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Effect of electrical pulse parameters on the machining performance in EDM

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In electrical discharge machining (EDM) material is removed through periodical electrical discharges between the tool and workpiece. The electrical discharge energy which is transformed into heat in the discharge zone is of key importance in EDM. The machining performance of EDM is defined by the characteristics of electrical discharge pulse. For these reasons, the principle of EDM and the characteristics of electrical pulse parameters are analyzed in this paper. Discharge current and pulse duration are selected as the most important electrical pulse parameters. In addition, their influence on material removal rate, tool wear ratio, gap distance and surface roughness are experimentally investigated. The experiments are conducted on an manganese-vanadium tool steel using graphite tool electrodes. The study allows efficient identification of relevant electrical pulse parameters, and the results obtained represent a technological knowledge base for the selection of optimal EDM machining conditions.

Keywords: EDM, Discharge current, Pulse duration, Machining performance

Electrical discharge machining (EDM) is one of the most important non-conventional machining processes. It is primarily used for machining difficult-to-machine materials and complex geometry parts for which traditional techniques 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. Moreover, this process is only available for machining metals (hardened alloy steel, high speed steel, cemented carbide) and materials that offer minimal electrical conductivity.

EDM is an electro-thermal production process[1] in which material is removed through periodical electrical discharges between the tool and workpiece. Figure 1 shows the phases of a single electrical discharge in the EDM. Upon establishing the voltage, a strong electric field is established between the tool and workpiece (ignition phase). Due to the attractive force of the electric 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 breakdown 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. An avalance ionisation process is set off, 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. Through electrical discharge, electrical energy is transformed into thermal energy[2]. A discharge zone is formed at temperatures as high as 40000°C[3]. Such high temperature causes local heating, melting, evaporation, and incineration of workpiece material. High temperature also produces lower machining

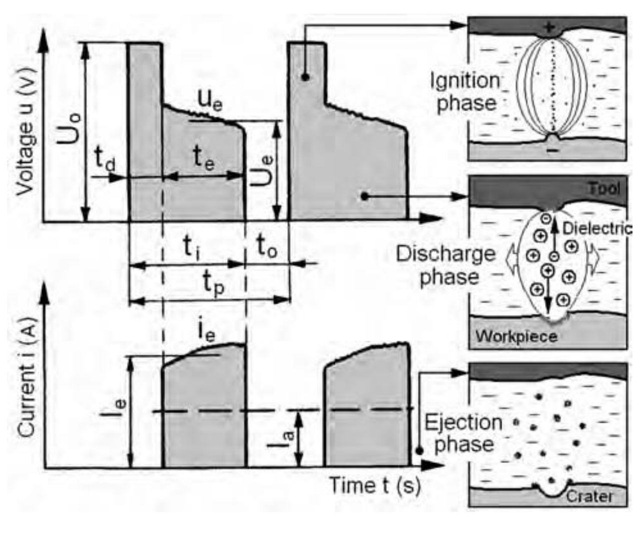

Fig. 1— Principle of EDM and characteristics of electrical pulse parameters

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quality, tool wear and thermal dilatations. 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).

Similar to other machining processes, the most important EDM machining performances are: productivity[4], tool wear[5], machining accuracy[6], surface integrity[7] and machining costs. Productivity is expressed as the material removal rate and refers to the speed of removal per time unit. Tool wear is quantified by tool wear ratio which is the ratio between the eroded volume of the tool and workpiece. Machining accuracy is defined by the tolerances on dimension and shape of the workpiece. Surface integrity is expressed through the surface roughness and surface layer properties. Machining costs include creating tools, machining time, power consumption and investments. The importance of machining performance is relative and depends on the 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 performance of EDM mostly depends on electrical pulse parameters[8,9]. During an electrical discharge there are voltage and current pulses which vary in time (Fig. 1). Electrical pulses are interdependent, and they are determined by the following parameters: U_o – open gap voltage, U_e – discharge voltage, t_d – ignition delay time, t_e – discharge duration, $t_i=t_d+t_e$ – pulse duration, t_o – pulse off time, $t_p=t_i+t_o$ – pulse cycle time, I_e – discharge current, and I_a – average current. The derived parameters are: $f=1/t_p$ – pulse frequency, $\tau=t_i/t_p$ – duty factor and $W_e=U_eI_et_i$ – discharge energy.

The open gap voltage and the discharge voltage do not exert direct influence on the machining performance. The open gap voltage exerts influence on the ignition delay time of the discharge. The discharge voltage depends on the paired electrode materials and machining conditions. It ranges between 15 and 30 V[10]. With proper machining conditions, electrical discharge occurs instantaneously and is independent of other electrical pulse parameters. 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 pulse off time provides a deionization of dielectric fluid and stability of electrical discharge pulse. Minimal possible values of pulse off time are set.

