ELECTRICAL DISCHARGE MACHINING OF TUNGSTEN CARBIDE WITH COPPER-TUNGSTEN ELECTRODES

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Abstract. *The tungsten carbide-cobalt is a composite material with high compressive strength and hardness, chemical stability and good tenacity. These properties ensure a wide application of this material to manufacture cutting tools, metal forming dies and components under erosion. The products of tungsten carbide are generally made by powder metallurgy. In some cases this process is unable to produce details with very complex geometry. Additional machining processes are then required. In this context, the process of electrical discharge machining (EDM) is an efficient solution. However, the values of EDM parameters have to be properly set for any different tungsten carbide-cobalt composition and electrode material, targeting an appropriate level of machining performance and surface integrity, which is the objective of the present work. EDMachining experimental tests about the influence of important electrical variables on the workpiece material removal rate, volumetric relative wear and surface roughness were carried out under rough and finish machining regimes. A special grade of tungsten carbide-cobalt was used as workpiece and copper-tungsten as electrode material. From the results the main conclusions are the following: the increase of discharge duration promotes better material removal rates and produces poorer surface roughness; the variation of the duty factor from small to high values does not improve the material removal rate and promotes slightly influences on the surface roughness; the open circuit voltage does not affect significantly the values of material removal rate and surface roughness.*

Keywords*: tungsten carbide-cobalt, electrical discharge machining, process parameters.*

1. INTRODUCTION

Electrical discharge machining (EDM) is a thermoelectric process of non-conventional machining, where electrical discharges occurs between two electrodes promoting heating, vaporization and removal of material, as shown by König & Klocke (1997). It is widely applied in hard materials to produce three dimensional details with complex geometrical shapes. The EDM products usually include injection molding tools and forming dies, aerospace prototypes and electronic components, as well as very accurate micro components at any electrical conductive material.

Ho & Newman (2003) point out that a significant number of recent researches are still focused in improving EDM performance characteristics such as material removal rate, electrode wear rate and surface integrity. The interrelationship among the different process parameters is the main factor that contributes to the overall machining efficiency. Löttgen (1998) also remarked that the majority of CNC EDM machine-tools are delivered with technology tables made under standardized machining conditions. These technology tables consist of the most appropriate EDM electrical and non-electrical parameters settings. The tests developed by the manufacturers to build the technology tables are carried out under optimum machining conditions. This is normally not the case faced by the tooling industry. Thus, the customer himself has to develop much time-consuming tests for each different kind of work in order to achieve reliable results under realistic machining conditions. In this context, the research of process parameters complements the information concerning the adequate EDM process, leading to higher machining performance.

The tungsten carbide-cobalt (or hard metal) is a metal matrix composite material. It has a ceramic phase of tungsten carbide (WC) and a metal phase, usually cobalt (Co). According to Byrne et al (2003), hard metal shows useful properties such as high compressive strength and hardness, chemical stability and good tenacity. It is widely used in industry to make cutting tools, injection molds, metal-forming and stamping dies and components under erosion. The powder metallurgy is the usual process for obtaining the tungsten carbide. In this process powder raw material is compacted and sintered. However, in some cases the powder metallurgy is unable to produce very complex geometries. In these cases, additional machining operations are required. Mahdavinejad & Mahdavinejad (2005) remind that sometimes the conventional machining has its use restricted due to the high hardness of WC-Co composite, combined with small and intricate shape geometries of the workpiece to be machined. In this context, the electrical discharge machining is an effective solution.

Abbas et al (2007) report that the optimization among the different EDM parameters and the thermophysical properties of electrode and workpiece materials are the main factors that contribute to the overall machining efficiency. Throughout the last decades many researchers carried out theoretical and experimental tests aiming at optimizing the EDM electrical and non-electrical variables for many kinds of workpiece and electrode materials. In this context, Dreyer et al. (1999) state that the two parameters namely the ratio of Co to WC and the WC particle size, control the material properties and consequently the machininability of tungsten carbide by EDM. In addition Lee & Li (2001) states that from the literature the electrical discharge machining performance of tungsten carbide regarding machining parameter settings is rather lacking deep investigation.

In this work experimental tests about the influence of important EDM electrical variables on machining characteristics of tungsten carbide-cobalt under rough and finish regimes using copper-tungsten electrodes are carried out. The CW-Co alloy used in this work is recently applied to manufacture forming dies and stamping tools for electric engines components such as stators and rotors, as reported by Hespanhol (2008). Three important machining characteristics regarding the EDM performance are investigated. The first one is the material removal rate V_w, which means the volume of material removed from the workpiece electrode per minute. The second is 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. The third characteristic is the surface roughness R_a. In order to optimize these technological characteristics the electrical parameters namely discharge current $\hat{\imath}_e$, discharge duration t_e and open circuit voltage u_i are varied keeping the electrode negatively polarized. Additionally to the electrical parameters described above the duty factor τ and its influence on the machining characteristics of the EDM performance is also investigated.

