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Influence of discharge energy on machining characteristics in EDM [†]

Marin Gostimirovic[*], Pavel Kovac, Milenko Sekulic and Branko Skoric
Department of Production Engineering, Faculty of Technical Science, University of Novi Sad, 21000 Novi Sad, Serbia

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Abstract

The machining characteristics of electrical discharge machining (EDM) directly depend on the discharge energy which is transformed into thermal energy in the discharge zone. The generated heat leads to high temperature, resulting in local melting and evaporation of workpiece material. However, the high temperature also impacts various physical and chemical properties of the tool and workpiece. This is why extensive knowledge of development and transformation of electrical energy into heat is of key importance in EDM. Based on the previous investigations, analytical dependence was established between the discharge energy parameters and the heat source characteristics in this paper. In addition, the thermal properties of the discharged energy were experimentally investigated and their influence on material removal rate, gap distance, surface roughness and recast layer was established. The experiments were conducted using copper electrode while varying discharge current and pulse duration. Analysis and experimental research conducted in this paper allow efficient selection of relevant parameters of discharge energy for the selection of most favorable EDM machining conditions.

Keywords: Discharge energy; Electrical discharge machining; Gap distance; Material removal rate; Surface integrity

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1. Introduction

Electrical Discharge Machining - EDM is a method for material removal which is suitable for all kinds of electroconductive materials, regardless of their physical and metallurgical properties [1]. It is used for machining complex geometry workpieces and difficult-to-machine materials, for which conventional methods are not applicable. The use of EDM is especially essential for the accurate production of forming tools, prototype parts, micro parts and other highly specialized products [2, 3].

The important machining characteristics of EDM are productivity, machining accuracy and surface integrity [4-6]. In EDM, productivity is expressed as the material removal rate. Machining accuracy is defined as tolerances on dimension and shape of the workpiece. Surface integrity is expressed through surface roughness and surface layer properties. The importance of these characteristics 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 machining characteristics of EDM primarily depend on the physical principles on which the material removal is based. In EDM, material is removed through periodical electrical discharges between the tool and workpiece. Within a small volume of the discharge zone, electrical energy is transformed into heat. A plasma zone is formed at temperatures as high as 40,000°C, while the workpiece surface reaches 10,000°C [7]. Such high temperatures cause local heating, melting, evaporation, and incineration of workpiece material. The disruption of current supply annihilates the discharge zone, causing abrupt cooling, which results in an explosive flushing of molten matter and solid particles off the workpiece surface. A series of discharges result in a number of small craters with relevant surface roughness. High temperatures also produce recast layer, electrode wear, thermal dilatations, etc. [8, 9].

It is evident that EDM is complex and stochastic in nature, and involves a combination of several disciplines such as electric, magnetic, thermal, mechanic, dynamic or hydraulic. A number of attempts to model the process have been reported in the literature based on electro-thermal concepts. Thereby, analytical [10, 11], numerical [7, 12, 13] or empirical methods [14-16] with different characteristics and approximation results are used to solve the models.

As previously mentioned, efficiency of EDM mostly depends on generation and distribution of thermal energy within the discharge zone [17-19]. The generated thermal energy depends on the power and duration of heat source, while the distribution of thermal energy depends on heat sinking characteristics. In practice, efficient EDM control implies variation

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[*] Corresponding author. Tel.: +381 21 450 366, Fax.: +381 21 544 495
E-mail address: maring@uns.ac.rs

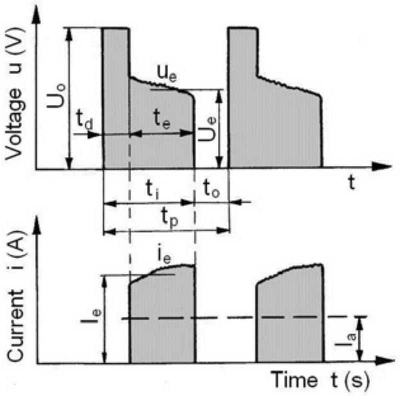

Fig. 1. Characteristic values of voltage and current impulses.

of discharge energy parameters.