Besides the electric parameters described above, the polarity (±) of electrodes, has important effects on the EDM results[10,11]. The polarity can be either positive or negative and it depends on tool material, workpiece material, current density and pulse 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 to attain good material removal rate and the minimum relative tool wear ratio.

Therefore, the most important electrical pulse parameters of EDM are discharge current and pulse duration[11,12]. These parameters directly influence the machining performance. However, the impact of discharge current I_e is limited by the tool surface area S_e which is interfacing the workpiece, i.e., the current density ($\gamma=I_e/S_e$). In cases 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 pulse duration is also limited. It is known from experience that the pulse duration must be limited for a particular discharge current. Otherwise, an electric arcing occurs which damages both the tool and workpiece.

In this paper a model for selection of optimal electrical pulse parameters in EDM is investigated.

Experimental Procedures

Experimental investigation was conducted on EDM machine tool ″FUMEC – CNC 21″ of South Korea (I_e=0÷100 A, t_i=0÷1.000 μs, t_o=0÷100 μs, and U_o=0÷100 V). The 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 nodular graphite (average grain size 12 μm, specific density 1.780 kg/m^3, melting temperature 3.410°C, electrical resistivity 1.37 μΩ·cm), 20×10 mm cross-section (S_e=200 mm^2). The dielectric was petroleum (specific density 830 kg/m^3, ignition temperature 126°C, viscosity 5.3 CSt). Due to the 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 γ=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 electric pulse parameters were held constant, according to manufacturer's recommendations (U_o=100 V, τ=0,8 and positive tool electrode polarity).

The experiment was conducted according to the specified experimental plan. Input parameters were varied and the resulting machining performance of EDM process was monitored and recorded. Material removal rate V_w, tool wear ratio υ, gap distance a, and surface roughness R_a were measured.

Material removal rate 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 material removal rate was calculated as the ratio of removed material volume, and the effective machining time. Tool wear ratio was calculated as the ratio of the volume of material removed from the tool to the volume of material removed from the workpiece ($\upsilon = V_e/V_w$). The precise quantifications of tool and workpiece material removal before and after machining were measured on an analytical balance Toledo Mettler PM 2000 (resolution of 0.01 g). The machining accuracy of EDM was monitored through the change of side gap distance. The gap distance was calculated as the half of a difference between the tool and workpiece contour dimensions. The measurements were conducted using electronic callipers (precision of 0.001 mm). The surface integrity was assesed by measuring surface roughness. Mahr Perthometer S5P was used to measure the arithmetic average deviation of the assessed profile (ISO 4287).

Results and Discussion

Figure 2 shows the effect of the most important electrical pulse parameters on the material removal rate of tool steel using graphite tool electrode. The diagram shows the dependence of material removal rate on pulse duration for various discharge currents. The results of experimental investigation show that for every discharge current I_e there is a corresponding optimal pulse duration $t_{i(opt)}$ which allows maximum material removal rate $V_{w(max)}$. This value increases with the increase of discharge current.

On the other side, Fig. 3 shows that at constant pulse duration, the increase of discharge current increases the material removal rate. Moreover, it is evident that the increase of discharge current is limited by the current density. When the current density oversteps γ=10÷15 A/cm^2 the material removal rate is reduced.

For this reason, the influence of the discharge current and pulse duration on material removal rate cannot be determined without ambiguity. The experimentaly 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 pulse duration increase material removal rate, as well as gas bubbles in the discharge zone. Due to the impaired evacuation of machining products, a portion of the discharge energy is spent on re-melting and evaporation of solidified metal particles. Also, a larger portion of discharge energy takes place in a gaseous environment, thus being lost irreversibly. Such impaired process stability affects the EDM productivity.

