STUDY ON PARAMETERS SETTINGS FOR FINISHING RAM EDM OF AISI P20 TOOL STEEL

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Abstract. *The AISI P20 steel is traditionally applied by the tooling industry as material for injection molding tools used to produce large batches of varied types of plastic products, ranging applications from the automotive industry up to household goods and leisure industries. It is known that the EDM process parameters technology installed at the majority of CNC EDM machines do not cover some of the daily necessities of the tooling industry concerning process parameters for a wide range of workpiece materials. Considering this situation, the costumers are required to develop their own process parameters. In respect to the above discussion and in order to provide useful technical information to the Brazilian tooling industry, it has been carried out an experimental investigation on the EDM of the AISI P20 tool steel under finish machining. The material removal rate V_w, volumetric relative wear ϑ and workpiece surface texture R_a, which are representative EDM performance aspects, were analyzed against the variation of some of the most important EDM electrical variables using copper tool electrodes under positive and negative polarity. The EDM machine generator was also programmed to actuate under isoenergetic mode and relaxation mode. The results are technically discussed and then appropriate process parameters for EDM of AISI P20 are suggested.*

Keywords. EDM, finish machining, AISI P20 tool steel, process parameters.

1. Introduction

The electrical discharge machining process, shortly EDM, is traditionally engaged in the environment of the tooling industry for decades. Klocke (1998) points out that EDM is particularly used when geometrically complex shapes – like dies, punches and plastic injection molding tools – have to be produced in difficult to machine materials. Figure (1), adapted from König & Klocke (1997), briefly presents the phases of a discharge in EDM process. The first one is the ignition phase, which represents the lapse corresponding to the occurrence of the breakdown of the high open circuit voltage $\hat{u}_i$, applied across the working gap, until the fairly low discharge voltage u_e. This period is known as ignition delay time t_d [µs]. The second phase, which instantaneously occurs right after the first one when the current rapidly increases to the operator specified peak current $\hat{\imath}_e$ [A], is the formation of a plasma channel surrounded by a vapor bubble. The third phase is the discharge phase; when the high energy and pressure plasma channel is sustained for a period of time t_e [µs] causing melting and evaporation of a small amount of material in both electrodes. The fourth and last phase is the collapse of the plasma channel, after turning off the electric energy, which causes the molten material to be violently ejected. At this time, known as pulse interval time t_o [µs], a part of the molten and vaporized material is flushed away by the flow of the dielectric fluid across the gap and the rest is solidified in the recently formed crater and surroundings. Klocke (2001) remarks that the main electrical parameters that influence the EDM performance are discharge the duration t_e, the pulse interval time t_o, the polarity of the tool electrode and generator actuation mode.

Löttgen (1998) report that during the last decades there were more and more low cost EDM machines delivered with technology tables made under conditions described by VDI 3402 norms (1990). These technology tables consist of the most appropriate EDM parameters settings regarding the performance aspects such as material removal rate, volumetric relative wear and surface texture, among others. However, the tests developed by the manufacturers to build the technology tables are carried out under optimum machining conditions and by using standard materials, which is not normally the cases daily faced by the tooling industry. So, in order to achieve reliable results under realistic machining conditions the manufacturer or the costumer himself has to develop further tests for each different kind of work, e.g., concerning the cavity geometry as well as the type of workpiece material.

Considering the above discussion and in order to provide useful technical information to the Brazilian tooling industry, this work has carried out and experimental study on the variation of discharge current $\hat{\imath}_e$, discharge duration t_e, tool electrode polarity and generator actuation mode (isoenergetic and relaxation circuit) and their influences on the following important technological aspects concerning the EDM performance under finish machining: (a) the material removal rate V_w, which means the volume of material removal removed from the workpiece electrode per minute; (b) the volumetric relative wear ϑ that corresponds to the ratio between the tool electrode wear rate V_e and the material removal rate V_w and (c) the surface texture R_a of the EDMachined workpiece samples.

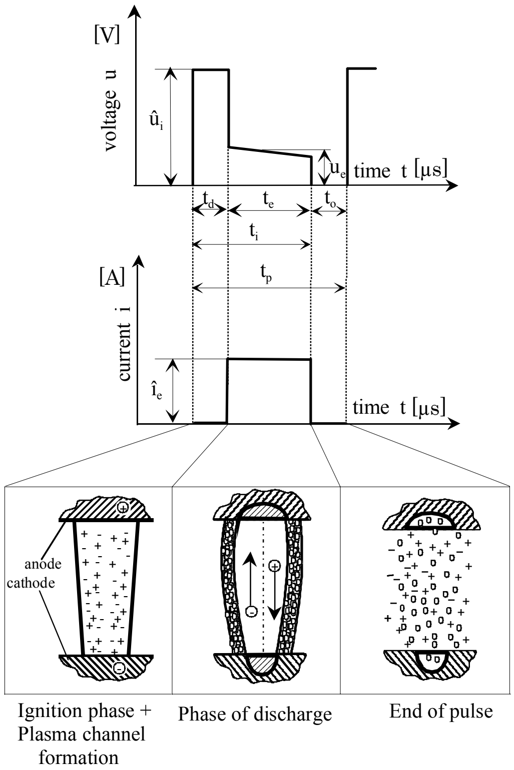


Figure 1. The phases of an electric discharge in EDM.

