AN EXPERIMENTAL INVESTIGATION ON THE PERFORMANCE OF GRAPHITE VERSUS COPPER ELECTRODES ON THE FINISH EDM OF TOOL STEEL

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Abstract. *In Electrical Discharge Machining (EDM) technology many types of materials can be used as tool electrodes. Despite the fact that each one of the materials has its own advantages and disadvantages, it is known that graphite and copper are the most commonly used materials to manufacture tool electrodes. In order to provide practical information on the use of graphite, this work has carried out a series of experimental tests on the finish EDM of AISI P20 tool steel with a special grade of graphite. It has been investigated the material removal rate V_w, volumetric relative wear ϑ and work piece surface texture against the variation of some important EDM electrical variables. Tests with copper electrodes were also carried out for comparison with those of graphite. The main conclusions can be summarized as follows: the best results of material removal rate V_w were reached when EDM with negative graphite electrodes. For positive polarity graphite and copper tools presented similar results of V_w. For graphite and copper tools the lower values of volumetric relative wear were achieved for positive polarity. The best surface roughness R_a was obtained for copper electrodes under negative polarity.*

***Keywords**: Sinking EDM, graphite and copper electrodes, tool steel, process parameters.*

1. Introduction

During the last four decades EDM has advanced to one of the major manufacturing processes applied in die and mold making industry to generate deep and three-dimensional complex cavities in many different classes of materials in roughing and finishing operations. Examples include precision machining of hardened steels, carbides, ceramic materials and any other that offers 0,01 S/cm of electrical conductivity, as presented by König and Klocke (1997). Other works (Amorim & Weingaertner 2002, 2004) also report that special aluminum-based alloys and copper-beryllium alloys, used to produce injection molding tools, have been also machined by EDM. However, according to Masuzawa (2001), it is important to remark that nowadays EDM is gaining more and more importance on the production of very accurate small parts (dimensions ≤ 0,5 mm) on any electrical conductive material. This is a market trend known as Micro-EDM.

The best supported theory still accepted to the explanation of electrical discharge machining process is the thermoelectric phenomenon. According to Zolotych (1955) and other researchers like Van Dijck et al. (1974), Crookall & Khor (1974), Dibitonto et al. (1989) and König & Klocke (1997), the material removal in electrical discharge machining is associated with the erosive effect produced when spatially and discrete discharges occur between two electrical conductive materials. Sparks of short duration (0,1 to 3600 μs) are generated in a liquid dielectric gap separating tool and work piece electrodes. The phases of an EDM discharge can be briefly presented as follows: the first one is the ignition phase that 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 $\hat{i}_e$ [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 one phase is the collapse of the plasma channel caused by turning off the electric energy. This phase causes the molten material to be violently ejected. At this time, known as interval time t_o [μs], a part of the ejected molten and vaporized material is flushed away by the flow of the dielectric across the gap and the rest is solidified in the recently formed crater and the surroundings. This process continues until the designed geometry of the work piece is completely machined.

According to the aforementioned EDM theory the mechanical properties of the work piece and the tool electrode have only a very few influence on the performance of machining. However, the thermophysical properties of the work piece and tool electrode, such as thermal and electrical conductivity, thermal expansion, heat to vaporize from room temperate, melting and boiling temperature have a considerable influence on the EDM process performance in terms of material removal rate, electrode wear and surface integrity of the work piece.

Drozda (1998) inform that the tool electrode is responsible to transport the electrical current to the work piece. So, any material to be used as a tool electrode is required to conduct electricity. In fact there is a wide range of materials used to manufacture electrodes. For instance it can be cited brass, copper-tungsten alloys, tungsten carbides, silver-tungsten alloy, tellurium-copper alloys, copper-graphite alloys etc. However, the most popular are electrolytic or pure copper and very special grades of graphite. Each one of those materials has its own advantages and disadvantages.

In respect to the application of pure or electrolytic copper and graphite as tool electrodes, Drozda (1998) and Oarmolds (2005) summarize the following arguments:

(1) *COPPER:* it works very well as an electrode material and is widely used when smooth work piece surface finishes are required. This material can be machine by all conventional methods such as drilling, turning, milling, grinding etc. But machining can be sometimes difficult because copper has a tendency to drag on the edge defined cutting tool and grinding wheel. In this case 2%Tellurium-copper alloy, which presents better machinability, can be a choice. However, copper machines very easily on Wire EDM, much better than graphite. Very complex shapes can be Wire EDM onto copper electrodes. Another advantage of copper in comparison to graphite is its ability to be coined and then to be a very good material for engraving electrodes. For certain applications, such as electrodes to be used in medicine engineering field, copper is the best choice because its facility to be highly polished.