2. ELECTRICAL DISCHARGE MACHINING PHENOMENON

According to DiBitonto et al (1989) and Eubank et al (1993) 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, ranging from 0,1 to approximately 4000 µs, are generated in a liquid dielectric gap separating tool and workpiece electrodes. The electrical energy released by the generator is responsible to melt a small quantity of material of both electrodes by conduction heat transfer. Subsequently, at the end of the pulse duration a pause time begins and the melted pools are removed by forces which can be of electric, hydrodynamic and thermodynamic nature.

Figure 1, adapted from König and 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, which normally ranges from 15 to 30 V. 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 discharge 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 plasma channel of high energy and pressure 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, which causes the molten material to be violently ejected. At this time, known as 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. During the interval time t_o also occurs cooling of the electrodes and the de-ionization of the working gap necessary to promote an adequate dispersion of the successive discharges along the surfaces of the electrodes. This process continues until the geometry of the workpiece is completed.

Considering the aforementioned EDM phenomenon an asymmetric material removal of the electrode and the workpiece can be achieved by the appropriate choice of electrical parameters, electrode polarity, type of working gap flushing, planetary movement of the electrode and thermophysical properties of electrode/workpiece materials. According to Amorim & Weingaertner (2002) another EDM variable strictly associated to the electrical parameters and that influences on the machining characteristics is the duty factor τ, illustrated in Fig.1. The duty factor may affect the material removal rate V_w, the volumetric relative wear ϑ and the workpiece surface roughness R_a.

The duty factor τ is the ratio between the pulse duration t_i and the pulse cycle time t_p $(t_i + t_o)$. The value of duty factor τ should be chosen as high as possible. The usual procedure to increase the value of τ is by reducing the pulse interval time t_o and keeping the pulse duration t_i constant. This procedure leads to the increase of discharge frequencies promoting better rates of V_w and lower values of ϑ.

An important aspect regarding the choice of high values of τ is associated with the elevation of the contamination concentration in the working gap. According to Schumacher (1990) some concentration of sub-microscopic particles, fibers or moisture drops in the working gap can reduce the ignition delay time t_d. It happens because these particles arrange themselves in such a way that a kind of a bridge occurs intensifying the electric field. This then quickly fires another discharge. On the other hand very high values of duty factor τ is responsible to promote many short-circuits, and arc-discharges causing low values of V_w and high levels of ϑ.

In current practice of EDM of metal alloys conservative decisions are taken to gain safer machining performance as stated by Wang et al. (1995). This means the use of duty factor $\tau = 0,5$ ($t_i = t_o$) in order to avoid short-circuit, arc-discharges and good flushing conditions. For duty factor higher than 0,5 ($t_i > t_o$) the machining conditions may become worse and arcing damage can occur. Values of duty factor lower than 0,5 ($t_i < t_o$) lead to low machining rate.

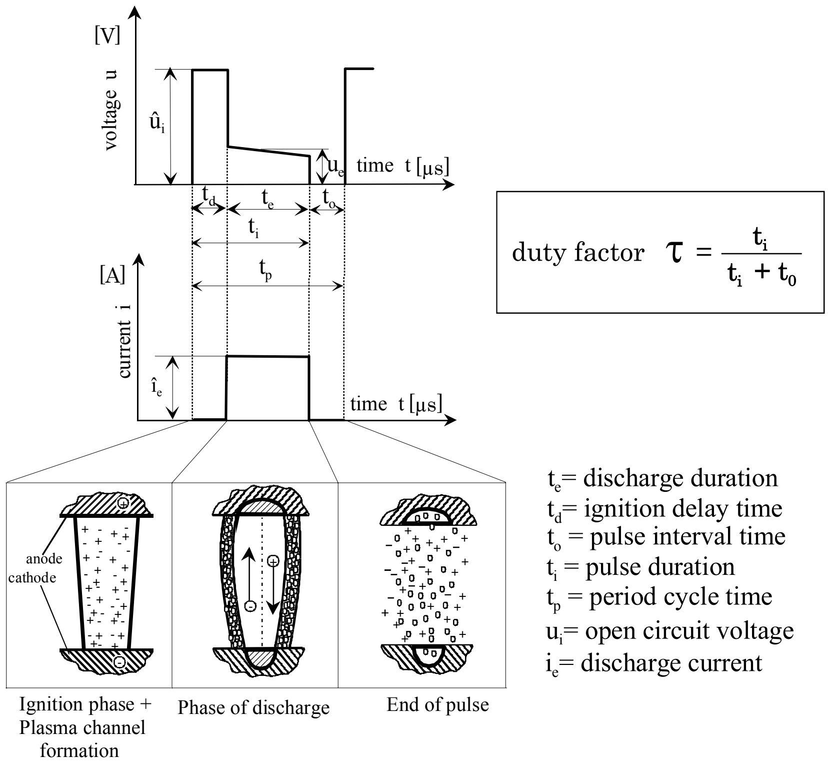

Figure 1. The phases of an electric discharge in EDM and the concept of duty factor τ.