This paper takes a different approach towards effect to the discharge energy on machining performance in EDM, using a simple empirical concept. Based on the previous investigation, discharge energy characteristics are identified. Analytical dependence of heat source parameters was established. Theoretical analysis is based on the electro-thermal model. As the proposed method uses an empirical concept, it requires experimental results. For that reason, an experimental investigation was conducted for the influence of heat source parameters on machining characteristics in EDM.

2. Analytical approach

EDM requires the tool and workpiece to be submerged into a liquid dielectric at a small depth, and they must be connected through an electronic switch to a DC power source. Upon establishing the voltage, a strong electric field is established between the tool and workpiece. There is a chain reaction in which a large number of negative and positive ions are produced. The ionization initiates creation of an electro-conductive zone between the workpiece and tool, thus causing electrical discharge. Between the periodic discharges, the products of machining are evacuated from the discharge zone.

2.1 Discharge energy

During an electrical discharge, there exist voltage and current impulses which vary in time (Fig. 1). Electric impulses are determined by the following values: U_o - open gap voltage, U_e - discharge voltage, t_d - ignition delay time, t_e - discharge duration, t_i - pulse duration, t_o - pulse off time, t_p - pulse cycle time, I_e - discharge current, and I_a - average current. The derived values are: $f=1/t_p$ - pulse frequency and $\tau=t_i/t_p$ - duty factor.

The most important parameter of EDM is the discharge energy. The discharge energy is the mean value of electrical energy per one impulse which is transformed into heat, and can be expressed by the following equation:

$$E_e = \int_0^{t_e} u_e(t) \cdot i_e(t) \cdot dt \cong U_e \cdot I_e \cdot t_e . \tag{1}$$

In proper machining conditions, electrical discharge occurs instanteniously and is independent from other electric values. In this case, ignition delay time can be neglected, $t_d \approx 0$, i.e. the discharge duration is equal to pulse duration, $t_e \cong t_i$. The final expression for discharge energy now takes the following, more practical, form:

$$E_e = U_e \cdot I_e \cdot t_i . \tag{2}$$

As can be seen from Eq. (2), the discharge energy is influenced by the discharge voltage, discharge current, and pulse duration. Their influences are interconnected and depend on the rest of the machining parameters.

The discharge voltage depends on the paired tool and workpiece materials. It ranges between 15 and 30 V [6, 20]. Inherent to the electrode materials are thermal properties and the speed of recovery in the discharge zone, so that for every electrodes combination there is a corresponding discharge voltage. On this value cannot be influenced under the given machining conditions.

The discharge current directly impacts the discharge energy. However, the impact of the discharge current is limited by the current density at the electrodes. If the current density oversteps the limit for the given machining conditions (approximately $10 \div 25$ A/cm^2), the stability of the impulse discharge will be threatened [4, 8]. This process initiates continuous current flow and occurrence of arcing or short circuiting. This lengthens the time required to deionize the discharge channel, thus reducing the efficiency of EDM.

The pulse duration is another parameter which allows direct control of discharge energy. However, here too the independent regulation of process parameters is limited. It is known from experience that pulse duration must be limited for a particular discharge current. Otherwise, electric arcing occurs, damaging both the tool and workpiece.

2.2 Thermal state

The thermal state of the EDM discharge zone can be defined by heat sources and sinks [17, 19]. The generated heat, which is the result of a transformation of electrical energy, acts as a heat source. The heat source is established immediately and is extremely intensive and transient. The tool, workpiece and dielectric act as heat sinks since they allow the developed heat to be evacuated from the discharge zone. Shown in Fig. 2 is the electro-thermal model of the EDM.