2. Materials and experimental procedures

The experiments were conducted at the Machining Processes Laboratory – LAUS of the Pontifical Catholic University of Paraná – PUCPR, in Curitiba, using a Charmilles ROBOFORM 30 CNC die-sinking EDM machine. To accurately achieve reliable results the following materials and procedures were considered:

(a) AISI P20 workpieces square samples 25 mm wide and 15 mm thick presenting a R_a= 2 μm surface texture.

(b) Electrolytic copper cylindrical bars, with a diameter of 20 mm and a 4 mm central hole, were mounted axially in line with workpieces and used as tool electrodes under positive and negative polarity.

(c) The Arclean Electron hydrocarbon dielectric – viscosity of 3 cSt at 20^oC - produced by Archem Química Ltda was injected under 0,01 MPa through the electrode hole providing adequate flushing of the eroded particles away from the working gap.

(d) Two actuation modes of the generator were set. The first one was the isoenergetic generator, which means that is possible to set - among others EDM parameters - the discharge duration t_e and to control the ignition delay time t_d as a percentage of t_e. In this work t_d was kept as 30% of t_e for all the experiments. The second mode was the relaxation circuit. In such a generator, the DC-power supply charges a capacitor until the tension between the electrodes is sufficiently high to cause a discharge, that then releases the electrical energy via the plasma channel. When the tension over the gap becomes low the discharge is automatically ended. This type of generator is normally used in fine EDM operations, although a limited control of the EDM process is possible.

(d) In order to optimize the results of V_w, ϑ and R_a, pilot tests on the variables named open circuit voltage $\hat{u}_i$, discharge duration t_e, pulse interval time t_o and discharge current $\hat{i}_e$ were carried out to properly scan them. Afterwards, the main tests were performed under the conditions presented in Tab. (1). The precise quantification of V_w and ϑ was possible by using a precise balance, with resolution of 0,0001 g, to weigh the electrodes (tool and workpiece) before and after an average machining time of 30 minutes. The tests were done three times for each parameters settings.

Table 1. Experimental electrical discharge machining parameters settings.

Discharge current $\hat{i}_e$ [A]	Discharge duration t_e [μs]	Pulse interval time t_o [μs]	Open circuit Voltage $\hat{u}_i$ [V]	Tool electrode polarity	Generator mode
3; 6; 8	6,4; 12,8; 25; 50; 100; 200	6,4; 12,8; 25; 50; 100; 200	160	(+) and (-)	isoenergetic
1; 2	1,6; 3,2; 6,4; 12,8; 25	1,6; 3,2; 6,4; 12,8; 25	200	(-)	relaxation

3. Results and discussions

In finish conditions of electrical discharge machining one of the most important objectives is to achieve the best workpiece surface quality together with a low level of volumetric relative wear. In order to assure this aim, in this work, the duty factor τ, which means the ratio between the pulse duration t_i and the pulse cycle time t_p ($t_p = t_i + t_0$), was chosen to be constant at 0,5 for all the tests. This value of τ, i.e., $t_i = t_o$, was used because the good stability normally observed on EDM operations for this condition, which means a few occurrence of short-circuits and arc-discharges as a consequence of the proper flushing of eroded particles away from the working gap. Smaller values of duty factor ($t_i < t_o$), which is commonly established by keeping t_i constant and increasing the value of t_o, would lead to very low discharges frequencies, consequently decreasing the material removal rate. On the other hand, levels of τ higher than 0,5 ($t_i > t_o$), set by reducing the value of t_o in relation to t_i, would probably cause an over-concentration of debris in the working gap leading to non-uniform material removal along the frontal surfaces of both the tool and the workpieces electrodes as well as a possible increase of the roughness.

The open gap voltage $\hat{u}_i$ has an intrinsic relation with the magnitude of the working gap, i.e., the distance between the electrodes during the spark. The higher is the value of $\hat{u}_i$ the larger is the working gap. So, it is a common practice to set $\hat{u}_i$ at lower levels – 80, 100, 120 V - when EDM under rough conditions, because the high average energy $W_e = u_e \cdot \hat{i}_e \cdot t_e$ [J] is able to keep a larger working gap which, by its turn, causes proper expulsion of debris. As the energy W_e is decreased so is the working gap magnitude. Thus, in finish EDM operations is recommended to establish higher values of $\hat{u}_i$ in order to promote a more adequate working gap. In this work, the value of $\hat{u}_i$ = 160 V was established for the tests with discharge currents of 3, 6 and 8 A after pre-tests with 120 and 200 V. This magnitude of $\hat{u}_i$ guaranteed a proper dispersion of the sparks along the frontal area of the electrodes and good flushing conditions.