3. EXPERIMENTAL METHODOLOGY

In this work a sequence of experiments on the electrical discharge machining of a special grade of tungsten carbide-cobalt using copper-tungsten as electrodes, under rough and finish process conditions, is performed on a Charmilles ROBOFORM 30 CNC machine tool. The tests are designed to assess the effect of the EDM input independent parameters namely discharge current i_e, discharge duration t_e , open circuit voltage u_i and duty factor τ on the EDM output dependent machining characteristics material removal rate V_w, volumetric relative wear ϑ and workpiece surface roughness R_a.

3.1. Experimental Procedure

The optimization of EDM machining characteristics (material removal rate V_w, volumetric relative wear ϑ and surface roughness R_a) is carried out into three stages. The range of electrical variables to perform the experiments is shown in Tab.1. The implemented sequence for each stage is described as follows:

First stage - Effect of Discharge Duration (t_e): at the first stage the value of duty factor τ is fixed at 0,5 and the machining characteristics is optimized against the variation of discharge duration t_e. Rough and finish machining regimes are analyzed for discharge currents i_e of 32 A and 6 A, under an open circuit voltage u_i respectively at 80 V and 120 V. The range of discharge duration t_e varies from 3,2 to 50 µs for the finish machining and for EDM under the rough machining t_e goes up to 400 µs.

Second stage - Effect of Duty Factor (τ): here the optimum discharge duration t_e that promoted the best machining characteristics is kept constant and the values of pulse interval time t_o are modified. This promotes the variation of the duty factor τ in order to further improve the machining characteristics. The range of interval time t_0 was specified as 100; 50; 25; 12,8 µs for the finishing machining and for the rough machining as 200; 100 50; 25µs. The respectively determined duty factors are then 0,11; 0,20; 0,33; 0,5 for finish machining and 0,5; 0,67; 0,8; 0,89 for the rough machining.

Third stage - Effect of Open Circuit Voltage ($\hat{u}_i$): At the last stage, using the best discharge duration t_e and the most appropriate duty factor τ obtained in stage two, the open circuit voltage is scanned from 80 to 200 V to verify its influence over the EDM machining characteristics under rough and finish regimes.

Table 1. Stages and electrical parameters values for the experimental tests.

Stage	Discharge current $\hat{i}_e$ [A]	Discharge duration t_e [μs]	Duty factor (dimensionless)	Open circuit voltage $\hat{u}_i$ [V]
1st	6	3,2; 6,4; 12,8; 25 and 50	0,50	120
	32	3,2; 6,4; 12,8; 25; 50; 100; 200; 400		80
2nd	6	Optimum values selected	0,11; 0,20; 0,33; 0,50	120
	32		0,50; 0,67; 0,80; 0,89	80
3rd	6	Optimum values selected	Optimum values selected	80, 120, 160, 200
	32			

3.2. Materials and equipment

(i) Workpiece: square samples of H40S tungsten carbide-cobalt 15 mm wide and 10 mm depth with R_a = 1,2 μm on the surface to be machined. The chemical composition of H40S carbide is as follows: 88,2% of WC, 11,5% of Co+Ni and 0,3% of impurities. The WC average grain size is 2,5 μm. This alloy has 14,30 g/cm^3 of density, 1240 HV10 hardness, 2597 ^{o}C of melting point and 420 kgf/mm^2 of compressive strength. Figure 2 shows the microstructure of the H40S samples used in this work illustrating the WC grains and the cobalt substrate.

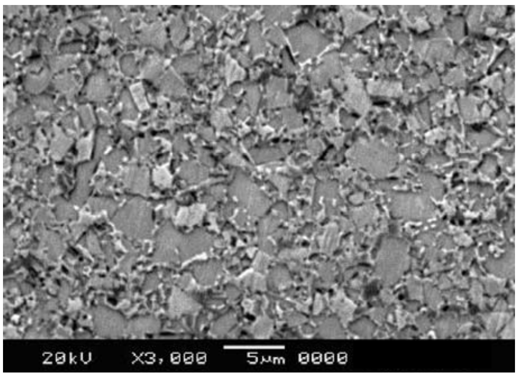

Figure 2. SEM image of the surface of tungsten carbide-cobalt workpiece.

