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MACHINING CHARACTERISTICS OF ELECTRICAL DISCHARGE MACHINING – A REVIEW

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Abstract: *In electrical discharge machining (EDM) the machining characteristics of the process directly depend on the discharge energy which is transformed into heat in the machining area. The generated thermal energy leads to high temperatures which result in local melting and evaporation of workpiece material. However, the high temperature also impacts various physical and chemical properties of tool and workpiece. Process parameters and machining characteristics of EDM are identified in this paper. Based on the previous investigations, an analytical dependence was established between the parameters of discharge energy and technological performance. In addition, properties of discharge energy were experimentally investigated and their influence on productivity, accuracy and quality of EDM was established. Mathematical and experimental researches conducted in this paper allow development of intelligent modeling approaches for efficient selection of relevant parameters of EDM discharge energy. The results obtained represent a technological knowledge base for the selection of optimal conditions of EDM process.*
Key words: *EDM, machining parameters, technological performance, modeling, optimization*

Pregled tehnoloških karakteristika procesa elektroerozivne obrade. *Kod elektroerozivne obrade (EDM) tehnološke karakteristike procesa direktno zavise od energije pražnjenja koja se u zoni obrade pretvara u toplotu. Generisana toplotna energija dovodi do pojave ekstremno visokih temperatura usled čega dolazi do trenutnog rastapanja i isparavanja lokalnog dela materijala obratka. Međutim, visoka temperatura istovremeno uslovljava i niz fizičko-hemijskih promena u površinskom sloju materijala alata i obratka. U ovom radu se sistematizuju parametri obrade i tehnološke karakteristike EDM procesa. Na osnovu prethodnih istraživanja, uspostavljena je analitička zavisnost između parametara energije pražnjenja i tehnoloških pokazatelja procesa. Pored toga, eksperimentalno su istražene specifičnosti energije pražnjenja i njihov uticaj na proizvodnost, tačnost i kvalitet EDM obrade. Sprovedena matematička i eksperimentalna istraživanja omogućila su razvoj inteligentnog modela i pristupa za efikasnu selekciju releventnih parametara EDM energije pražnjenja. Tako dobijeni rezultati predstavljaju adekvatnu tehnološku bazu znanja pri izboru optimalnih uslova procesa elektroerozivne obrade.*
Ključne reči: *elektroerozivna obrada, parametri obrade, tehnološki pokazatelji procesa, modeliranje, optimizacija*

1. INTRODUCTION

Modern manufacturing is facing complex demands on a daily basis. Manufacturing flexibility, productivity and quality are the most vital demands facing the market oriented industrial systems. Only modern equipped industrial systems will be able to adjust their manufacturing process to these high market demands. In this context, there can be little doubt that the machining processes shall remain important integral part of the technological process of product manufacturing and assembly. Basic advantages of machining process are high technological performance (efficiency, precision and quality) with the ability to cope with hard materials and complex surfaces [1-4].

On the basis of the current research and future projections, one can expect increased application of electrical discharge machining (EDM) in comparison with others available conventional and non-conventional machining processes [5-7]. EDM is one of the most important non-conventional machining processes that is used for complex machining of many different classes of electrically conductive materials, regardless of their physical and metallurgical properties [8].

Clearly, the benefits of EDM are considerable. It is often appropriate to EDM instead of using conventional machining processes, but not always, because the EDM has certain technological drawbacks. EDM process includes machining of materials that offers minimum 0,01 S/cm of electrical conductivity [9]. Productivity is relatively low compared to conventional machining. Tool wear affects the accuracy of the machined features. The machining accuracy of the EDM is limited to about ±0.001 mm. Minimum surface roughness average is about 0,1 μm. EDM induces thermal stress in machined surfaces. Surface integrity can be as good as or better than a ground surface [10,11].

2. BASICS OF ELECTRICAL DISCHARGE MACHINING

The origin of electrical discharge machining goes back to 1770, when J. Priestly discovered the effect of electrical discharges. In 1943, B. Lazarenko and N. Lazarenko have developed the controlled EDM process for machining materials. The evolution of EDM since the 1970 was due to the numerical control, powerful generators, new wire tool electrodes, improved machine intelligence and better technological aspects. In recent times, the incorporation of EDM within a computer integrated manufacturing resulting in significantly reduced machining costs and competitiveness.