Furthermore, tool wear ratio was conducted for low, medium, and high discharge parameters. Selected discharge current following optimal pulse duration yields maximum material removal rate. The calculated value of the tool wear ratio is shown in Fig. 4. The diagram shows that the increase of electrical

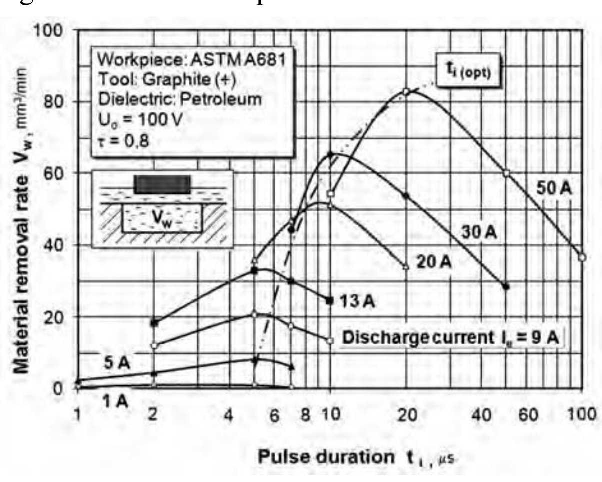

Fig. 2— Dependence of material removal rate on pulse duration for various discharge currents

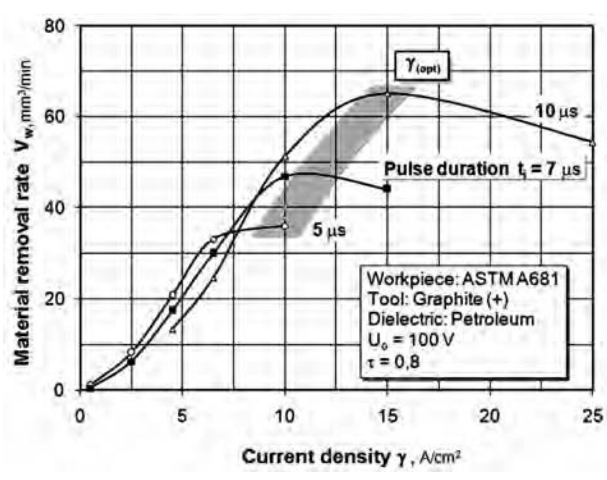

Fig. 3— Influence of the current density on material removal rate

pulse parameters results in increased tool wear. Figure 4 shows the image of the tool working surface before and after EDM, at medium electrical pulse parameters. It is evident that the tool wear is not uniform over the tool working surface. Rapid tool wear happens on sharp edges of the tool. For this reason, identification of tool wear is quantified by tool wear ratio.

Figure 5 shows the influence of discharge current and pulse duration on gap distance. The diagram shows that the increase of electrical pulse parameters results in increased gap distance. Although the influence of discharge current and pulse 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 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.

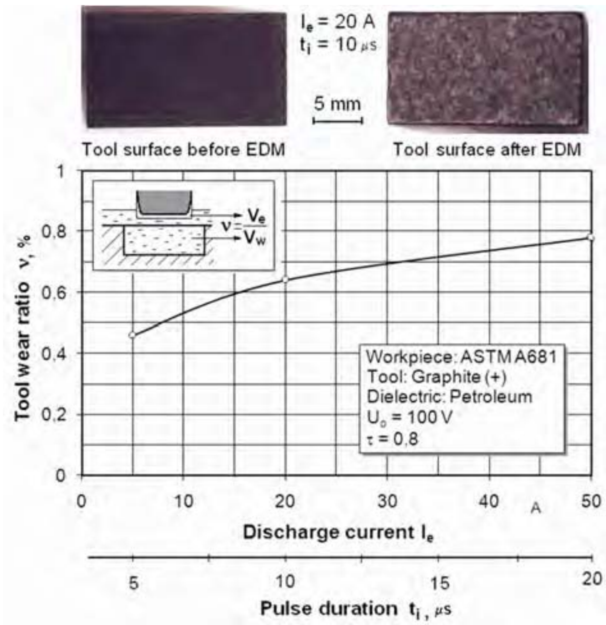

Fig. 4— Relationship between tool wear ratio and electrical pulse parameters

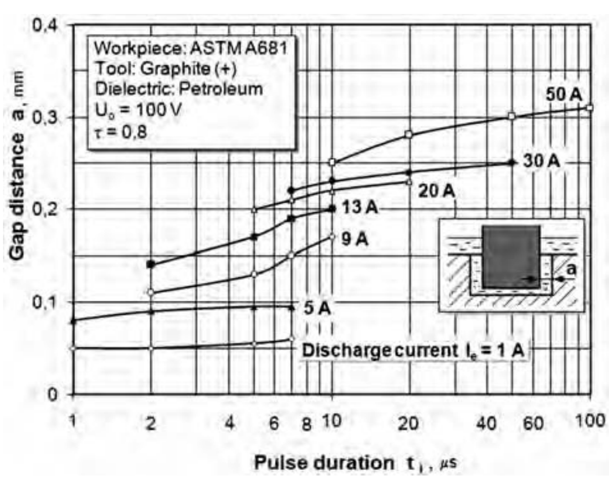

Fig. 5— Influence of the electrical pulse parameters on gap distance

The relationship between the surface roughness and electrical pulse parameters is shown in Fig. 6. The results of experimental investigation show a slight increase of surface roughness with the increase of pulse duration, while the discharge current has a more pronounced influence on surface roughness. As the discharge current increases, so does the discharge heat concentration on the workpiece surface, which results in larger craters, i.e., greater surface roughness. Figure 6 shows 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.