(ii) Electrode: copper-tungsten alloy cylindrical bars with 10 mm diameter and 100 mm length under negative polarity having chemical composition containing 70% of tungsten and 30% of copper. The properties of the alloy used in this work are the following: hardness of 37 HRC, melting point of 3500 ^{o}C, density of 12,6 g/cm^3.

(iii) Machine tool: a Charmilles ROBOFORM 30 CNC die-sinking machine tool, equipped with an isoenergetic generator that allows setting the value of discharge duration t_e. An important parameter is the ignition delay time t_d. The time t_d elapses between applying the open circuit voltage $\hat{u}_i$ across the gap until the discharge current $\hat{i}_e$ is established. When finish EDMachining is carried out longer times of t_d are applied. In this work t_d is set as 30% of discharge duration t_e for finish machining. For rough EDMachining operations lower times of t_d are used because the working gap is normally large. Here t_d is set to be 15% of discharge duration t_e. These values of t_d were established based on pilot tests results.

(iv) Flushing method: a hydrocarbon dielectric fluid with 3 cSt at 40^0 C is used during the tests. In this work shallow cavities of small diameter are machined. Therefore, a jet of dielectric fluid directly against the gap and the immersion of the pair electrode/workpiece into the dielectric fluid are applied as flushing technique. This method is sufficient to evacuate the excess of eroded particles away from the working gap as well as to promote adequate cooling. In order to further improve the flushing efficiency both an alternation between periods of machining U [s] and periods of electrode retraction with no discharges R [s] are introduced, as shown in Fig. 3. The values of U and R were defined after pilot tests.

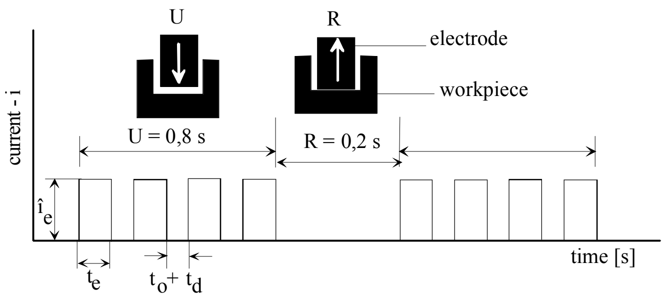

Figure 3. Series of pulses U followed by a pause time R.

4. RESULTS AND DISCUSSION

In this study an experimental investigation on the die-sinking EDM of tungsten carbide-cobalt using copper-tungsten electrodes under rough and finish conditions was performed. The objective was to set appropriate level of machining performance and surface integrity. In order to achieve this target the experiments were carried out into three stages. The first stage deals with the variation of discharge current t_e, the second stage aims at using the best results of the first stage to analyze the influence of duty factor τ and the last stage is concerned with the influence of the open gap voltage u_i.

4.1. First stage - Effect of discharge duration t_e

The discharge currents i_e = 6 and 32 A were chosen to analyze the EDM behavior under finish and rough machining conditions. The value of duty factor τ = 0,5 was established because good EDM process stability is promoted. The results of the material removal rate V_w against the variation of discharge duration t_e for negative copper-tungsten electrode are summarized in Fig. 4.

The global values of V_w obtained for the discharge current $\hat{i}_e$ = 6 A are much lower than those achieved for $\hat{i}_e$ = 32 A. This occurs because the material removal rate V_w is dependent of the energy $W_e = u_e.\hat{i}_e.t_e$ [J] released into the working gap, *i.e.*, the increase of discharge current i_e leads to higher values of V_w. It can be noticed that as the discharge duration t_e increases, the value of V_w also increases up to a maximum value for a specific optimum t_e. The highest material removal rate V_w is approximately of 4,3 mm³/min for $\hat{i}_e$= 32 A to the optimum discharge duration t_e = 200 µs. After this point V_w starts decreasing. It occurs because longer discharge duration t_e diminishes the pressure and energy of the plasma channel over the molten material of the electrode and the workpiece. As a consequence, this phenomenon brings instability to the process lowering the material removal rate V_w.

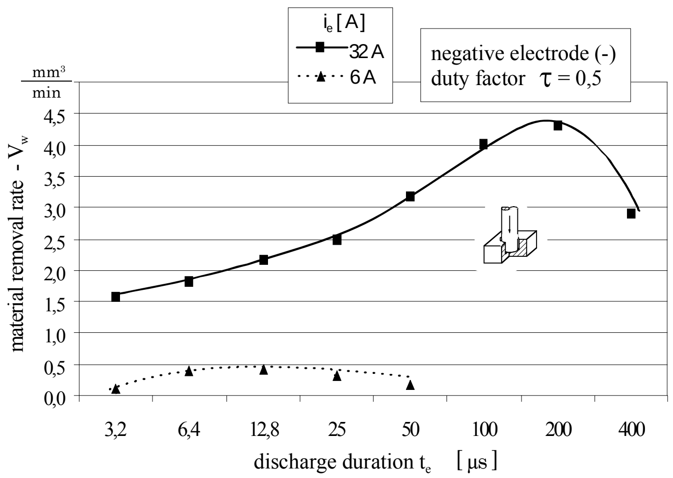

Figure 4. The results of material removal rate V_w against the variation of discharge duration t_e .