The EDM is basically a complex process which is based on periodical transformation of electrical energy into thermal energy [12-14]. Thermoelectric energy is created between the tool and workpiece with the passage of electric current. Both the tool and workpiece electrode materials have to be conductors of electricity and submerged in a dielectric fluid. A specific small gap is maintained between the tool and the workpiece. A power supply controls the timing and intensity of the electrical discharges and the movement of the tool in relation to the workpiece. Shown in Fig. 1 is schematically the basic working principle of EDM, input process parameters (workpiece, tool, machine and dielectric) and output technological performances (productivity, machining accuracy and surface integrity).

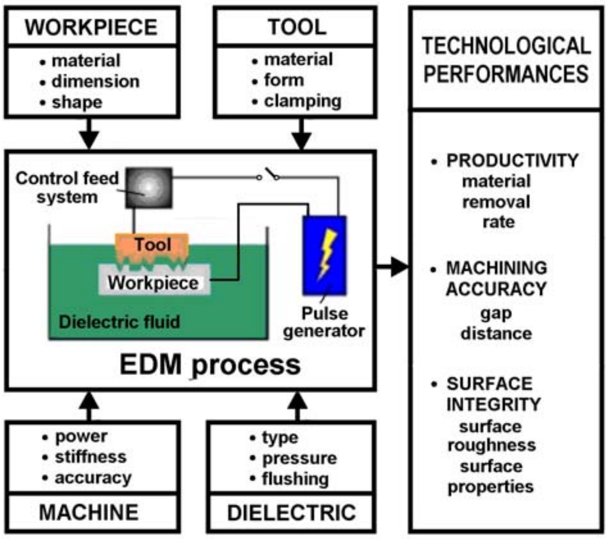

Fig.1. EDM process with machining characteristics

2.1 Working principle of EDM process

The working principle of EDM process is based on a series of non-stationary electrical discharge which remove material from a workpiece [15,16]. Material removal rate occurs at the spot where the electric field is strongest. Upon establishing the voltage, a strong magnetic field is established between the tool and workpiece (ignition phase). Due to attractive force of the magnetic field, at the shortest local distance between the tool and workpiece there is a build-up of particles from the machining process which float in the dielectric fluid. This forms the electrical circuit and the electrons begin to move towards the positively charged electrode. On their way, the accelerated electrons collide with the neutral particles from the machining process and the dielectric fluid. There is a chain reaction in which a large number of negative and positive ions are generated (discharge phase). The ionization initiates creation of electro-conductive zone between the workpiece and tool, thus causing electrical discharge. In electrical discharge, electrical energy is transformed into thermal energy. A discharge zone is formed at temperatures as high as 40.000 °C. Such high temperature cause local heating, melting, evaporation, and incineration of workpiece material. High temperatures also produce lower machining quality, tool wear, thermal dilatations, etc. The disruption of current supply annihilates the discharge zone, causing abrupt cooling which results in an explosive flushing of melted matter and solid particles off the workpiece surface (ejection phase). Fig. 2 shows a single electrical discharge of the EDM process with electrical pulse parameters [17,18].

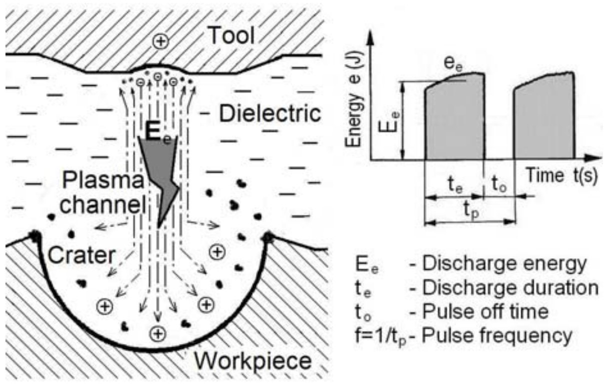

Fig. 2. Mechanism of a single discharge in EDM

Between the periodical discharges there is a deionization of dielectric liquid and the products of machining are evacuated from the work zone. This process provides stability of pulse discharge by preventing the continuous current flow and generation of electric arc or a short circuit.

During an electrical discharge there are the voltage and current pulses which vary in time, Fig. 2. Electrical pulses are interdependent, and are determined by following parameters: U_e – discharge voltage, I_e – discharge current, t_e – discharge duration, t_o – pulse off time and t_p – pulse cycle time. The derived parameters are: $E_e=U_e \cdot I_e \cdot t_e$ – discharge energy, $f=1/t_p$ – pulse frequency and $\tau=t_e/t_p$ – duty factor.

The most important parameter of EDM is the discharge energy. The discharge energy is the mean value of electric parameter which is transformed into heat during discharge. It is directly influenced by the characteristics of electric pulses. Their influences are interconnected and depend on the rest of the machining parameters [19,20].