(2) *GRAPHITE*: This material is available in many different grades from large grain sizes (200 µm), used in rough EDM operations, to very fine grains (1 µm) for finish EDM operations, particularly in steel. The costs of graphite vary from inexpensive, for coarse-grain sizes, to very expensive for fine-grain sizes. It provides a high material removal rate and low electrode wear - depending on the EDM parameter settings - as compared to metallic electrodes. At the present there is a trend to incorporate the entire geometrical configuration of the work piece onto a single large electrode, instead of partitioning the tool in many small pieces. Thus, the weight of the electrode becomes very important because it affects many factors in handling construction and use of the electrode. Graphite has a much lower density than copper which makes it the best material for large electrodes. Although graphite is very abrasive it is relatively easy to be machined by all the conventional machining processes. Milling, drilling, turning and grinding provide excellent finishes in graphite. The major drawback of graphite is the fine dust it produces during its machining. It is able to settle on the ways of the machine tool and when mixed with the machine's cutting fluid it will act like a lapping compound to eventually destroy the accuracy of the machine. So precautions must be taken when machining graphite.

Vartanian & Rosenholm (1992) present that for many years there have been discussions about the relative merits of the different EDM electrode materials. However, the major debates are about copper versus graphite. According to them the EDM users in different parts of the world have been using different electrode materials to do exactly the same jobs. Normally, copper is mainly used in Europe or Asia for historical reasons. Graphite is the chosen material by the majority of EDM users from the United States of America. They report that any EDM job that can be done with copper can also be executed with graphite. The end result might be same, but the cost to accomplish it can be vastly different. In practical terms the choice of the electrode material will depend mainly on the tool size, the work piece requirements, type of EDM machine and the methods of making the electrodes.

In addition Intech EDM (1996) also reports that other factors shall be considered when selecting the electrode material:

(a) *Work piece material removal rate* V_w *[mm^3/min].* A correct choice of EDM parameters to the pair tool electrode material/work piece will increase the value of V_w.

(b) *Electrode resistance to wear.* There are four types of wear: volumetric, corner, end and side wear. Of the four, volumetric and corner wear are very important in finish EDM operations of fine details. Minimization of those wear requires choosing adequate EDM parameters and the proper electrode material.

(c) *Work piece surface roughness*. Good work piece quality is obtained by the proper choice of electrode material, good flushing conditions and adequate EDM parameter settings.

(d) *Tool electrode material machinability.* Copper and graphite are the most commonly used. However, it is important to select an electrode material where the macro and microgeometry of the work piece can be easily machined and then promoting reduction of machining time and costs.

(e) *Tool electrode material cost.* On average, fine graphite is about three times more expensive than copper. The choice shall be done considering the company facilities (e.g, machine-tools, CAD/CAM software technology etc), the know-how on machining copper and graphite electrodes, the complexity of the electrode and its difficulty to be redressed and the knowledge on EDM parameters.

This research has two major objectives. It is known that graphite is a relatively new electrode material to the Brazilian EDM users. Then the first objective of the present work is to provide practical information on the use of graphite when electrical discharge machining steel work pieces in finishing conditions. The second objective is to attain some more understanding about the EDM phenomena when machining with graphite in comparison to copper electrodes.

So, it has been investigated the material removal rate V_w, volumetric relative wear ϑ and work piece surface texture against the variation of some important EDM electrical variables. Tests with copper electrodes were also carried out for comparison with those of graphite.