For the discharge current $\hat{i}_e$ = 6 A the variation of discharge duration t_e from 3,2 to 50 µs did not affect significantly the material removal rate V_w, . This is related to the small working gap, which hinders the total molten material to be properly expelled. As a result, the molten and vaporized material mainstream solidifies in the recently formed crater and surroundings. The best V_w = 0,5 mm^3/min for the discharge current i_e = 6 A is achieved at t_e = 12,8 µs.

The volumetric relative wear ϑ represents the ratio between the electrode wear rate V_e [mm^3/min] to the workpiece material removal rate V_w [mm^3/min]. The performance of ϑ [%] against the variation of discharge duration t_e for the discharge currents i_e = 6 and 32 A is shown in Fig. 5.

For the discharge current i_e = 6 A increasing the discharge duration t_e a decrease of ϑ is observed, reaching a minimum of about 20% at the optimum t_e = 12,8 µs. It is also seen that the variation of discharge duration t_e did not affect significantly the values of ϑ for rough the machining with i_e = 32 A. For this current the volumetric relative wear ϑ trends to approximately 18% up to the optimum t_e = 200 µs.

Independently of the discharge duration t_e the higher the discharge current i_e the lower the volumetric relative wear ϑ when machining with CuW electrode. This phenomenon arises of the CuW electrode chemical composition (30% Cu and 70% W). The elevated concentration of tungsten, with high melting point (3410 ^{0}C), promotes a higher resistance of the electrode against the thermal wear during machining. The result is less electrode wear rate V_e and better material removal rate V_w, which causes a decrease of volumetric relative wear ϑ (Ve/Vw) when the discharge current i_e increases.

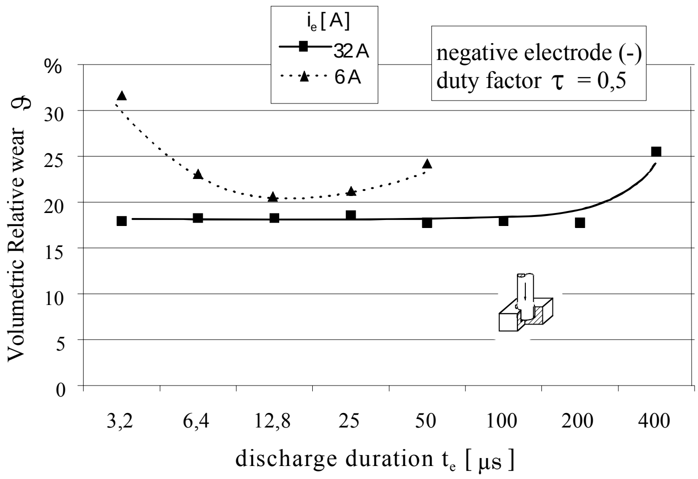

Figure 5. Volumetric relative wear ϑ against the variation of discharge duration t_e .

Figure 6 shows the results of the surface roughness R_a versus the discharge duration t_e. The lowest R_a = 1,2 µm is reached for the discharge current i_e = 6 A and t_e = 3,2 µs. For i_e = 6 A the variation of discharge duration t_e from 3,2 to 50 µs did not change considerably the values of the surface roughness R_a. This has to do with the small working gap that does not promote an adequate evacuation of the eroded particles, but instead accumulate them in the crater and surroundings. When machining with i_e = 32 A is detected an increase of the surface roughness R_a as the discharge duration t_e is raised. This is due to the higher values of material removal rate V_w that produces deeper and larger craters on the surface of the workpiece.

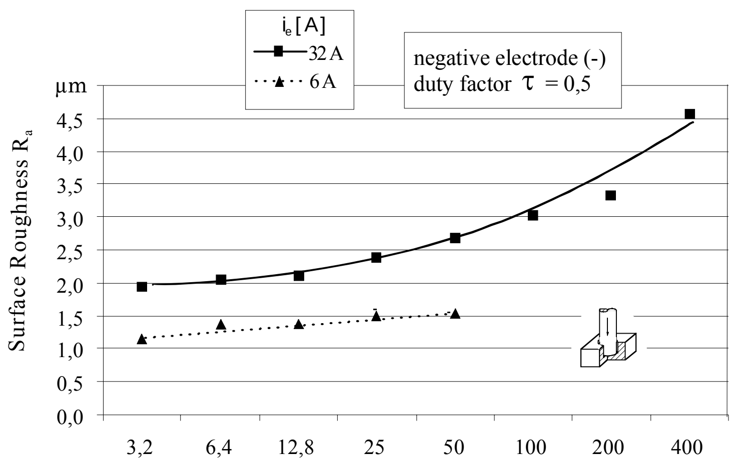

Figure 6. Surface roughness R_a against the variation of discharge duration t_e .