The discharge voltage depends on the paired electrode materials and machining conditions. It ranges between 15 and 30 V [21]. For proper machining conditions, electrical discharge occurs instantaneously and is independent from other electrical pulse parameters. Therefore, the most important electrical pulse parameters of EDM are discharge current and discharge duration. However, the impact of discharge current is limited by the tool surface which is interfacing the workpiece, i.e. the current density [22,23]. In case when the current density oversteps the limit for the given machining conditions, the process of deionization of the discharge zone deteriorates, thus reducing the efficiency of EDM. The independent regulation of the discharge duration is also limited. It is known from experience that discharge duration must be limited for a particular discharge current. Otherwise, an electrical arcing occurs which damages both tool and workpiece.

Besides the electric parameters described above, the polarity (±) of electrodes, has important effects on the EDM results. The polarity can be either positive or negative and it depends on tool material, workpiece material, current density and discharge duration. Because the plasma channel is made of ion and electron flows, and electrons have mass smaller than anions, for that reason electrode polarity is usually positive, allowing attaining good material removal rate and the minimum relative tool wear ratio [24,25].

2.2 Machining characteristics

Similar to other machining processes, the most important EDM machining characteristics are: productivity, machining accuracy and surface integrity, Fig. 1. Productivity is expressed as the material removal rate and refers to how fast is workpiece material removed per time unit. Machining accuracy is defined by tolerances on dimension and shape of the workpiece. Surface integrity is expressed through surface roughness and surface layer properties. The importance of machining performance is relative and depends on machining conditions and the desired function of parts. Together with machining costs, productivity determines the overall cost-effectiveness of the machining process, while accuracy and quality impact the functional value of product.

The material removal process in EDM is associated with the erosive effects which occur as a result of an extremely high temperature due to the high intensity of discharge energy through the plasma channel, Fig. 2. The material removal rate and the surface integrity correspond to the adjusted crater profile that is defined through the radius. The crater radius is assumed to be a function of discharge energy [17,26,27].

Now it can be logically assumed that the material removed volume of a single electric pulse would be proportional to the discharge energy:

$$V_e = C_V \cdot E_e \quad (1)$$

where C_V is the constant that depends on the workpiece material.

The material removal rate represents the average volume of material removed over the machining time and there follows the expression for material removal rate:

$$V_w = V_e \cdot f = C_V \cdot U_e \cdot I_e \frac{t_e}{t_e + t_o} \quad (2)$$

On the other hand, the material removal in a single pulse discharge is determined by computing the volume of the crater, under the assumption of hemispherical shape with a radius equal to R_{max}:

$$V_e = \frac{2}{3}\pi \cdot R_{\max}^3 \quad (3)$$

In Eq (3), R_{max} is defined as the maximum surface roughness observed over maximum height of irregularities.

From the Eq. (3) also using Eq. (1), one derives expression for maximum height of irregularities:

$$R_{\max} = \left(\frac{3}{2\pi} C_V \cdot E_e \right)^{1/3} \quad (4)$$

In practice, the surface quality is defined over the surface roughness $R_a \cong R_{max}/4$. The surface roughness is defined as the arithmetic average deviation of the assessed profile (ISO 4287).

Theoretically, dependence of the gap distance and the discharge energy is given by equation:

$$a_e = C_a \cdot E_e^m \quad (5)$$

where C_a and m are the constants that depend on the machining conditions.

2.3 Different types of EDM

EDM system comes in two basic types (Fig. 3): die-sinking and wire-cut. Die-sinking EDM, also known as ram EDM or standard EDM, is the oldest form of EDM machining. The wire-cut EDM, also known as WEDM or spark EDM, is controlled by CNC following the assigned geometry for the part to be produced [5-7,28,29].

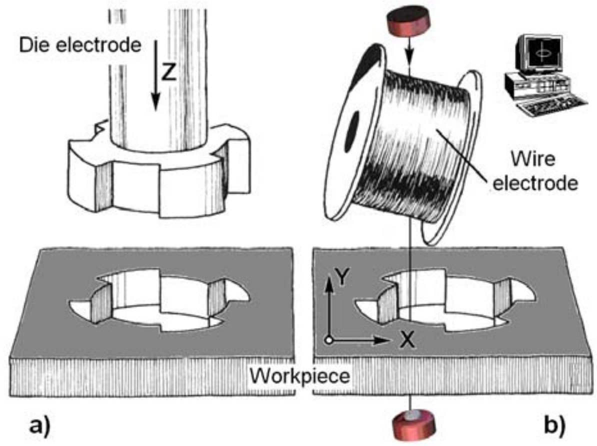

Fig.3. Different types of EDM
a) Die-sinking EDM, b) Wire-cut EDM

Die-sinking EDM reproduces the shape of the tool into the part or assembly. Die-sinking EDM are generally used for complex geometries where the machine uses a shaped graphite or copper electrode. Many die-sinking EDM machine with CNC control, can rotate the electrodes around more axis allowing machining of internal cavities. This makes die-sinking EDM a highly capable manufacturing process.