The heat source characteristics are judged by the type, dimensions, shape, duration and power. The heat source has a fixed location and its effect is immediate. The heat source is classified as an internal heat source as it is generated in a relatively closed space between the electrodes.

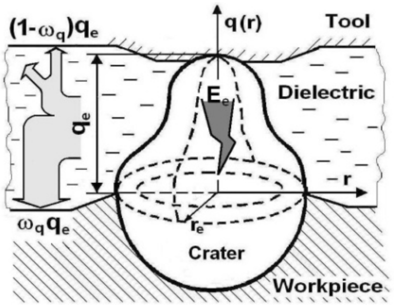

Fig. 2. Electro-thermal model of the EDM.

Besides being defined by heat quantity Q, the heat source power is more often expressed by means of heat flux density q. The heat flux, as the amount of heat transferred across a surface of unit area, S, in a unit time t, is:

$$q = \frac{Q}{\int dS \int dt}\,. \tag{3}$$

Analytical definition of discharge heat considers the fact that in EDM the heat quantity is equivallent to discharge energy:

$$Q \cong E_e\,. \tag{4}$$

By substituting Eqs. (4) and (2) in Eq. (3), an expression for discharge power per one impulse is found:

$$q_e \cong \frac{U_e \cdot I_e}{r_e^2 \pi} \tag{5}$$

where r_e is the discharge radius.

The heat source duration of a single impulse is identical to discharge duration, and for the sake of simplicity, is considered equal to pulse duration:

$$t_e \cong t_i\,. \tag{6}$$

Heat sinking characteristics depend on the EDM conditions as well as the thermal and physical material properties of the workpiece, tool and dielectric [10, 21, 22]. Considering the efficiency of EDM, the heat quantity evacuated through workpiece is of most importance. The ratio of the heat distribution in workpiece q_w and total discharge heat q_e is defined by the heat distribution factor, which is expressed by the following equation:

$$\omega_q = \frac{q_w}{q_e}\,. \tag{7}$$

The heat source characteristics (Eqs. (5) and (6)) and the heat distribution factor (Eq. (7)) impact the efficiency of melting, evaporation and combustion of the workpiece material, but they also affect electrode wear, machining accuracy and surface integrity.

3. Experimental procedures

Experimental investigation was conducted on an EDM machine tool ″FUMEC – CNC 21″ in South Korea (I_e=0÷100 A, t_i=0÷1000 µs, t_o=0÷100 µs, and U_o=0÷100 V). The work material used in the experiment was manganese-vanadium tool steel, ASTM A681 (0.9% C, 2% Mn, and 0.2% V), hardness 62 HRc. The tool was made of electrolytic copper with 99.9% purity and 20×10 mm cross-section. The dielectric was petroleum. Due to small eroding surface and depth, natural flushing was used.

The machining conditions included variable discharge current and pulse duration. The range of the discharge current was I_e=1÷50 A (current density 0.5÷25 A/cm^2), while the pulse duration was chosen from the interval t_i=1÷100 µs to accomodate the chosen current. The rest of the parameters of electric impulse were held constant, according to the manufacturer's recommendations (U_o=100 V, τ=0.8 and positive tool electrode polarity).

The experiments were conducted according to the specified experiment plan. Input parameters were varied and the resulting machining parameters of EDM process were monitored and recorded. Measured parameters were material removal rate V_w, gap distance a, and surface roughness R_a. Metallographic examinations of the surface aspect were conducted on several specimens.

Material removal rate (ratio of removed material volume and the effective machining time) was measured indirectly, by monitoring the machining time for the set eroding depth. The depth and time of eroding were monitored using the machine tool CNC control unit. The machining accuracy of EDM was monitored through the change of side gap distance. Gap distance was calculated as the half of difference between the tool and workpiece contour dimensions. Measurements were conducted using electronic callipers (precision: 0.001 mm). Surface integrity was assesed by measuring surface roughness and research of the surface layer properties. ″PERTHOMETER S5P″ of Mahr, Germany was used to measure the arithmetic average deviation of the assessed profile (ISO 4287). Metallographic examinations of microstructure and microhardness were performed on an optical microscope ″ARISTOMET″ of Leit, Germany with 200 x magnification.