4.2. Second stage - Effect of Duty Factor τ

From the optimized values of discharge duration t_e obtained in stage one the duty factor τ was varied to analyze its influence on the EDM performance. The value of the duty factor τ at 0,5 was the starting point as shown in Fig.7. The optimum discharge duration t_e is kept fixed and the interval time t_o is modified.

From the best conditions for finish machining (t_e = 12,8 µs, i_e = 6 A) the duty factor τ is reduced from 0,5 to 0,11 by increasing the interval time t_o within the range of 12,8; 25; 50; 100 µs. It observed from Fig.7 that this variation of duty factor τ does not affect significantly the values of material removal V_w. This occurs because the energy $W_e = i_e.u_e.t_e$ [J] supplied to process is not changed.

For the discharge current i_e = 32 A at the optimum discharge duration t_e = 200 µs the duty factor τ is raised from 0,5 up to 0,89 by lowering the interval time t_o at the sequence of 200, 100, 50, 25µs. It is noticed a little increase of the material removal rate $V_w \approx 4{,}5$ mm^3/min for the duty factor τ of 0,67. Higher values of duty factor (τ = 0,8 and 0,89) reduces the material removal rate. This is caused by the low interval times t_o which brings instability into the working gap either in the form of arc discharge pulses or short-circuit pulses.

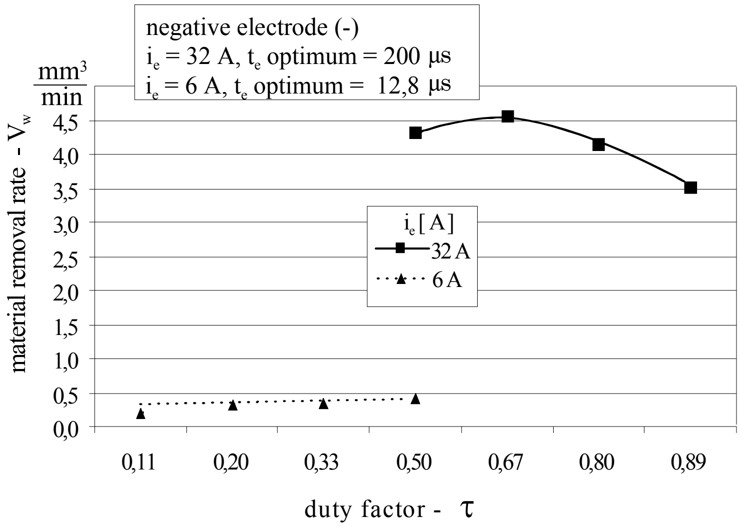

Figure 7. The results of material removal rate V_w against the variation the duty factor τ.

Figure 8 shows that for both rough and finish machining (i_e = 32 and 6 A) the variation of duty factor τ significantly influences the values of volumetric relative wear ($\vartheta = V_e/V_w$). For the discharge current i_e = 32 A the increase of duty factor τ from 0,5 to 0,89 promotes an elevation of the volumetric relative wear ϑ up to about 22%. This is due to the low interval times t_o that promote an over-concentration of debris in the working gap reducing the material removal rate V_w. For the finish machining the decrease of duty factor τ from 0,5 to 0,11 reduces the volumetric relative ($\vartheta = V_e/V_w$). Here it occurs because longer interval times t_o improve the flushing conditions by reducing the occurrence of arc-discharges and short-circuits promoting more stability to the machining.

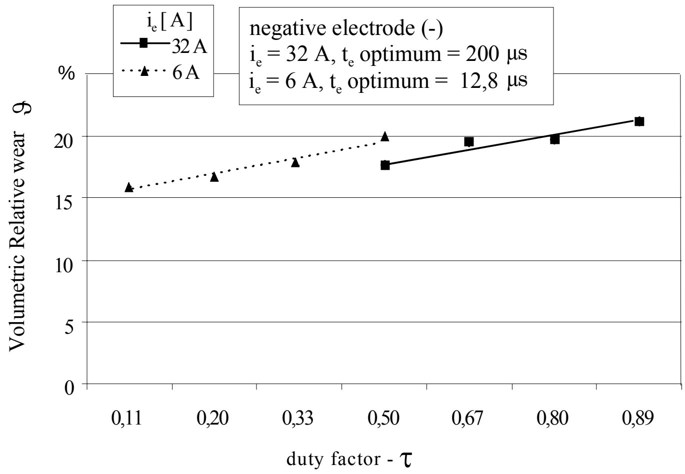

Figure 8. Volumetric relative wear ϑ V_w against the variation the duty factor τ.