Figure (2) depicts the results of material removal rate V_w against the variation of discharge current $\hat{i}_e$ when using the tool electrode positively charged (anode) and the generator under the isoenergetic mode. It is observed that the best material removal rate V_w is approximately 8 mm^3/min for $\hat{i}_e$ = 8 A and an optimum discharge duration t_e = 50 µs.

For the discharge current $\hat{i}_e$ at 6 A the maximum V_W = 4 mm^3/min was reached for t_e of 50 µs. It is also clearly seen that the global levels of V_w obtained for $\hat{i}_e$ = 3 and 6 A are much lower than those achieved for $\hat{i}_e$ = 8 A. It occurs because the material removal rate V_w is proportional to the energy $W_e = u_e \cdot i_e \cdot t_e$ [J] released into the working gap, i.e., higher levels of W_e leads to better values of V_w. In the case of $\hat{i}_e$ = 3 A, although there is just a slightly difference among the levels of V_w when the discharge duration varies from 12,8 to 50 µs, the best stability of the process was noticed when EDM under discharge duration of 25 µs which promoted V_w of about 1 mm^3/min.

Regarding the behavior of material removal rate for each different discharge current $\hat{i}_e$, it can be pointed out from Fig. (2) that as the discharge duration t_e increases, V_w also increases up to a maximum value for a specific optimum t_e. Beyond this point V_w starts decreasing. The explanation for V_w behavior after its maximum point is concerned to a very high plasma diameter global expansion due to the longer discharge durations t_e, that diminish pressure and energy of the plasma channel over the molten material of the electrodes, as discussed by Dibitonto et al. (1989). As a consequence, this phenomenon brings instability into the process lowering the material removal rate.

It is important to remark that, independently of the discharge current $\hat{i}_e$ (3,6,8 A), the stability of the process in terms of the occurrence of arc-discharges and short-circuits was rather good, presenting a proper evacuation of debris and an uniform material removal from both electrodes (tool and workpieces) when EDM under the optimum values of discharge durations t_e.

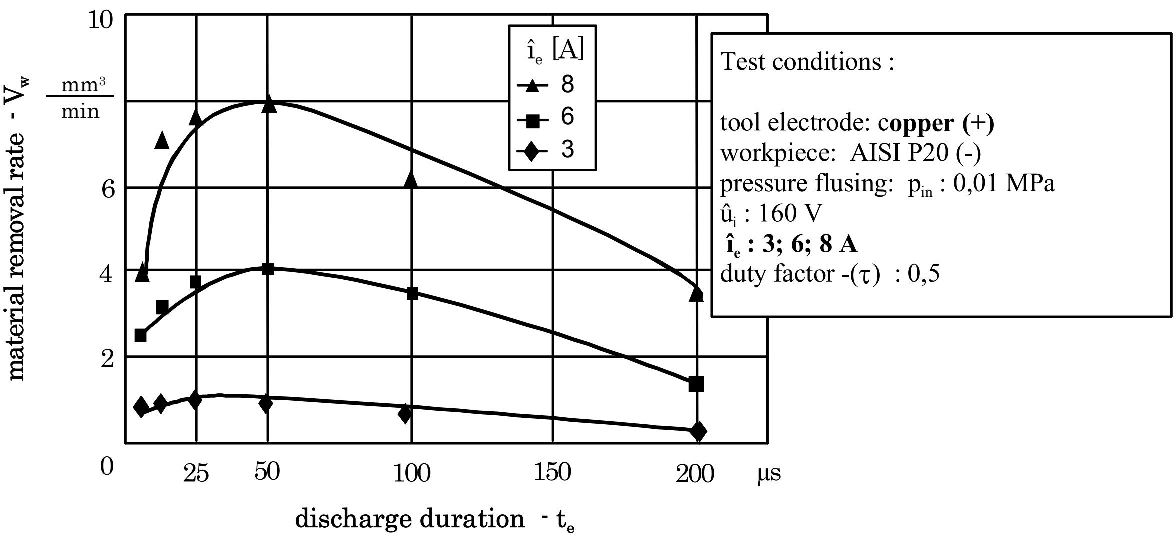


Figure 2. Material removal rate V_w against the variation of discharge duration t_e for discharge currents $\hat{i}_e$ = 3,6,8 A using a positive polarity for the tool electrode under isoenergetic generator mode.