2. Experimental Procedures

The Electrical Discharge Machining experiments were conducted at the Laboratory for Research on Machining Processes (LAUS) of the Pontifical Catholic University of Paraná (PUCPR), Curitiba-Brazil. The following materials, equipment and methods were applied for all the series of tests:

(a) *EDM machine:* a Charmilles ROBOFORM 30 CNC machine equipped with an 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 because a finish machining would be carried out, which means that low energy would be applied and then longer would be the ignition delay time.
(b) *Tool electrodes:* 100 mm long cylindrical bars of graphite and copper with diameter of 20 mm and a 4 mm central hole. The main specifications of the graphite used for the tests are 10 μm average grain size, 1,5 μm average pore size, 1,77 g/cm^3 density and 80 W/mK thermal conductivity.
(c) *Work piece*: AISI P20 tool steel square samples 25 mm wide and 15 mm thick with a roughness R_a of 2μm on the surface to be machined were prepared by Wire EDM. The work piece material was chosen because it is traditionally used by the die and mold making industry.
(d) *Dielectric:* Hydrocarbon fluid for universal application in EDM operations with properties such as viscosity of 3CSt at 20 ^{0}C, flash point of 125 ^{o}C, density of 0,783 g/ml and 0,3 % of aromates.
(e) *Flushing method:* The dielectric fluid was injected through the 4 mm electrode hole with 0,01 MPa providing adequate flushing of the eroded particles away from the working gap. In order to further improve the flushing efficiency an alternation between periods of machining U [s] and periods of tool electrode retraction with no discharges R [s] were introduced, as shown in Fig. 1. The values of U and V were defined after some pre-tests.

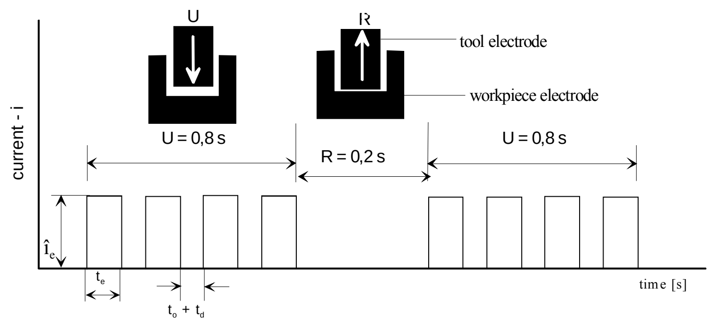

Figure 1. Series of pulses U followed by a pause time R.

(f) *Electrical Variables:* The major variables that influence on the performance of EDM, which are discharge current $\hat{i}_e$, discharge duration t_e and tool polarity (+/-), were investigated through the values presented in Tab.1.

Table 1. Electrical variables used for the experiments with graphite and copper electrodes.

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

In finishing EDM operations a very important objective is to achieve the best work piece roughness with a low level of volumetric relative wear. So that it could be possible, the duty factor τ (t_i/t_p), which represents the ratio between pulse duration t_i and pulse cycle time t_p ($t_p = t_i + t_0$), was chosen to be 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 for this condition. It means a few occurrence of short-circuits and arc-discharges. As a consequence, proper flushing of eroded particles away from the working gap is promoted. 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. It would result in 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. This would lead to non-uniform material removal along the frontal surfaces of the tool and the work piece as well as a possible increase of the roughness.

The open gap voltage $\hat{u}_i$ has an intrinsic relation with the size 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 the working gap. So, it is common 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] keeps a larger working gap and proper expulsion of debris. As the energy W_e is decreased so is the working gap size. Thus, in finishing EDM 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. This magnitude of $\hat{u}_i$ guaranteed a proper dispersion of the sparks along the frontal area of the electrodes and good flushing conditions.
(g) The precise quantification of V_w and ϑ was possible using a precise balance, with resolution of 0,0001 g, to weigh the tool and work piece before and after an average machining time of 30 minutes. The tests were done three times for

each parameter settings and no significant difference was observed. It is important to mention that during EDMachining graphite absorbs some quantity of the dielectric fluid. To avoid any error when measuring the mass of the graphite tool it was necessary to carry out a drying period. The electrodes were kept in a furnace at 400 °C for 24 hours before and after the each EDM test.

3. Results

Figure 2(A) shows the results of material removal rate for positive graphite and copper tools. For both tool materials the optimum discharge duration t_e was 50 µs for $\hat{\imath}_e$ = 3, 6 and 8 A, where the best stability of the EDM process was observed. For $\hat{\imath}_e$ = 6 and 8 A the values of V_w are almost the same for both materials. However, when EDM with graphite tool at $\hat{\imath}_e$ = 3 A the value of V_w was about 1,5 mm^3/min higher in comparison to copper, which is not so significant in this case. In general it can be said that the performance of EDMachining is quite similar. A series of some tests with longer discharge duration (t_e = 100 µs) were carried out, but the values of V_w had a trend to deeply decrease for both electrode materials.

