very thin ribs. For this reason, it is very important to use low-grain materials in the areas of the problematic access of the dielectric fluid into the machining spot.

Tab. 7.6 EDM machining time comparison.

Material	**EDM machining time** [min]		
	Square	**Spherical**	**Rib**
Cu	36:47	17:27	18:19
EDM-1	27:45	16:28	7:56
EDM-200	22:49	14:01	9:05
EDM-180	25:15	12:30	6:38
EDM-160	23:04	9:48	11:02

Tab. 7.7 Fabrication time of electrodes.

Material	**Fabrication time** [min]		
	Square	**Spherical**	**Rib**
Cu	25:00	23:00	23:00
EDM-1	11:35	8:00	11:00
EDM-200	11:35	8:00	11:00
EDM-180	11:35	8:00	11:00
EDM-160	11:35	8:00	11:00

Unlike EDM software, the graphite milling machine does not have an intuitive system. Thus, it is unable to respond to the different properties of actual machining (such as material depreciation, damage to cutting tools etc.). Therefore, the time of milling of each electrode of the same shape is exactly the same.

Surface roughnes of cavities

Surface roughness was visually compared to the VDI grain plate supplied by POCO graphite material supplier.

As expected, the VDI surface fully corresponds to the grain size. Fig. 7.19 assigns the VDI surface to the excavated surface of the individual cut shapes. This visual comparison was made on the basis of Fig. 7.20.

The rigidity of the material to keep the sharp corner fully corresponds to the sharp corner design in the workpiece material.