4. Results and analysis

As analysed in the analytical approach, the machining characteristics of EDM predominantly depend on the thermal state which is defined in the discharge zone. Moreover, the thermal state is influenced by the discharge energy, which can be modulated by the discharge current and pulse duration.

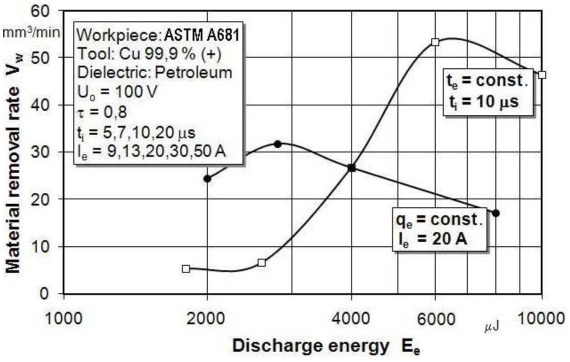

Fig. 3. Influence of the heat source parameters on material removal rate.

4.1 Material removal rate

Fig. 3 shows the influence of the heat source parameters (discharge power q_e and discharge duration t_e) on the material removal rate. The diagram shows that the increase of discharge power (by discharge current I_e=9÷50 A) results in increased discharge energy for steady discharge duration (t_e=const.), which ultimately leads to a higher material removal rate. Moreover, it is evident that the increase of discharge current is limited by the current density. When the current density oversteps 15 A/cm^2 (I_e=30 A) the material removal rate decreases. Also, Fig. 3 shows that for steady discharge power (q_e=const.) there exists an optimal pulse duration (t_i=7 μs) which results in maximum material removal rate.

This efficiently precludes us from unambiguous determination of the influence of the discharge energy on material removal rate. The analytical considerations presented in this paper show that the increase of the heat source parameters increases the material removal rate. The discharge power (Eq. (5)) increases with the increase of discharge current, and the discharge duration (Eq. (6)) increases with the increase of pulse duration. However, the experimentaly established optimal influence of the heat source parameters on material removal rate does not agree with the analytically expressed influence. In real conditions, discharge current and pulse duration cause enormous concentration of removed material, 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, and is thus irreversibly lost. Such impaired process stability affects EDM productivity.

Fig. 4 shows the graphical and analytical influence of discharge energy on the material removal rate. For optimal machining conditions ($t_{i\ (opt)}$), the analytical relationship between material removal rate and discharge energy has a high coefficient of determination, R^2. The coefficient of determination is a measure of how well an analytical model is likely to predict future outcomes. The coefficient of determination is the square of the Pearson's correlation coefficient between the observed and modeled data values. This correlation coefficient is calculated by dividing the covariance of two variables by their standard deviations [23].

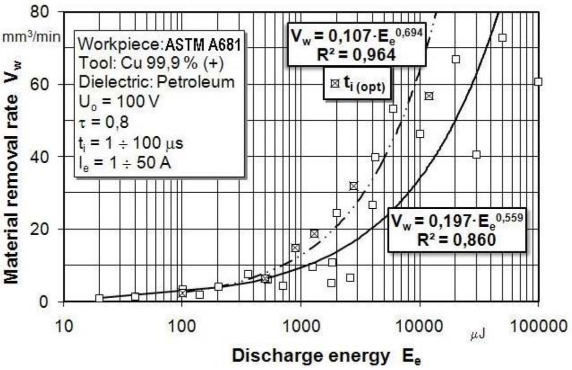

Fig. 4. Dependence of material removal rate on discharge energy.