Figure 2(B) depicts the values of volumetric relative wear ϑ. It is clearly seen that graphite wears much more than copper from t_e = 6,4 µs up to t_e = 25 µs which represents very short discharge duration t_e and interval time t_o. When EDMachining at the optimum discharge duration (t_e = 50 µs) graphite presented an average value of ϑ of about 6% while copper has achieved 2%. Here it is important to mention that the material grain size is one of the most important qualities of graphite, because during machining the nature of EDM process causes particles from the tool electrode to be lost. Thus the electrode wear becomes more critical as the grain size increases. This occurs because the particles from the electrode tend to clog the working gap causing short-circuits and arc-discharges. This phenomenon decreases the material removal rate V_w and increases the volumetric wear ϑ. Probably the 10 µm grain size of the graphite used for the experiments of this work should be applied with higher discharge currents, when the working gap width would be bigger and the EDM performance could be more stable. It means that higher V_w and lower electrode wear would be reached.

In a few words one can see that the highest value of V_w was about 8 mm^3/min for both graphite and copper tool when EDM with $\hat{\imath}_e$ = 8 A and t_e = 50 µs. The lowest values of volumetric wear ϑ were obtained for copper electrodes for all the tested $\hat{\imath}_e$ and t_e, reaching a minimum of about 2% for $\hat{\imath}_e$ = 3 A and t_e 50 µs.

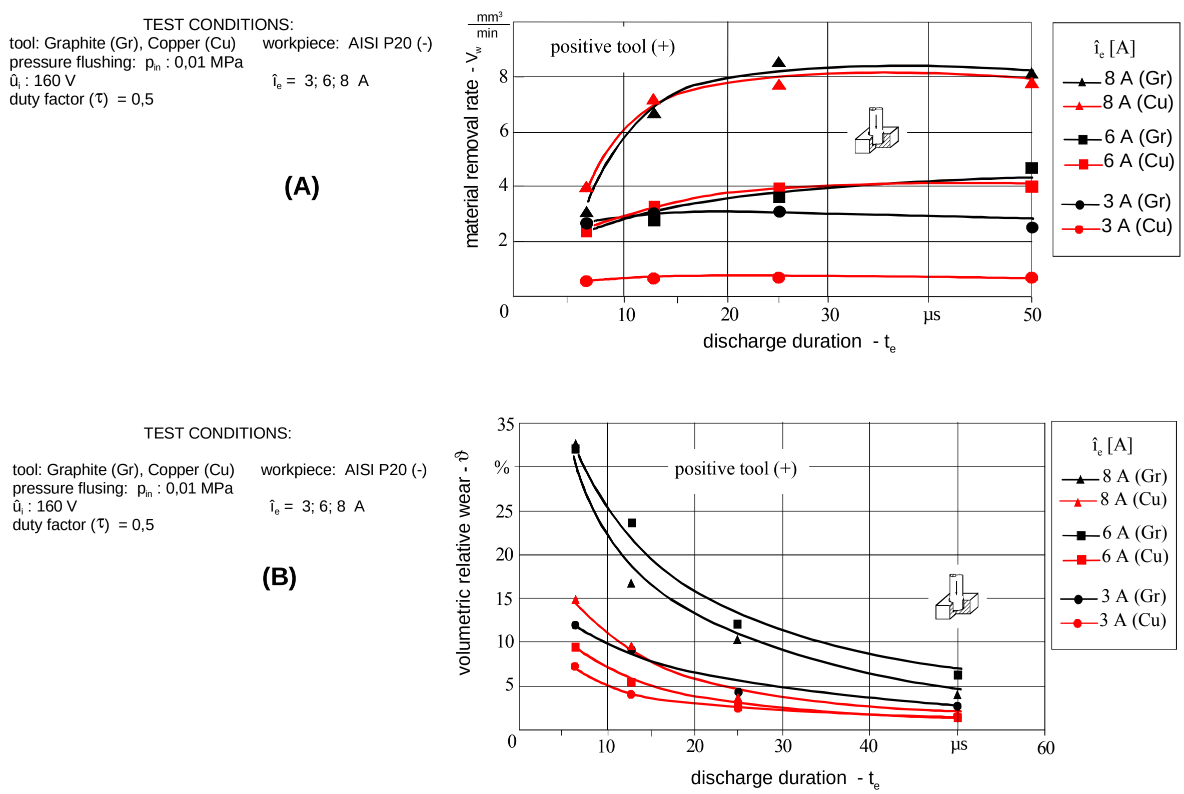

Figure 2. (A) Material removal rate V_w with variation of discharge current $\hat{\imath}_e$ and discharge duration t_e and (B) volumetric relative wear ϑ for EDM with positive graphite and copper electrodes.