Figure (3) presents for discharge currents of $\hat{i}_e$ = 3, 6, 8 A the results of material removal rate V_w against the variation of discharge current $\hat{i}_e$ when using the tool negatively charged (cathode). From the observation of Fig. (2) and Fig (3) it becomes straight seen that the material removal rate V_w is much better for positive polarity of the tool electrode (anode) than for the negative polarity (cathode). On the second case, when the tool is the cathode, the maximum value of material removal rate V_w is about 0,13 mm^3/min for $\hat{i}_e$ = 8 A at an optimum t_e = 12,8 μs as shown below in Fig. (3), while for $\hat{i}_e$ = 8 A at positive polarity the maximum V_w was about 8 mm^3/min, as presented in Fig.(2).

This performance of V_w is due to the different melting behavior of cathode and anode during a discharge, which can be explained by the following phenomenon: during the discharge, the plasma channel diameter near the molten pool on the anode side (workpiece) becomes very large, which decreases the energy density of the flow of electrons over the molten pool. Due to the decreasing energy density and to the heat conduction to the cooler part of the anode, the molten pool at the anode (workpiece) starts to solidify already during the discharge. So, at the end of the discharge - when the interval time is set - only a small part of material is ejected away, because the rest has already solidified. At the cathode side (tool electrode) on the other hand, the diameter of the plasma channel remains very small during the discharge, which causes the energy density to be very concentrated over a small area. So, what happens is a continuous melting of material on the cathode side (tool).

This phenomenon also explains the difference in (a) the resulting surface roughness of the workpiece electrode and (b) the volumetric relative wear ϑ between the pair of electrodes, when the tool electrode is positively (anode) or negatively charged (cathode), as discussed ahead.

From Fig. (3) it is also observed that when EDMachining with the tool negatively polarized the optimum discharge duration t_e is not as long as it is for positive polarity, e.g., $\hat{i}_e$ = 6, 8 A at positive polarity the optimum t_e = 50 μs and for $\hat{i}_e$ = 3, 6, 8 A at negative polarity the optimum t_e = 12,8 μs. The phenomenon described above also explains this behavior. It means that for longer discharge durations more material of the molten pool of the anode (workpiece) will be solidified during the discharge and then lower is the material removal rate V_w achieved. So, when EDMachining with the tool under negative polarity the best levels of V_w are obtained for short discharge durations, as shown in Fig. (3).

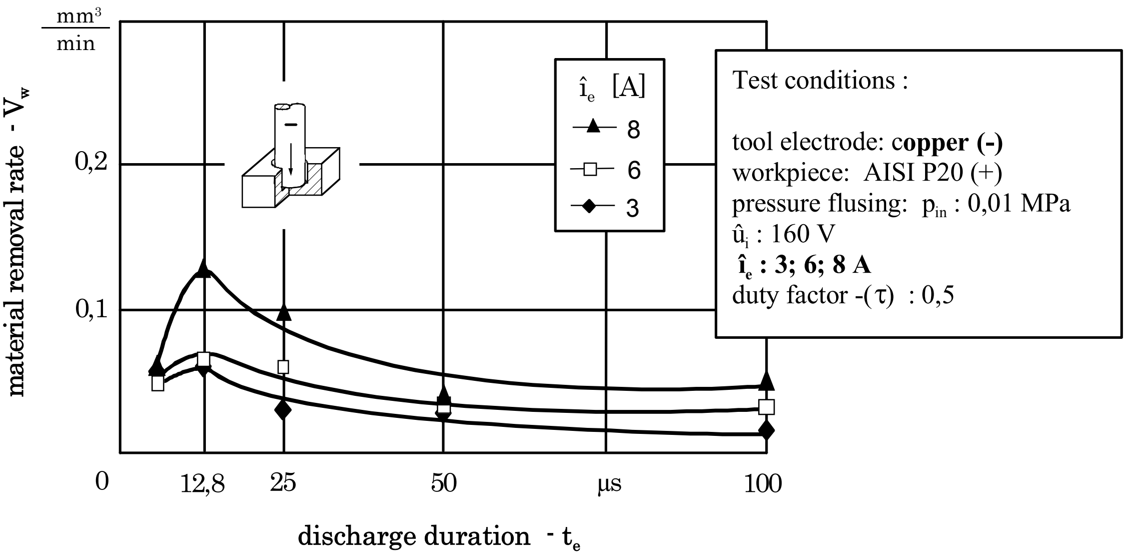


Figure 3. Material removal rate V_w against the variation of discharge duration t_e for discharge currents $\hat{i}_e$ = 3,6,8 A using a negative polarity for the tool electrode under isoenergetic generator mode.