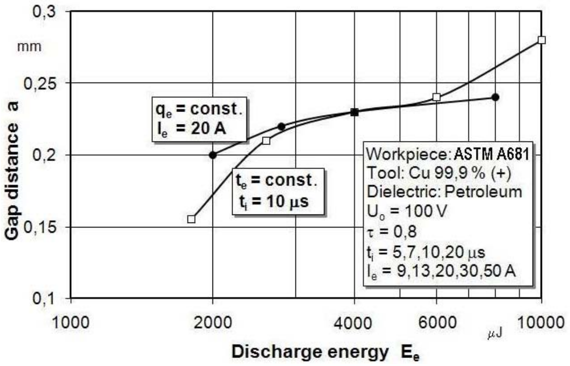

Fig. 5. Influence of the heat source parameters on gap distance.

4.2 Gap distance

Fig. 5 shows the influence of the heat source parameters on gap distance. The diagram shows that the increase of discharge power and discharge duration results in increased discharge energy, which ultimately leads to higher gap distance. Moreover, the discharge power (discharge current) has a somewhat larger influence on the gap distance.

Graphical and analytical relationship between gap distance and discharge energy can be seen in Fig. 6. It is evident that the gap distance follows the discharge energy in order to maintain the stability of EDM. Otherwise, the deionization of the discharge zone would be affected, which could result in either low or uncontrolled material removal rate. The experimental results confirm the analytical assumptions.

4.3 Surface integrity

Fig. 7 shows the influence of the heat source parameters on surface roughness. The diagram shows that the increase of discharge power and discharge duration results in increased surface roughness. Moreover, the heat source parameters have

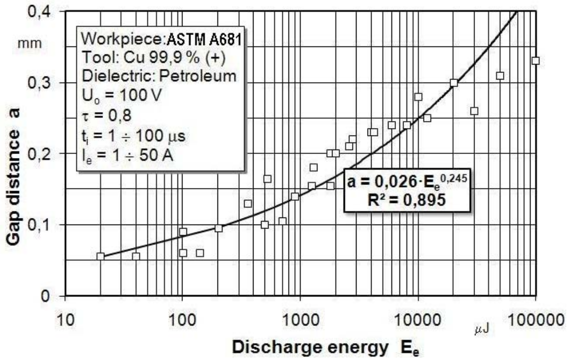

Fig. 6. Dependence of gap distance on discharge energy.

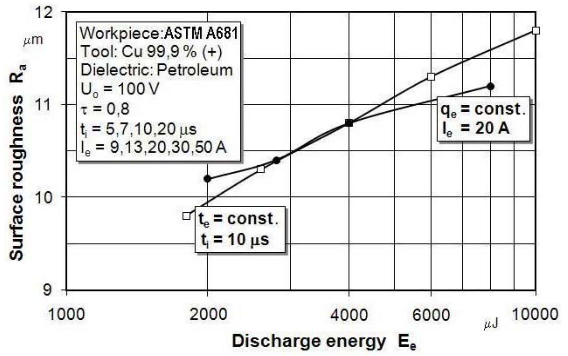

Fig. 7. Influence of the heat source parameters on surface roughness.

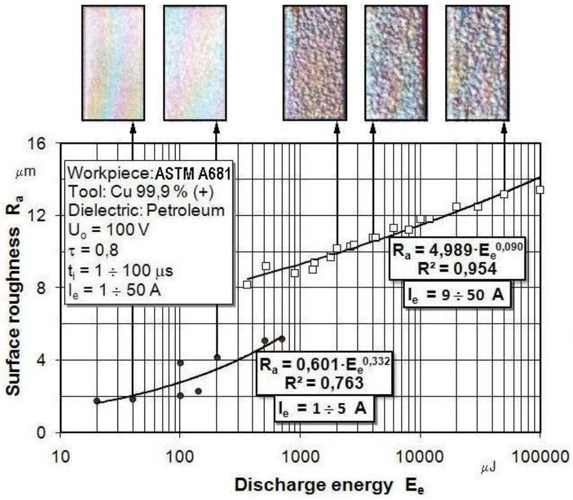

Fig. 8. Dependence of surface roughness on discharge energy.