Figure 3(A) presents the values of material removal rate V_w when EDM with negative graphite tool (cathode). It is easily observed that negative polarity for graphite promoted very much higher values of V_w in comparison to the ones achieved with the positive polarity (anode), as depicted behind in Fig. 2(A). For negative polarity the maximum value of V_w = 23,5 mm^3/min was obtained, while for positive tool the maximum Vw =8 mm^3/min was reached under the same optimum discharge duration t_e = 50 µs. This EDM performance can also be noticed for $\hat{i}_e$ at 3 and 6 A, where maximum V_w =10 mm^3/min was reached.

When comparing Fig. 3 (A) against (B), where V_w for negative copper tools (cathode) are presented, the results of material removal V_w for graphite *versus* copper are vastly different. In the case of copper the maximum V_w was about 0,12 mm^3/min when EDM with $\hat{i}_e$ = 8A at the optimum t_e = 12,8 µs , much lower than those of graphite tools in any circumstances.

The performance of any electrical discharge machining operation greatly depends on the thermophysical properties of the electrode material, as mentioned before. The discharge peak current $\hat{i}_e$ just takes place after the break down of the open circuit voltage $\hat{u}_i$. The occurrence of this phenomenon is just possible when the cathode electrode starts to emit electrons. At this time, the electrons from the cathode collide with molecules of the dielectric fluid and more electrons are released together with positive ions. As a result dielectric fluid is vaporized and a high energy plasma channel is formed. Drozda (1998) arguments that the cathode must be hot enough to permit electrons to absorb enough energy to escape. The thermophysical properties of copper are very different from graphite. When the cathode is copper it is able to emit electrons, to carry the current, only after some of its own material is melted and boiled. On the other hand, when graphite is the cathode it is able to emit electrons below its boiling temperatures. Therefore graphite is more stable than copper as cathodes, which promotes higher material removal rates V_w, as can be seen in Fig 2.