The volumetric relative wear ϑ, expressed in percentages, corresponds to the ratio between the tool electrode wear rate V_e [mm^3min] and the material removal rate V_w [mm^3min]. In Fig (4) are presented the results of volumetric relative wear versus discharge duration for $\hat{i}_e$ = 3, 6, 8 A when EDMachining with a positive tool (anode). In general terms it can be said that higher is the discharge current $\hat{i}_e$ higher is the relative wear ϑ to the EDMachining with copper electrodes. A possible explanation to this fact is due to the low resistance of copper against the thermally influenced wear. From Fig. (4) it is clearly seen that for $\hat{i}_e$ = 6 and 8 A at the optimum discharge duration t_e = 50 μs the relative wear ϑ is about 2% and for $\hat{i}_e$ = 3 A at optimum t_e = 25 μs the level of ϑ reached approximately 2,5%. By the analysis of the experiments, under the optimum value of t_e for each discharge current for EDM with a positive tool, the volumetric relative wear ϑ is considerably low.

In the case of EDMachining with the tool electrode negatively charged (cathode) it was observed very high levels of volumetric relative wear ϑ, reaching approximately 10% for $\hat{i}_e$ = 8 A at the optimum t_e = 50 μs. In the case of $\hat{i}_e$ = 3 and 6 A the values of ϑ were even higher, ranging about 40 %. It was also noticed by visual inspections a considerable wear at the corner of the tool electrodes for all the discharge currents (3, 6, 8 A). Particularly for EDM under $\hat{i}_e$ = 3 and 6 A with a negative tool, the process was unstable if compared to that observed for the positive tool.

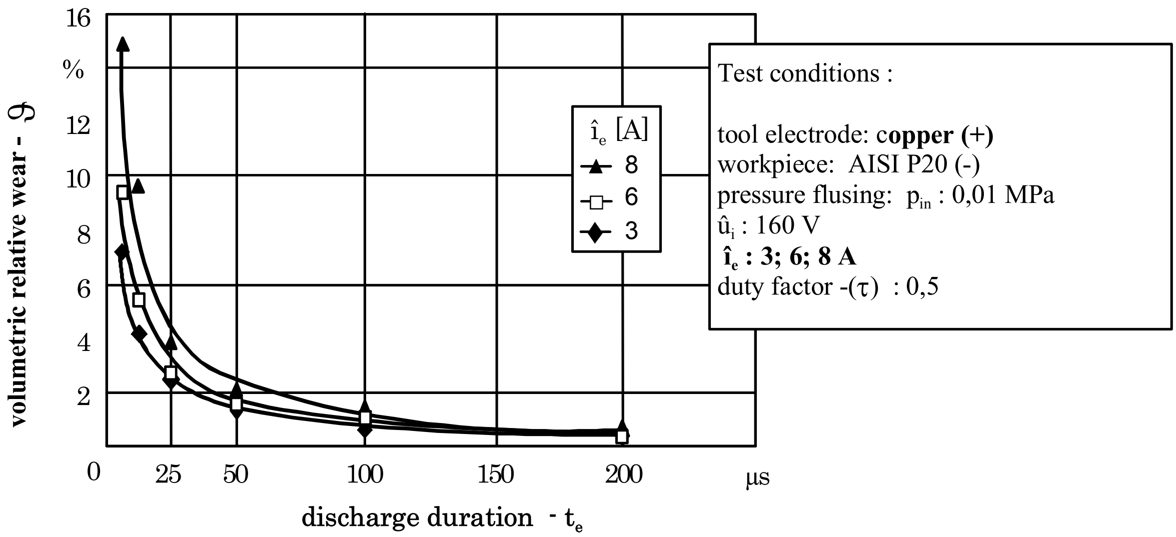


Figure 4. Volumetric relative wear ϑ against the variation of discharge duration t_e for discharge currents $î_e$ = 3,6,8 A using a positive polarity for the tool electrode under isoenergetic generator mode.

In respect to the average surface roughness of the workpiece electrode for EDM with a positive tool electrode, it is observed from the Fig.(5) that the increase of surface roughness – which means that larger and deeper craters are produced on the surface of the workpiece - is directly related to the increase in discharge current $î_e$ and discharge duration t_e. For the optimum t_e = 50 µs to discharge currents $î_e$ = 6 and 8 A the roughness R_a were respectively around 4,5 and 5,5 µm, while for $î_e$ = 3 A under the optimum t_e = 25 µs the value of R_a reached 1,8 µm.

The decrease of the surface roughness after the optimum values of discharge duration t_e – independently of the level of $î_e$ = 3, 6, 8 A and the polarity of the tool electrode – can be related to the very long discharge duration that causes an over-increase of the plasma channel diameter, which decreases the pressure of the plasma over the molten cavities. As a consequence, the ejection of material from the molten cavities of the both electrodes, at the end of the discharge, occurs inadequately. This phenomenon may produce a smoother surface roughness on the workpiece electrode, although the process becomes quite unstable because the flushing conditions turns bad.