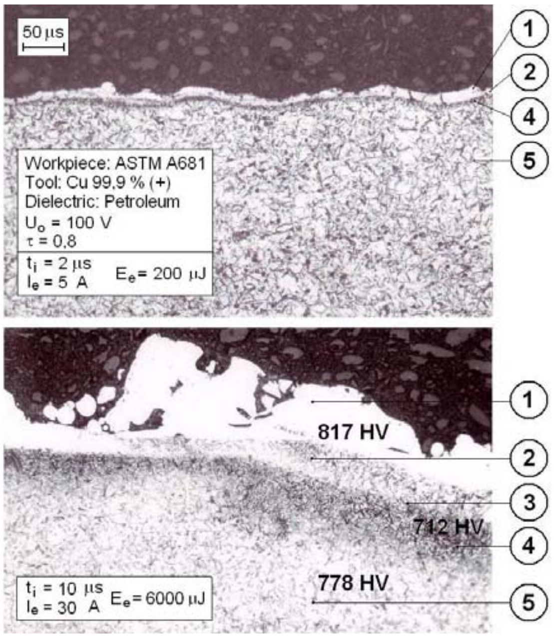

Fig. 9. Metallographic photos of recast layer for tool steel after EDM.

1 - melted layer; 2 - hardened layer; 3 - interface layer; 4 - tempered layer; 5 - bulk material.

a uniform increase on the surface roughness.

The relationship between the surface roughness and discharge energy, for finishing and roughing, is shown in Fig. 8. As the discharge energy increases, so does the thermal energy concentration on the workpiece surface (Eq. (5)), which results in larger craters, i.e. greater surface roughness. The analytical relationship between surface roughness and discharge energy has a good coefficient of correlation. Shown in Fig. 8 are images of machined surfaces at various parameters of discharge energy. The EDM surface consists of a number of craters of various dimensions, while the roughness is even in all directions.

Metallographic investigations show that there is heat affected zone and a recast layer (white layer) at low and high discharge energies, Fig. 9. The recast layer manifests through uneven thickness, microstructure transformations and a modified microhardness compared to the bulk material. That means that for all cases of EDM, for longer or shorter intervals, the surface layer temperature exceeded the temperature of previous tempering, which equals 520°C for the tool steel ASTM A681 (62 HRc) examined in these investigations.

Table 1 shows recast layers thicknesses of the tested specimens. In principle, the increase of discharge energy increases the recast layer thickness. The pulse duration has a more prominent influence on the hardened and tempered layer thickness, while the discharge current is dominant in the melted layer. Generally, the layer thickness is more influenced by discharge duration (Eq. (6)) than its discharge power (Eq. (5)). Fig. 10 shows the dependence of recast layer thickness on discharge energy. The analytical relationship between the recast layer thickness and discharge energy has a high interconnection.

The analysis of typical metallographic photos reveals four characteristic layers: melted layer, hardened layer, interface layer and tempered layer (Fig. 9). The melted layer is a sludge of lightly welded particles, which is a residue left after the ejection of melted material from the crater. The hardened layer consists of martensite, residual austenite and cementite. The interface layer consists of martensitic-austenitic grid and

Table 1. The recast layer thickness of tool steel in EDM.