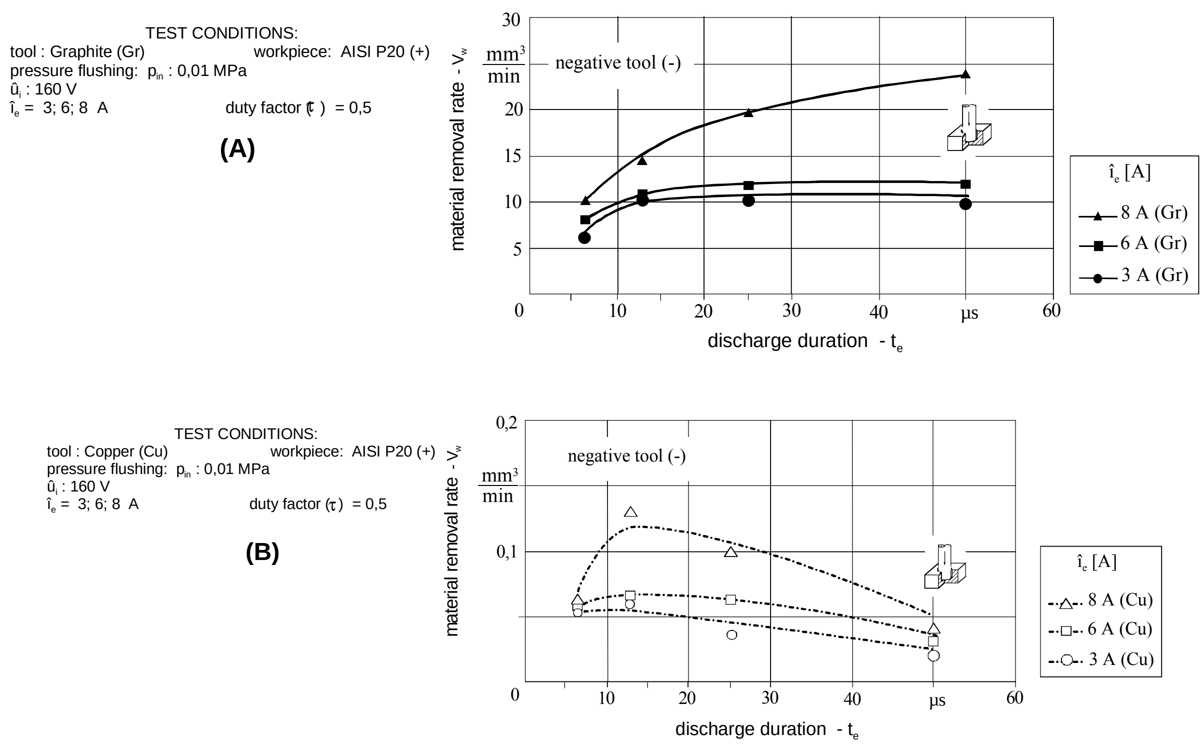

Figure 3. Material removal rate V_w against discharge current $\hat{i}_e$ and discharge duration t_e for EDM with (A) negative graphite and (B) with negative copper electrodes.

The results of work piece surface roughness can be seen in Fig. 4. When EDM with negative tool the graphite electrodes promoted higher roughness in comparison to copper for all the three discharge currents ($\hat{i}_e$ = 3, 6, 8 A) and discharge duration t_e evaluated. For EDM with graphite at the optimum t_e = 50 µs the R_a varied from 4 to 5 µm, In comparison, copper tools provided much better work piece surface quality. The best value R_a = 0,6 µm was attained for $\hat{i}_e$ = 3 A and t_e =12,8 µs. The higher surface roughness got with graphite is due to the higher V_w reached, which means that larger and deeper craters on the work piece surface were made.

Fig. 4 (B) depicts the results under EDM with positive polarity for both electrode materials. It is observed just a few divergences on the results. When EDM with $\hat{i}_e$ = 6, 8 A and t_e = 50 µs the difference of R_a was just about 1µm and for $\hat{i}_e$ = 3 A a smaller difference occurred.

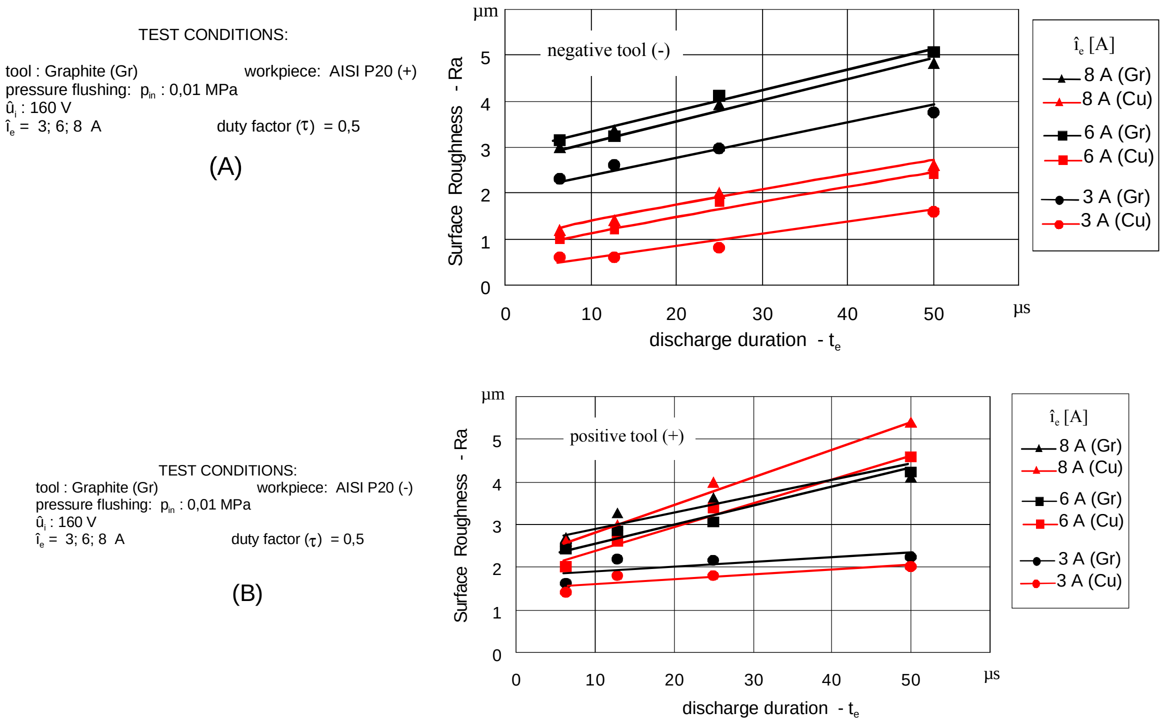

Figure 4. Results of surface roughness when (A) EDM with negative electrodes and (B) positive electrodes.