In wire-cut EDM a wire electrode is used to cut a programmed outline into the workpiece. Wire-cut EDM is used for shapes cutout of a flat sheet or plate. With a wire-cut EDM machine, an initial hole must first be drilled in the material, and then the wire can be fed through the hole to complete the machining assembly. The wire-cut EDM can produce all sorts of complex shapes that are very difficult with other processes.

2.4 EDM applications

EDM has become an indispensable process in the modern manufacturing industry. The use of EDM is especially essential for machining difficult-to-machine materials (hardened alloy steel, high speed steel, superalloy, cemented carbide) and complex geometry parts for which traditional techniques are not applicable [1,5].

It is primarily used for production of subtle cavities in forming tools or polymer injection, prototype parts and other highly specialized products. With the increased capability of EDM controls, new processes use simple-shaped electrodes to 3D EDM complex shapes. Since the tool does not touch the workpiece there are no cutting forces, therefore, very fragile parts can be EDM machined [30,31]. Also, there is a great importance of EDM on the production of very accurate small and micro parts. Some of the applications made by EDM process are shown in Fig. 4.

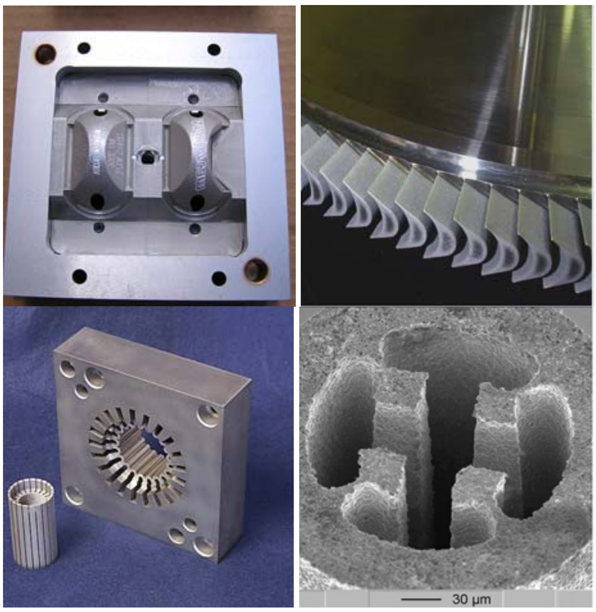

Fig.4. Applications of EDM

3. EXPERIMENTAL APPROACH

As analysed in section 2.2, the machining characteristics of EDM mostly depend on the discharge energy, i.e. discharge current and duration time [32-34].

Fig. 5. shows the effect of the most important electrical pulse parameters on the material removal rate of tool steel using copper tool electrode. The diagram shows dependence of material removal rate on discharge duration for various discharge currents. The results of experimental investigation show that for every discharge current there is a corresponding optimal discharge duration $t_{e(opt)}$ which allows maximum material removal rate. This value increases with the increase of discharge current [13,21].

This efficiently precludes us from unambiguous determination of the influence of the discharge current and pulse duration on material removal rate. The experimentally established optimal influence of the electrical pulse parameters on material removal rate, does not agree with the expected influence. In real conditions, discharge current and discharge duration increase material removal rate, as well as the increase of gas bubbles in the discharge zone. Due to impaired evacuation of machining products, a portion of the discharge energy is spent on re-melting and evaporation of solidified metal particles. Also, larger portion of discharge energy takes place in a gaseous environment, thus being lost irreversibly. Such impaired process stability affects the EDM productivity.

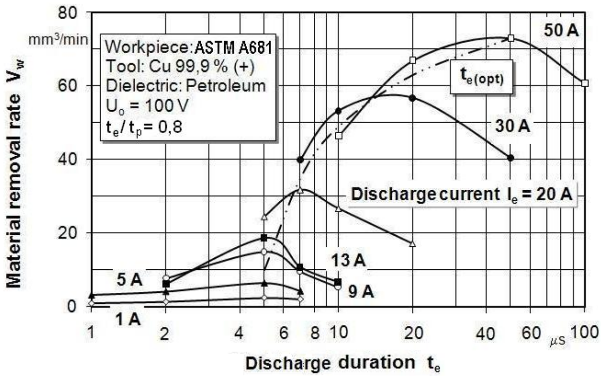

Fig. 5. Dependence of material removal rate on discharge duration for various discharge currents

Fig. 6 shows the influence of discharge current and duration time on gap distance. The diagram shows that the increase of electrical pulse parameters results in increased gap distance [13,21]. Although the influence of discharge current and discharge duration on gap distance is uniform, the discharge current has a somewhat larger influence on the gap distance. It is evident that the gap distance follows the electrical pulse parameters in order to maintain stability of EDM. Otherwise, the deionization of the discharge zone would be affected, which could result in either low or uncontrolled material removal rate.