From Fig. 9 is clearly seen that the surface roughness for rough machining is not significantly affected by the variation of the duty factor τ, remaining at about R_a = 3,5 µm. This has to do with the fact that the duty factor was varied by the modification of the interval time t_o, which does not influence on the energy $W_e = i_e.u_e.t_e$ [J] supplied to the machining process. For finish machining the reduction of duty factor from 0,5 to 0,11 caused insignificantly decrease on the surface roughness R_s from 1,5 to approximately 1,2 µm.

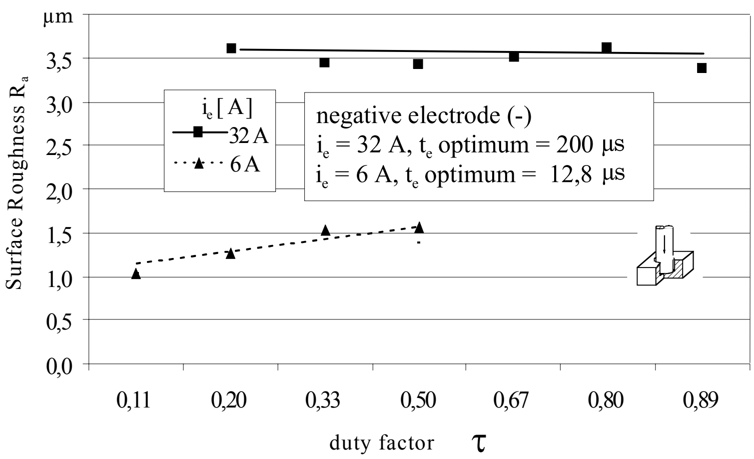

Figure 9. The results of surface roughness R_a aginst the variation the duty τ.

4.3. Third stage - Effect of Open Circuit Voltage u_i

Figure 10 shows the influence of the variation of the open circuit voltage u_i on the results of material removal rate V_w for the EDMachining of tungsten carbide-cobalt composite material. For the rough machining with i_e = 32 A , duty factor τ = 0,67 and the optimum t_e = 200 µs the variation of the open circuit (u_i= 80 to 200 V) provides a little raise on the value of V_w to 5,2 mm^3/min. This is due to the intrinsic relation of the open circuit voltage $\hat{u}_i$ with the size of the working gap, i.e., the distance between the electrode and the workpiece during the electric discharge occurrence. For rough EDMachining conditions higher values of $\hat{u}_i$ support larger working gaps. This fact promotes proper flushing of the eroded particles away from the working gap causing an improvement of the material removal rate V_w.

From Fig. 10 it is observed that for finish machining with i_e = 6 A under the optimum electrical parameters the variation of the open circuit voltage u_i does not affect the results of material removal rate V_w. This happens because the variation of u_i from 80 to 200 V does not enlarge enough the working gap so that the flushing conditions can be improved to provide better values for the material removal rate V_w.

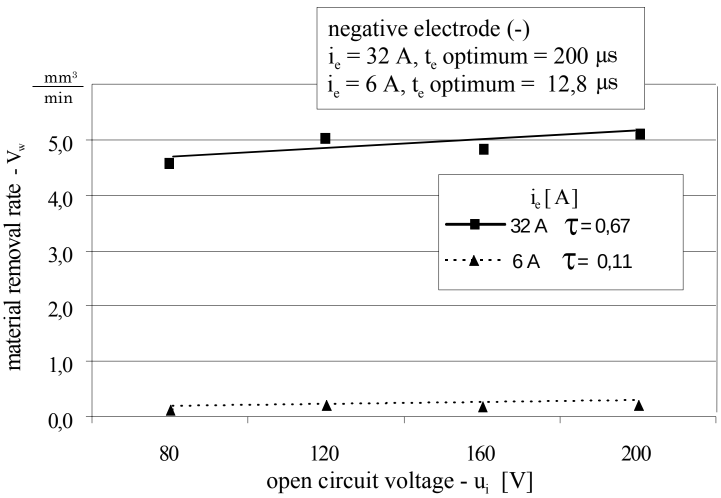

Figure 10. Material removal rate V_w against the variation of the open circuit voltage u_i.