Finally, in Figure 5 one can see the results of volumetric relative wear ϑ for EDM with negative electrodes. In this case the negative graphite tools presented a much higher volumetric wear ϑ = 30% (at $\hat{i}_e$ = 8 A and t_e = 50 µs) than with EDM at positive polarity tools (ϑ = 6% at $\hat{i}_e$ = 8 A, t_e = 50 µs which represent the best parameter settings) as shown before in Fig. 2.

The same behavior is also noticed for negative copper tools at their best EDM settings, i.e, for $\hat{i}_e$ = 8A t_e = 12,8 µs the volumetric relative wear is also about 30%. Although not represented in Fig. 5, when EDM with copper at $\hat{i}_e$ = 3 and 6 A for the optimum t_e = 12, 8 µs. the volumetric relative wear of 40% was observed.

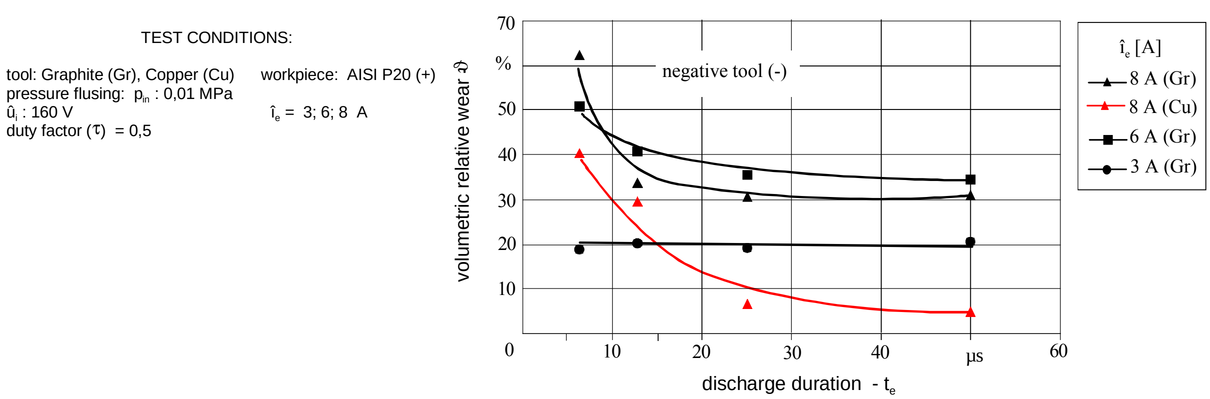

Figure 5. Volumetric relative wear ϑ for the variation of discharge current and discharge duration when EDM with negative graphite (3,6,8 A) and copper (8A).

3. Conclusions

This work has carried out experiments on the performance of special grade of graphite when electrical discharge machining the AISI P20 tool steel under finish process conditions. It has been investigated some important EDM variables such as discharge current, discharge duration and tool electrode polarity. Tests with copper electrodes were also executed for comparison. From the results of this work the following conclusions can be drawn.

(a) The highest material removal rates V_w were achieved for EDM with negative graphite electrodes, much better than the results reached with copper tools. Therefore graphite is more stable than copper when EDM as cathodes.

(b) For electrodes at positive polarity, graphite and copper presented similar results in terms of the values of V_w. Probably the 10 µm grain size of the graphite used for the experiments of this work should be applied with higher discharge currents, when the working gap width would be bigger and the EDM performance could be more stable. It means that higher V_w and lower electrode wear would be reached.

(c) The lower levels of volumetric relative wear ϑ were attained for EDM with graphite and copper at positive polarity regardless the EDM parameter settings.

(d) The best surface roughness R_a was obtained for copper electrodes under negative polarity.

4. Acknowledgements

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