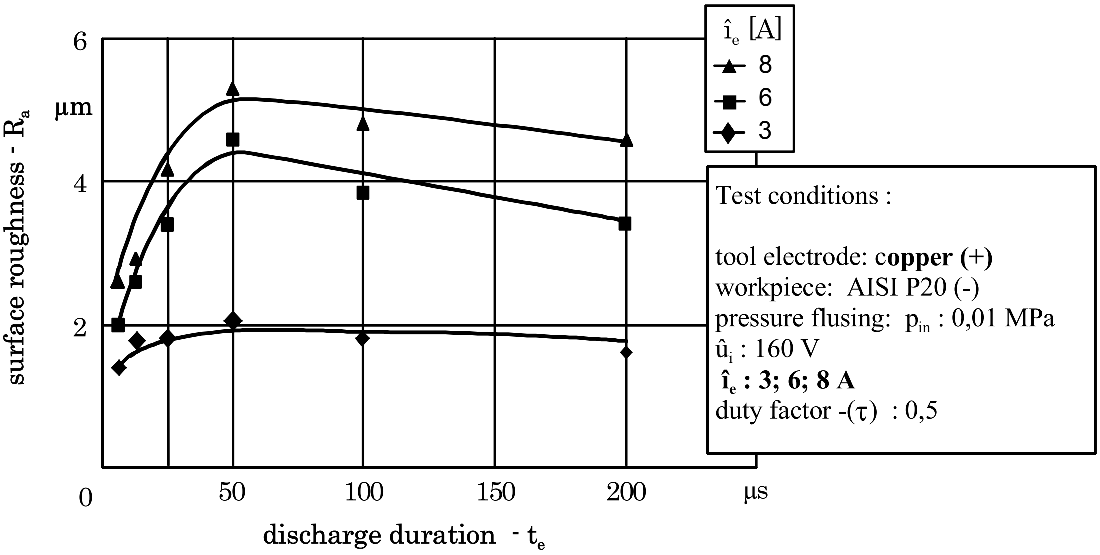


Figure 5. Average surface roughness R_a against the variation of discharge duration t_e for discharge currents $î_e$ = 3,6,8 A using a positive polarity for the tool electrode under isoenergetic generator mode

In Fig. (6) is presented the behavior of the surface roughness for EDMachining under a negative tool polarity. Comparing Fig. (5) to Fig. (6) it is clearly noticed that EDMachining with the tool negatively polarized promoted much better surface roughness on the workpiece. The minimum roughness R_a of about 0,6 µm were reached for discharge current $î_e$ = 3 A at the optimum t_e = 12,8 µs. For $î_e$ = 6 and 8 A at the optimum discharge duration t_e = 50 µs the average surface roughness R_a were respectively of 1,2 and 1,4 µm. Once again, the different melting behavior of cathode and anode during a discharge explains the best results for EDM with the tool negatively charged.

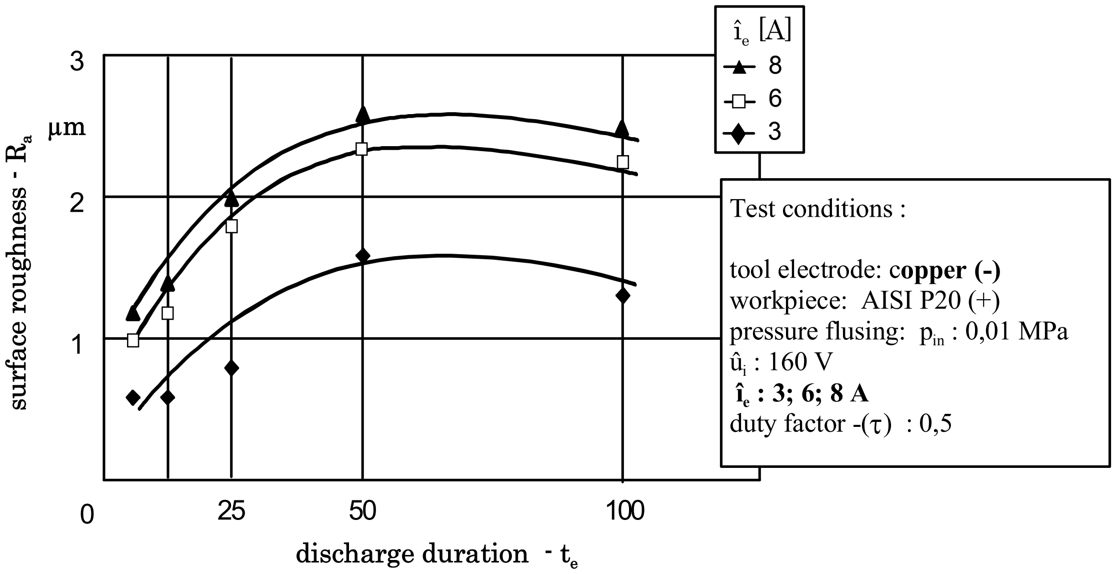


Figure 6. Average surface roughness R_a against the variation of discharge duration t_e for discharge currents $\hat{i}_e$ = 3,6,8 A using a negative polarity for the tool electrode under isoenergetic generator mode.