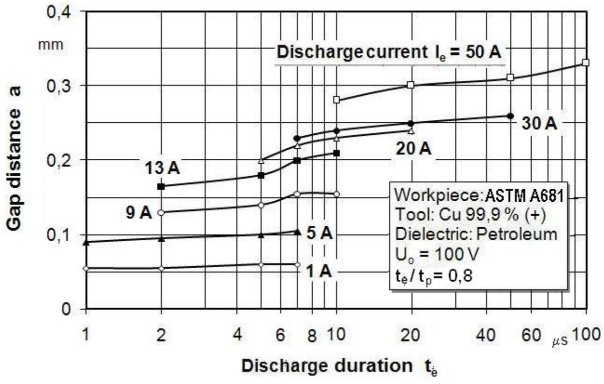

Fig. 6. Influence of the discharge parameters on gap distance

The relationship between the surface roughness and electrical pulse parameters is shown in Fig. 7. The results of experimental investigation show a slight increase of surface roughness with the increase of discharge duration, while the discharge current has a more pronounced influence on surface roughness. As the discharge current increases, so do the discharge heat concentration on the workpiece surface, which results in larger craters, i.e. greater surface roughness. Shown in Fig. 7 are typical images of machined surfaces at various electrical pulse parameters. The EDM surface consists of a number of craters of various dimensions, while the roughness is even in all directions [13,21].

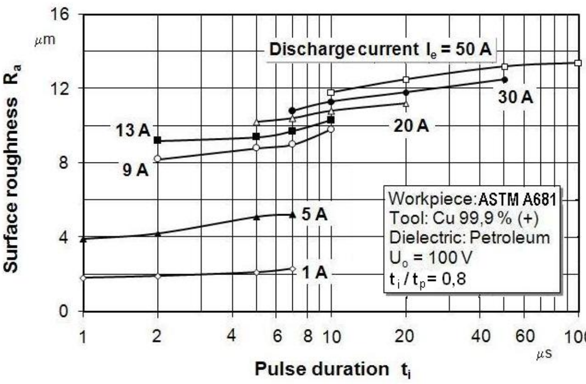

Fig. 7. Influence of the discharge parameters on surface roughness

As EDM generates extremely high temperatures in machining area, thermal defects are to be expected in the workpiece surface layer. Shown in Fig. 8 is metallographic image of the surface layer of hardened tool steel, which was eroded by a copper tool with a certain parameters of discharge energy.

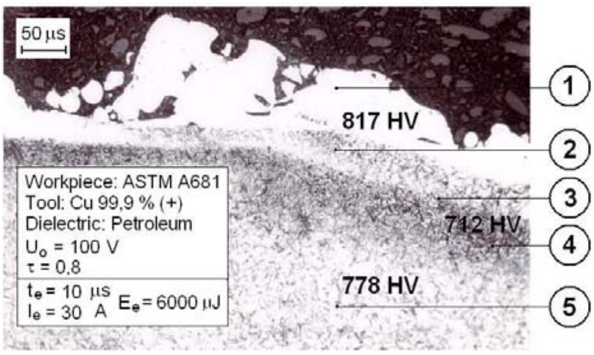

Fig. 8. Metallographic image of the surface layer of tool steel after EDM [18]
1. melted layer, 2. hardened layer, 3. interface layer, 4. tempered layer, 5. basic layer

Metallographic investigations shows that there was a change in workpiece surface layer. The changes manifest as uneven thickness, microstructure transformations, and a modified microhardness compared to the initial state of workpiece material. Fig. 9. shows the dependence of recast layer thickness on discharge energy [18,35-37].

The analysis of metallographic images reveals four characteristic secondary-changed workpiece surface layers: melted metal layer, hardened layer, interface layer, and tempered layer.