Level	Machining conditions			Recast layer thickness				
	Discharge current	Pulse duration	Discharge energy	Melted layer	Hardened layer	Interface layer	Tempered layer	Recast layer
(N^o)	I_e (A)	t_i (μs)	E_e (μJ)	*White zone* (μm)	*Light zone* (μm)	*Black zone* (μm)	*Grey zone* (μm)	*h* (μm)
1	5	2	200	15	5	-	5	25
2	9	5	900	25	20	-	25	70
3	13	10	2600	30	50	10	65	155
4	20	7	2800	30	30	5	35	100
5	30	10	6000	115	45	10	70	240

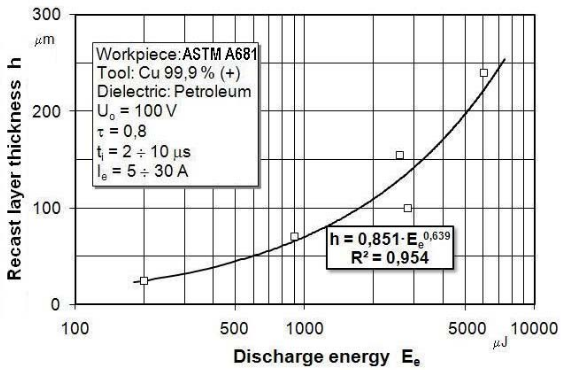

Fig. 10. Dependence of recast layer thickness on discharge energy.

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, which gradually phase into basic microstructure consisting of martensite with fine globular cementite.

Compared to the bulk material, the hardened layer has higher microhardness, while the tempered layer has lower microhardness (Fig. 9). 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.

4.4 Discussion

Based on analytical and experimental investigation it was established that machining performance of EDM directly depends on the thermal energy, which is the result of a transformation of electrical energy. As analyzed in the theoretical approach, the machining characteristics of EDM predominantly depend on the heat source parameters (discharge power and discharge duration) and thermal properties of the electrode materials. In practice, the heat source parameters can be changed by the discharge current and pulse duration.

Analytical approaches of influence of the discharge energy on machining characteristics in EDM are investigated through experimental verification. The result of experimental investigation influence of the heat source parameters on material removal rate does not agree with the analytical influence. On the other hand, experimental results confirm analytical influence of the heat source parameters on machining accuracy and surface integrity.

The theoretical analysis and experimental results show some good information which could be used by future researches for optimal control EDM machining conditions.

5. Conclusions

The conducted analytical and experimental investigations yield the following conclusions:

- Efficiency of EDM directly depends on the power and duration of the discharge energy which is transformed into thermal energy in the discharge zone;
- The increase of discharge energy increases the material removal rate. However, there exists an optimal discharge energy which yields maximum material removal rate. For an optimal discharge duration (pulse duration), the material removal rate increases with the increase of the discharge power (discharge current);
- When the discharge energy is increased, either through discharge duration or discharge power, the gap distance exerts greater influence on the machining accuracy of EDM. Moreover, the discharge power is more significant than discharge duration;
- Surface roughness directly depends on the discharge energy, so that the discharge power and discharge duration cause a uniform increase of surface roughness;
- Heat affected zone is present at all levels of discharge energy. The increase of discharge energy increases the recast layer thickness. The formed recast layer is influenced by heat source parameters, while the discharge duration has a more pronounced influence on the recast layer.

Acknowledgment

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Nomenclature

a : Gap distance
E_e : Discharge energy
f : Pulse frequency
h : Recast layer thickness
I_a : Average current
I_e : Discharge current
q : Heat flux density
Q : Heat source power
q_e : Discharge power
q_w : Heat distribution in workpiece
r_e : Discharge radius
R_a : Surface roughness
R^2 : Coefficient of determination
S : Surface of unit area
t : Time
t_d : Ignition delay time
t_e : Discharge duration
t_i : Pulse duration
t_o : Pulse off time
t_p : Pulse cycle time
U_e : Discharge voltage
U_o : Open gap voltage
V_w : Material removal rate
ω_q : Heat distribution factor
τ : Duty factor

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Marin Gostimirovic received his B.S, M.S. and Ph.D. degrees from the University of Novi Sad, Serbia, in 1982, 1989 and 1997, respectively. He is currently an associate professor at the Faculty of Technical Science at University of Novi Sad, Serbia. His research interests include advanced machining technologies - cutting techniques, nonconventional processes, heat phenomena and artificial intelligence.