The relaxation circuit generator is just normally used in very fine EDM operations, when the discharge current is very low and the discharge durations are particularly short, as it can be observed by the results of material removal rate V_w presented in Fig. (7).

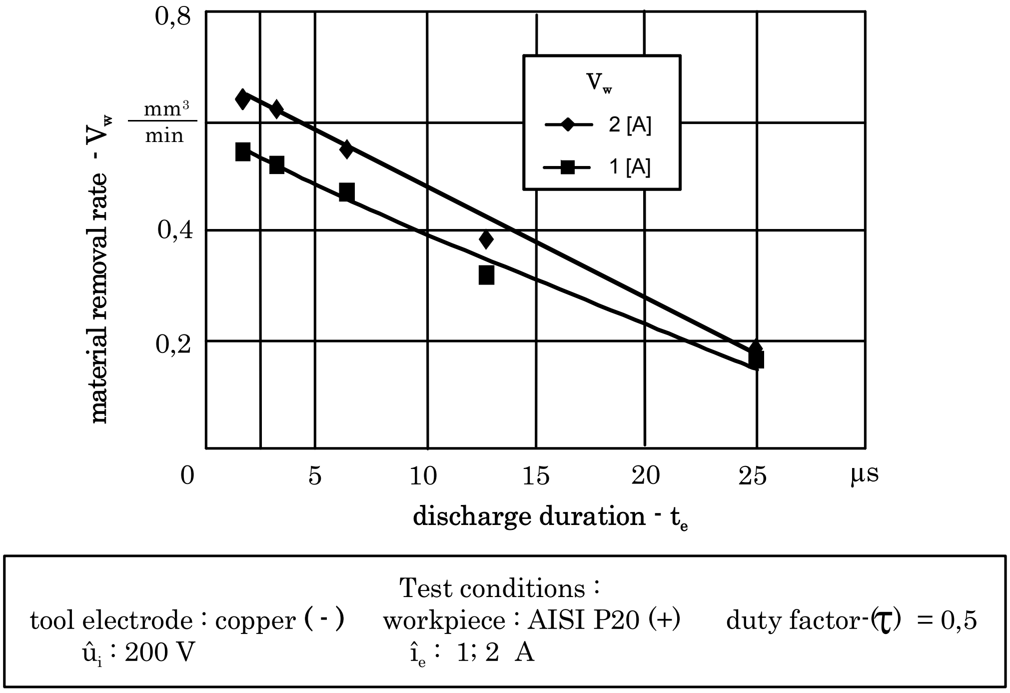
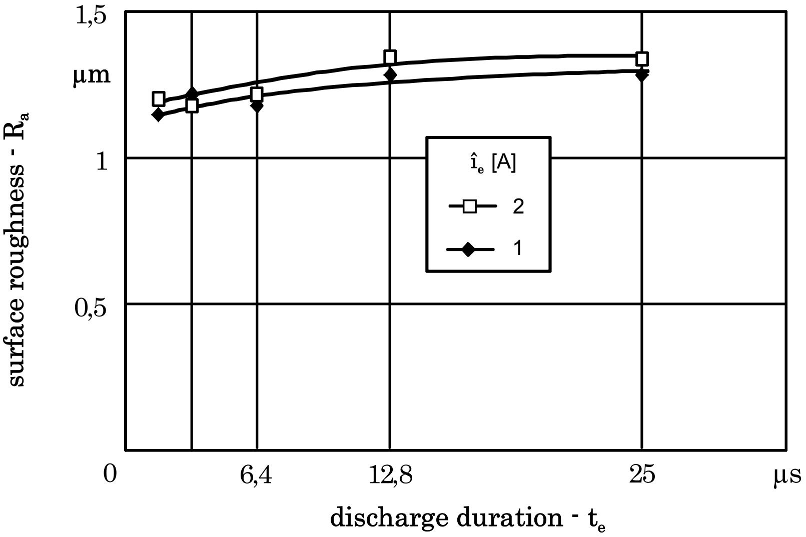


Figure 7. Material removal rate V_w against the variation of discharge duration t_e for discharge currents $\hat{i}_e$ = 1, 2 A using a negative polarity for the tool electrode under relaxation mode.