The melted layer is a sludge of lightly welded particles which is a residue left after ejection of melted material from the crater. The hardened layer consists of martensite, residual austenite with extremely pronounced grains, and cementite. The interface layer consists of martensitic-austenitic grid, and cementite, where the ratio of austenite diminishes with the distance from the tempered layer. The microstructure of the tempered layer is tempered martensite, and cementite, martensite, and cementite, which gradually phase into basic microstructure consisting of martensite with fine globular cementite.

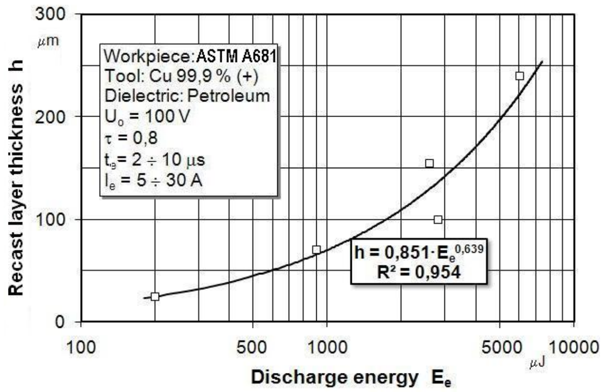

Fig. 9. Dependence of recast layer thickness on discharge energy [18]

Compared to the initial material condition, the secondary-hardened layer has higher, while the tempered layer has lower microhardness, Fig. 8. Higher microhardness of the hardened layer is the result of the austenitic-martensitic phase transition, while the lower microhardness of the tempered layer occurs around the highly tempered grains in the martensitic-austenitic grid.

4. MATHEMATICAL MODELING OF EDM

The mathematical modeling of the EDM process based on the electro-thermal model is conducted using analytical-numerical procedures. It is well known that thermal modeling of EDM processes is very difficult. The role of modeling behind thermal phenomena in the EDM is to adopt the most adequate mathematical model of factors in the discharge zone and their inter-relationships [38-40].

For defined thermal model of EDM, the partial differential equation of heat conduction in two-dimensional cylindrical coordinate system for the workpiece and tool is given as follows:

$$\rho c \frac{\partial T}{\partial t} = k\left(\frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2} + \frac{\partial^2 T}{\partial z^2}\right) \qquad (6)$$

Differential Eq. (6) should be considered in conjunction with the initial temperature which can be taken as normal room temperature of the dielectric in which the electrodes are completely dipped:

$$T(r,z,t)\big|_{t=0} = T_0 \tag{7}$$

and the boundary conditions of the system:

$$-k\frac{\partial T(r,z,t)}{\partial z}\bigg|_{z=0} = q(r,t)$$
$$-k\frac{\partial T(r,z,t)}{\partial z}\bigg|_{z=\infty} = 0 \tag{8}$$
$$-k\frac{\partial T(r,z,t)}{\partial r}\bigg|_{r=\infty} = 0$$

where T is the temperature, r is the radial cylindrical coordinate, z is the axial cylindrical coordinate, t is the time, k is the thermal conductivity, ρ is the material density, c is the specific heat and q is the heat flux density.

The finite element method (FEM) that is used to solve partial differential equations of heat conduction (Eq. 6) using the Galerkin's method can be expressed in matrix form as:

$$[k]\{T\} + [c]\left\{\frac{\partial T}{\partial t}\right\} = \{q\} \tag{9}$$

where $[k]$ is the thermal conductivity matrix; $[c]$ is the specific heat matrix; $\{T\}$ is the temperature vector and $\{q\}$ is the heat flux vector [41-43].

Example 3D axisymmetric finite element model of the EDM electrical pulse discharge process is shown on Fig. 10.

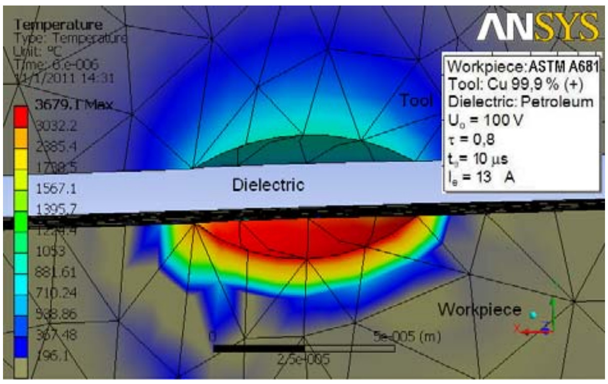

Fig. 10. FEM model of EDM process of a single electrical pulse

The results of FEM modeling of the volume of material removed was compared with the experimental results as shown in Fig. 11. The diagram show that the increase of discharge energy, results in increased radius and depth of the crater, which ultimately leads to higher volume of material removed from the workpiece. The average volume of material removed from the workpiece is calculated using numerical estimated value geometry of the crater.