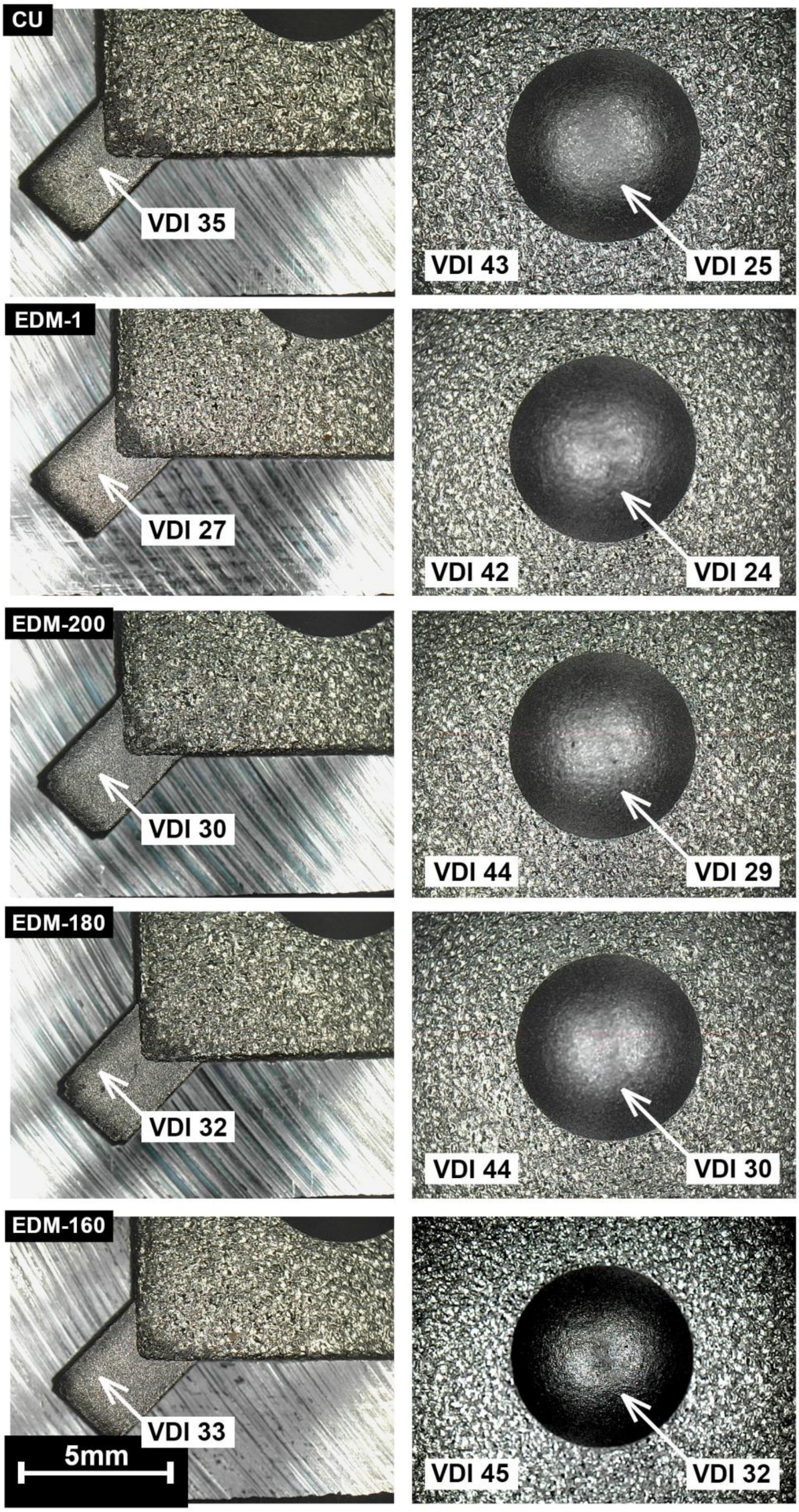


Fig. 7.19 Surface roughes of each cavity.

8 EVALUATION OF EXPERIMENT RESULTS

The main output of this experiment is the determination of graphite material grain size dependence on the flushing ability at the point of discharge. It has been verified that the lower grain graphite material exhibits less wear, thus a small amount which results in lower number of impurities that cause low discharge efficiency. This leads to significant increases in the time of EDM machining, which is a significant factor in the total cost of cavity production.

From the gathered informations, it is noticeable to recommend a higher grain sized materials (lower quality, lower price) for roughing operations. This can be applied when roughing with sufficient flushing. Therefore, these grain materials are used in roughing operations, precisely because the grain is separated more often (higher wear). It can result in a higher discharge and thus a greater material removal.

Copper was also compared in the experiment and that is mainly because its use in Asia, mainly used for mold prooduction. Copper does not exhibit such high wear values as graphite material of inferior quality, however the roughness of the machined surface does not reach the qualities that could be expected from the wear values of the electrode. Copper does not respond to knowledge:

- lower graphite = higher surface finish.

For the sinking of spherical shapes, an approximate ratio of 1:1 of On Time / Off Time is required. If these gradient parameters are not met, the current becomes too high and this results in burns of the surface.

On the other hand, the opportunity for copper electrode can be found when maching spherical cavities as it does not prone to create this burns.

9 ECONOMIC EVALUATION

To evaluate the economic point of view, it was necessary to calculate the costs associated with the individual material groups that were used for the experimental comparison of graphite.

For the calculation of costs, it was necessary first to determine the volume of material for individual electrode shapes (calculated according to equation 9.1). Since the price of copper is offered in CZK / kg, it was necessary to calculate the weight of copper that was used for the fabrication. This calculation was performed according to the equation 9.2. Subsequently, the price of the copper material used was calculated according to the equation 9.3.

A summary of the costs arising from the production and production of a given cavity for individual classes of tool electrode materials is shown in the Tab. 9.1. The total cost of cavity machining was calculated by the parcel cost, such as material costs and machining costs. Machinig costs include milling and EDM costs.

$$V_{square} = a_{square} \cdot b_{square} \cdot c_{square} \tag{9.1}$$

where: V_{square} – volume of the square electrode

$a_{square} \cdot b_{square} \cdot c_{square}$ - dimensions

$$V_{square} = 0{,}035 \cdot 0{,}035 \cdot 0{,}035\ [m^3]$$

$$V_{square} = 0{,}000043\ m^3$$

$$V_{rectangle} = 0{,}000045\ m^3$$

$$V_{circle} = 0{,}000025\ m^3$$

$$V_{total} = V_{square} + V_{rectangle} + V_{circle} = 0{,}000113\ m^3$$

$$m_{cu} = V_{total} \cdot \rho_{cu}\ [kg] \tag{9.2}$$

where: V_{total} – total volume of electrodes from individual material [m^3],

ρ_{cu} – density of copper [$kg \cdot m^{-3}$],

m_{cu} – weight of all copper electrodes.

$$m_{cu} = 0{,}000113 \cdot 8960 = 1{,}012\ kg$$

$$p_{cuelectrodes} = m_{cu} \cdot p_{offered}\ [Kč] \tag{9.3}$$

where: $p_{cuelectrodes}$ – price for the material of all copper electrodes [Kč],

$p_{offered}$ – price for a kilogram of copper material [$Kč \cdot kg^{-1}$].

$$p_{cuelectrodes} = 1{,}012 \cdot 300 = 303\ Kč$$

Tab. 9.1 Economic summary of cavity machining for each tool electrode material used in the experiment.