The best results of material removal rates were achieve for discharge duration t_e = 1,6 µs to the discharge currents $\hat{i}_e$ = 1 and 2 A, where material removal rates about 0,55 and 0,65 mm^3/min were respectively reached. In comparison to the maximum value of V_w = 0,13 mm^3/min obtained for $\hat{i}_e$ = 8 A with a negative tool, presented behind in Fig. (3), one can see that the EDM with $\hat{i}_e$ = 1 and 2 A under a relaxation generator produced better results of material removal rate V_w. It happened because the relaxation circuit diminishes to very low levels the residual electrical charges in the electrodes, resulting in a more stable EDM process and then promoting higher levels of material removal rate V_w and good flushing conditions.

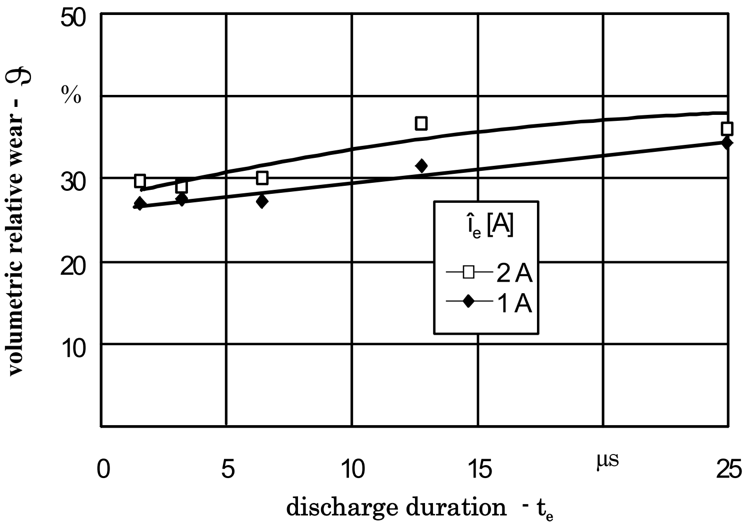
Figure (8) shows the results of the surface roughness for EDM with the relaxation mode for $\hat{i}_e$ = 1 and 2 A. The best values of R_s are approximately 1,2 µm, which are about the double found for EDM with an isoenergetic generator, discharge current $\hat{\imath}_e$ = 3 A and t_e = 12,8 μs with a negative tool. It is related to better stability of the process that conducted to higher material rate when EDM with the relaxation mode.



Test conditions :
tool electrode : copper (-) workpiece : AISI P20 (+) duty factor-(τ) = 0,5
$\hat{u}_i$: 200 V $\hat{\imath}_e$: 1; 2 A

Figure 8. Surface roughness R_a against the variation of discharge duration t_e for discharge currents $\hat{\imath}_e$ = 1, 2 A using a negative polarity for the tool electrode under EDM with relaxation mode.

Independently of the discharge current $\hat{\imath}_e$ and discharge duration t_e, the volumetric relative wear $\vartheta = V_e/V_w$ for EDM with the relaxation generator is very high. It is normal under EDM with negative tool, no matter the actuation mode of the generator. It is concerned to the different melting behavior of the cathode and anode during a discharge, as it has been explained at the rear text. This performance of volumetric wear for $\hat{\imath}_e$ = 1 and 2 A against the variation of discharge duration t_e can be seen in Fig. (8), where under the optimum t_e = 1,6 μs where reached values of ϑ from 27 to 29%.



Test conditions :
tool electrode : copper (-) workpiece : AISI P20 (+) duty factor-(τ) = 0,5
$\hat{u}_i$: 200 V $\hat{\imath}_e$: 1; 2 A

Figure 8. Volumetric relative wear ϑ against the variation of discharge duration t_e for discharge currents $\hat{\imath}_e$ = 1,2 A using a negative polarity for the tool electrode under EDM with relaxation mode.

4. Conclusions

From the experimental tests carried out in this work, the following conclusions can be drawn:
(a) The maximum material removal rate (V_w = 8 mm^3/min) was obtained for a discharge current $\hat{i}_e$ = 8 A and a discharge duration t_e = 50 µs, using the tool electrode positively charged and the generator under the isoenergetic mode.
(b) The minimum average surface roughness R_a = 0,6 µm was reached for discharge current $\hat{i}_e$ = 3 A and an optimum discharge duration t_e = 12,8 µs, when EDMachining with a negative tool polarity under isoenergetic generator mode.
(c) The general stability of the process, in terms of a few occurrence of arc-discharges and short-circuits, an adequate flushing condition and a uniform material removal from both electrodes, was better achieved when EDMachining with a positive tool electrode and the isoenergetic generator.
(d) Independently of the discharge current $\hat{i}_e$, discharge duration t_e and the generator actuation mode, the volumetric relative wear $\vartheta = V_e/V_w$ for EDMachining with a negative tool electrode is much higher than that with a positive tool polarity. This is related to the different melting behavior of the cathode and anode during a discharge.

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