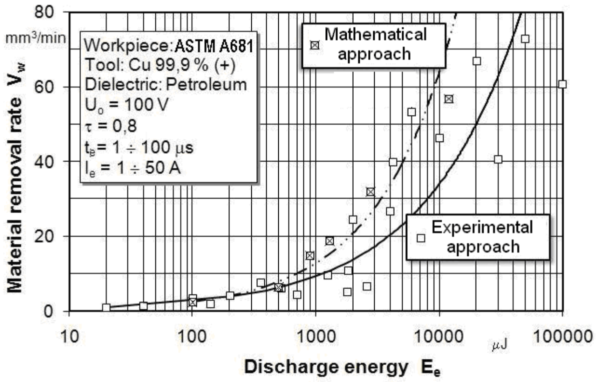

Fig. 11. Comparison of FEM modeling and experimental results of the material removed volume

5. MODELING OF EDM PROCESS USING ARTIFICIAL INTELLIGENCE

Recently, some initial investigations in applying the basic artificial intelligence approach to model machining processes, have been realized. To generalize the experimental results and develop the system model accurately, neural networks, fuzzy systems, evolutionary computation etc, are reported as an alternative approach. From the review of literature, it is observed that artificial intelligence techniques have found wide applications in modelling of process parameters and controlling the EDM system also [44-47].

Evolutionary algorithms, as their name is suggesting are based on principles of evolution and natural selection. Each solution to the problem is considered to be one individual who is evaluated by fitness function. Results of evaluation are directly determining each individual's probability of mating and thus transferring his genetic material onto next generation [48-50].

Evolutionary algorithms are a larger group of algorithms based on evolution but often only genetic algorithms (GA) and genetic programming (GP) are represented. Both of these algorithms are inspired by nature in same way: they apply evolutionary characteristics of selection, crossover and mutation on problem solutions while respecting main law of evolution, survival of the fittest, gradually progress towards optimal solution. In genetic algorithms, results are individuals while in genetic programming solutions are whole computer programs.

Example for a model of the genetic algorithms for material removal rate V_w, gap distance a and surface roughness R_a, depending on the discharge currents I_e and discharge duration t_e, is given by equations:

$$V_w = 0.86 \cdot I_e^{0.9} \cdot t_e^{0.202}$$
$$a = 0.054 \cdot I_e^{0.4} \cdot t_e^{0.054} \tag{10}$$
$$R_a = 2.125 \cdot I_e^{0.468} \cdot t_e^{0.041}$$

In the text below is presents the development and application of an ANFIS (adaptive neuro-fuzzy inference system) in electrical discharge machining for prediction of surface roughness. In this ANFIS system, discharge current and discharge duration are the input variables and output is surface roughness, Fig. 12. The proposed ANFIS model in this study provides a more precise and easy selection of EDM input parameters, leads to better machining conditions and decreases the machining costs [52,55].

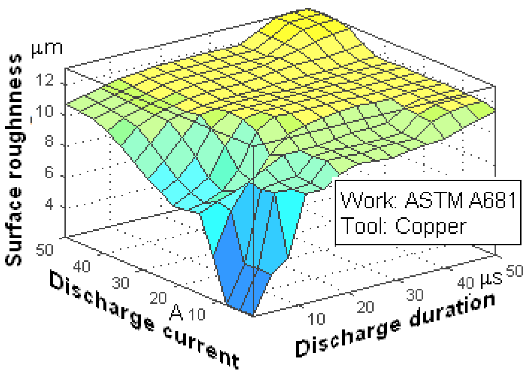

Fig. 12. ANFIS modeling of surface roughness in EDM process [55]

The ANFIS modeling of EDM was able to predict the experimental results and have shown the predictions on the surface roughness with a very small average error. ANFIS gives the mapping relation between the input and output data by using hybrid learning method to determine the optimal distribution of membership functions [53]. Both artificial neural network (ANN) and fuzzy logic (FL) are used in ANFIS architecture [54].

Fig. 13 describes the comparison of experimental, ANFIS ANN and GP predicted results for the surface roughness. It proved that the methods used in this paper are feasible and could be used to predict the surface roughness in an acceptable error rate for EDM. The compared lines seem to be close to each other indicating with good agreement. Comparative observation showed that the genetic algorithms gives slightly smaller deviation of the measured values of model than neuro-fuzzy model [51,55,56].