Figure 7 shows the summary of results of experimental investigation. The figure 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 chosing the discharge

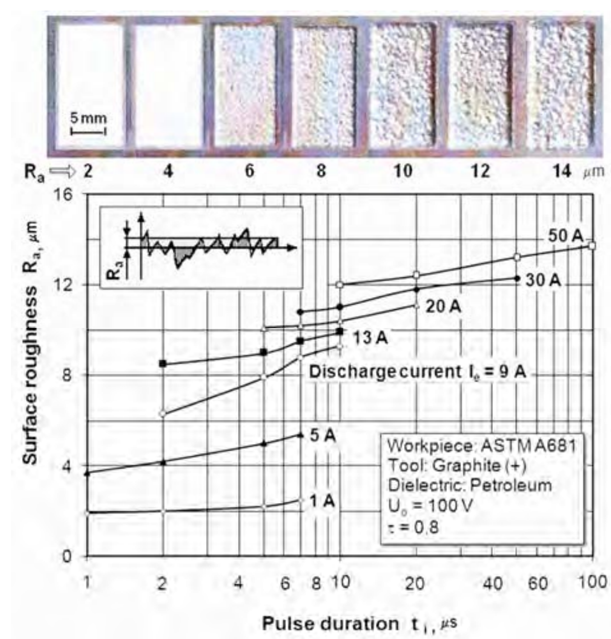

Fig. 6— Influence of the electrical pulse parameters on surface roughness

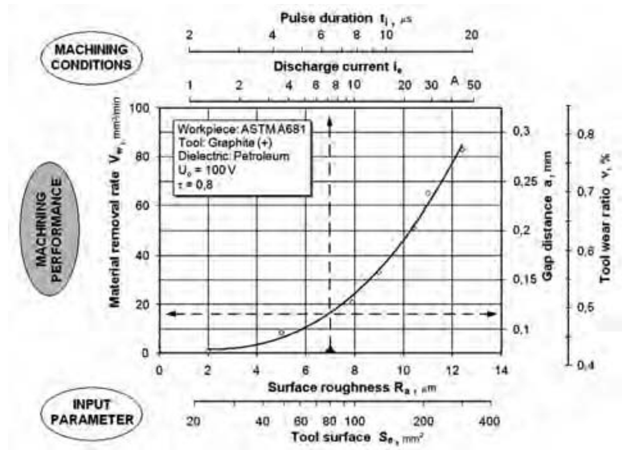

Fig. 7— Model for selection of the optimal electrical pulse parameters in EDM

current and pulse duration which result in maximum material removal rate, and the corresponding gap distance and tool wear ratio.

Conclusions

The conducted experimental investigations yield the following conclusions:

(i) The machining performance of EDM directly depends on the electrical pulse parameters. Their influence is interconnected and depends on the rest of the machining conditions. The most important electrical pulse parameters are the discharge current and pulse duration.

(ii) There exists an optimal condition of discharge current and pulse duration which yield maximum material removal rate. Moreover, the increase of discharge current is limited by the current density.

(iii) The increase of electrical pulse parameters increases the tool wear ratio. It is evident that the discharge current has a more pronounced influence on the tool wear.

(iv) Discharge current and pulse duration cause uniform increase of gap distance, indicating that when the electrical pulse parameters are increased, the gap distance has a greater influence on the machining accuracy.

(v) Surface roughness directly depends on the discharge current and pulse duration. However, the discharge current is more significant than pulse duration.

Nomenclature

a	=	gap distance, mm
f	=	pulse frequency, Hz
I_e	=	discharge current, A
I_a	=	average current, A
R_a	=	surface roughness, µm
S_e	=	tool surface, mm^2
t_d	=	ignition delay time, µs
t_e	=	discharge duration, µs
t_i	=	pulse duration, µs
t_o	=	pulse off time, µs
t_p	=	pulse cycle time, µs
U_e	=	discharge voltage, V
U_o	=	open gap voltage, V
V_e	=	tool removal rate, mm^3/min
V_w	=	material removal rate, mm^3/min
W_e	=	discharge energy, µJ
γ	=	current density, A/cm^2
υ	=	tool wear ratio, %
τ	=	duty factor

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