Electrode material	**Cu**	**EDM 1**	**EDM 200**	**EDM 180**	**EDM 160**
Material cost per one kilo [Kč/dm^3]	**2670**	**2900**	**1550**	**965**	**965**
Material costs [Kč]	**303**	**328**	**175**	**110**	**110**
Milling time [min]	**71**	**30**	**30**	**30**	**30**
Milling costs [Kč] **750 Kč per an hour**	**888**	**375**	**375**	**375**	**375**
EDM time [min]	**72**	**52**	**46**	**44**	**44**
EDM costs [Kč] **1000 Kč per an hour**	**1200**	**867**	**767**	**734**	**734**
Total cost for the cavity machining [Kč]	**2391**	**1570**	**1317**	**1219**	**1219**

As can be seen from the table, the highest cost for graphite materials is reported for EDM-1. On the contrary, the lowest grade material of the EDM-160 and EDM-180 is the cheapest option from current supplier.

The economically most sensitive parameter in comparison to each grade is the cost associated with graphite material as well as the EDM machining costs. The EDM-1 cavity production cost is 29 % higher compared to the lowest quality graphite materials (EDM-160, EDM-180) and 19 % higher compared to EDM-200 graphite.

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CONCLUSION AND DISCUSSION

One of the main outputs of this experiment was the determination of graphite material grain size dependence on the flushing ability at the point of discharge. It has been verified that the lower grain graphite material exhibits less wear, thus a small amount impurities is scattered into the dielectric fluid that may cause a low discharge efficiency. This leads to significant increases in the time of EDM machining, which is a significant factor in the total cost of cavity production. This knowledge is very important when selecting a material for machining very thin ribs. For this reason, it is very important to use low-grain materials (such as EDM-1) in the areas of the problematic access of the dielectric fluid into the machining spot.

From the gathered informations, it is noticeable to recommend a higher grain sized materials (lower quality, lower price) for roughing operations. This can be applied when roughing with sufficient flushing. Therefore, these grain materials are used in roughing operations, precisely because the grain is separated more often (higher wear) and this result in a higher discharge and thus a greater material removal.

Copper was also compared in the experiment and that is mainly because its extensive use in Asia, mainly used for mold prooduction. Copper does not exhibit such high wear values as graphite material of inferior quality, however the roughness of the machined surface does not reach the qualities that could be expected from the wear values of the electrode. On the other hand, the opportunity for copper electrode can be found when maching spherical cavities as it does not prone to create burns so easily.

The economically most sensitive parameter in comparison to each grade is the cost associated with graphite material as well as the EDM machining costs. The EDM-1 cavity production cost is 29 % higher compared to the lowest quality graphite materials (EDM-160, EDM-180) and 19 % higher compared to EDM-200 graphite.

The production costs for each cavity created by different quality grades of graphite are:

- EDM-1 = 1500 Kč,
- EDM-200 = 1317 Kč,
- EDM-180 = 1219 Kč,
- EDM-160 = 1219 Kč.

According to the price survey of the suppliers og graphite materials in the Czech republic and Slovakia in Chapter 5, it is recommended to invest in the research of the new graphite supplier.

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SYMBOLS AND ABBREVIATIONS

SYMBOL	UNIT	EXPLANATION
AC	A	Alternating current
CAD	-	Computer aided design
CAM	-	Computer aided manufacturing
DC	A	Direct current
ER	-	Electrical resistivity
F	-	Finishing
HSC	-	High Speed Cutting
I	A	Current
I_θ	A	Middle discharge current
L	H	Inductance
MRR	mm/min	Material removal rate
Q_i	mm^3	Volume of removed material
R	-	Roughing
R	Ω	Resistance
Ra	μm	Arithmetic average of the roughnessprofile
U	V	Voltage
U_Z	V	Starting voltage
U_θ	V	Middle discharge voltage
U_K	V	Middle voltage
VDI	-	EDM surface roughness
V_{circle}	m^3	Volume of the circle electrode
$V_{rectangle}$	m^3	Volume of the rectangle electrode
V_{square}	m^3	Volume of the square electrode
V_{total}	m^3	Total volume of electrodes from individual material
W_e	J	Single discharge energy
W_i	J	Discharge energy
WR	-	Wear resistence
d	mm	Diameter of a crater
h	mm	Depth of a crater
m_{cu}	kg	weight of all copper electrodes
$p_{cuelectrodes}$	Kč	price for the material of all copper electrodes
$p_{offered}$	Kč/kg	price for a kilogram of copper material
t_d	μs	Discharge delay
t_i	μs	Discharge duration
t_o	μs	Pause duration
q	-	Utilization of discharge
θ	%	Relative volumetric wear
ρ_{cu}	kg/m^3	Density of copper

ATTACHMENTS

Attachment 1	EDM approach program for square shaped electrodes
Attachment 2	EDM approach program for spherical shaped electrodes
Attachment 3	EDM approach program for rib shaped electrodes
Attachment 4	Powermill programs of experimental EDM electrodes
Attachment 5	Workpiece material list
Attachment 6	Properties of graphite material from different suppliers
Attachment 7	VDI surface roughness (used to evaluate VDI in the experiment)