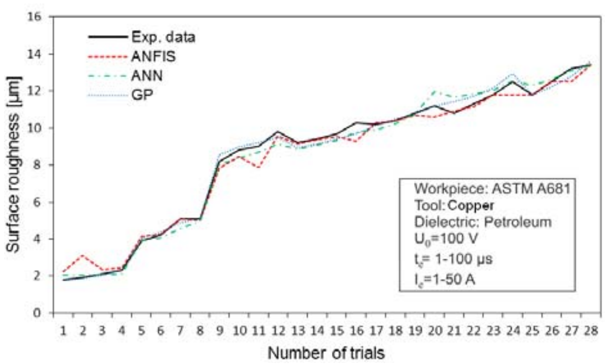

Fig. 13. Correlation between experimental, ANFIS, ANN and GP surface roughness value [46]

6. APPLICATION FOR SELECTION OF EDM PARAMETERS

Based on the summary of results of experimental investigation [13, 18, 21, 57], realised the model for selection of the optimal electrical pulse parameters in EDM. The Fig. 14 shows mutual dependence of material removal rate, tool wear ratio, gap distance and surface roughness for optimal electrical pulse parameters. Selected tool surface or surface roughness enables to choose discharge current and pulse duration which results in maximum material removal rate, and the corresponding gap distance and tool wear ratio.

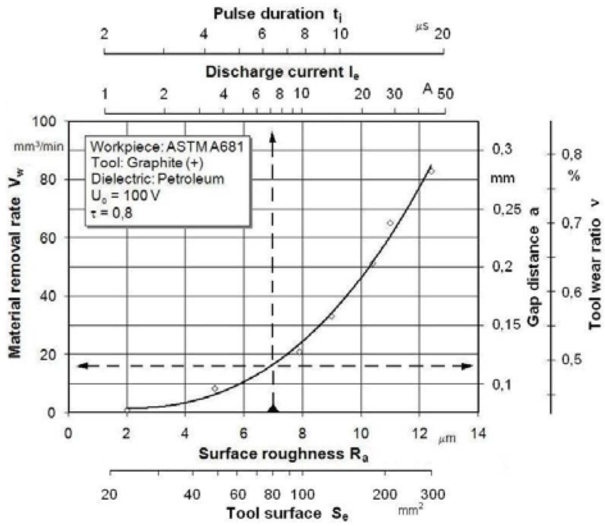

Fig. 14. Model for selection of the optimal electrical pulse parameters in EDM [21]

Fig. 15 shows application form for automatic selection of input parameters in electrical discharge machining.

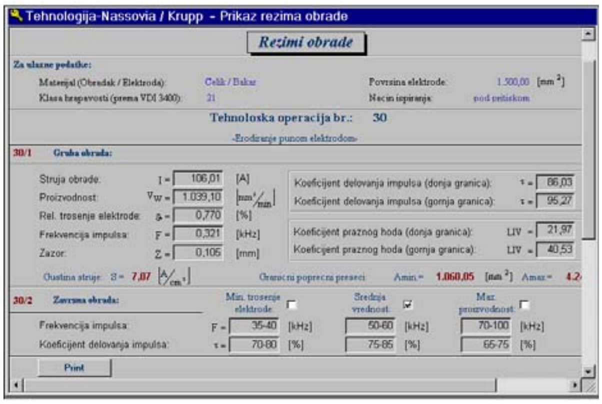

Fig. 15. Application for selection of EDM parameters

5. CONCLUSIONS

Based on the literature review, it follows that the electrical discharge machining (EDM) is a very common type of machining in manufacturing industries. Thereby, the machining characteristics of EDM mainly depend on generation and distribution of discharge energy within the machining zone. The energy generated depends on the discharge current and discharge duration, while the distribution of energy depends on physical and chemical characteristics of the discharge zone. Since the EDM process is complex and stochastic in nature, most attempts to model the technological performance of EDM process in literature, has been reported to be based on electro-thermal concepts. Thereby, for the modeling of EDM the experimental, mathematical, empirical or intelligent methods are used, with different characteristics and approximation results.

Conducted theoretical approach and experimental investigation of the machining characteristics of EDM, yields following conclusions:

- Technological performance of EDM directly depends on the discharge energy which is transformed into thermal energy in the discharge zone;
- An existence of optimal discharge energy which yields optimal productivity and machining quality;
- The analytical-numerical modeling of EDM is a practical way to reliably determine the mechanism of generation and distribution of thermal energy in the discharge zone and be estimate the material removal rate and surface roughness;
- Research showed that intelligent models give accurate prediction on technological performance in EDM;
- Values predicted by the mathematical and intelligent model largely agree with the experimental results and the difference between the modeling and experimental results are primarily due to the difficulty to incorporate all effects in the electro-thermal model of EDM process.

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