Figure 11 presents the results of volumetric relative wear ϑ for the variation of open circuit voltage u_i. In EDM the very small byproducts generated by the dielectric burning tends to adhere over the surface of the electrode promoting the formation of a protective layer against the wear. These byproducts concentration in the working gap depends on its size, i.e., the larger the working gap the easier the byproducts are removed by the flushing. For rough machining with $i_e = 32$ A the increase of u_i provided a working gap growth causing better flushing conditions, which then lowered the concentration of the byproducts. This prevented the formation of the protective layer on the surface of the electrode causing an increase of the values of electrode wear rate V_e. As a consequence the volumetric relative ($\vartheta = V_e/V_w$) is increased when the open circuit voltage varies from 80 to 200 V. For the finish machining ($i_e = 6$ A) the variation of u_i did not affect the values of the volumetric relative wear.

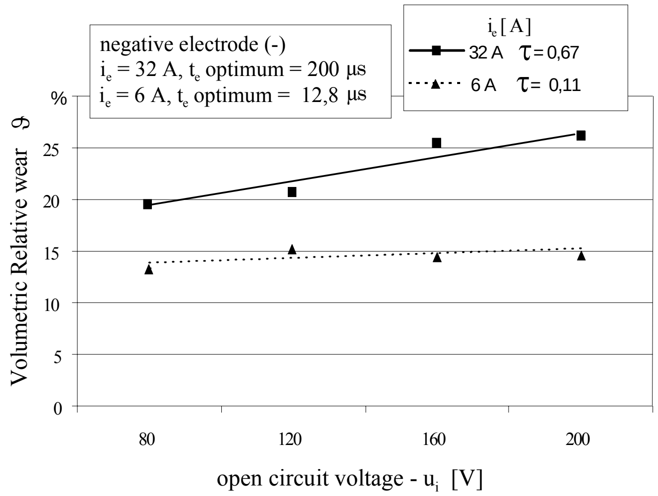

Figure 11. Volumetric relative wear ϑ against the variation of the open circuit voltage u_i..

Figure 12 shows that the elevation of the open circuit voltage u_i for the rough machining with $i_e = 32$ A considerably increased the surface roughness R_a from about 3,2 to 5,5 µm. This takes place because the variation of u_i raised the material removal rate V_w promoting deeper and larger craters on the surface of the tungsten carbide-cobalt workpiece. For finish machining ($i_e = 6$ A) it is observed that the levels of the surface roughness R_a is not influenced by the different values of the tested open circuit voltage u_i.

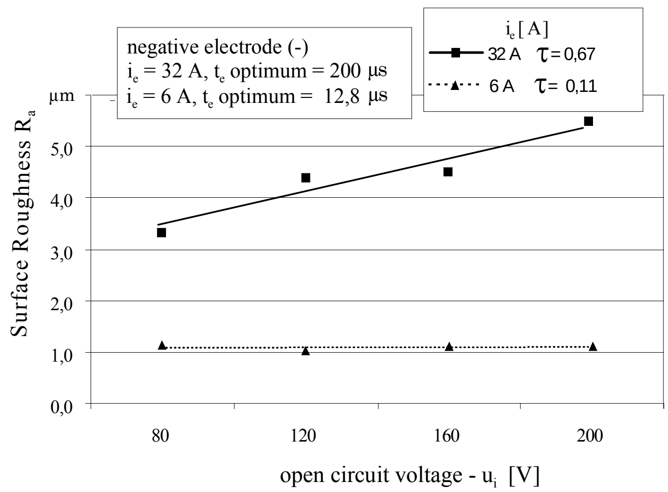

Figure 12. Results of surface roughness R_a against the variation of the open circuit voltage u_i.

4. CONCLUSION

The values of EDM parameters have to be properly set, targeting an appropriate level of machining performance and surface integrity of a workpiece. In this work a sequence of experiments on the electrical discharge machining of a special grade of tungsten carbide-cobalt using copper-tungsten as electrodes under rough and finish process conditions were performed. Electrical discharge machining experimental tests regarding the variation of discharge duration t_e, duty factor τ and open circuit voltage u_i and their influences on the workpiece material removal rate V_w, volumetric relative wear ϑ and surface roughness R_a were carried out. From the results the following conclusions can be drawn:

(i) The increase of discharge duration t_e promotes higher material removal rate V_w and produces poorer surface texture R_a for rough machining regimes, but not affects considerably the values of V_w and R_a for finish machining. The volumetric relative wear ϑ reduces with the increase of t_e for finish machining but is not to affected for rough machining regime.

(ii) The variation of the duty factor τ slightly improves the material removal rate V_w for both rough or finish machining regimes. The surface texture R_a is not affected significantly by the variation of the duty factor τ. The volumetric relative wear ϑ for rough and finish regimes is significantly influenced by the variation of the values of the duty factor.

(iii) The open circuit voltage u_i increases the material removal rate V_w and the surface texture R_a for rough machining regime. For finish machining the values of V_w and R_a does not change with the variation of the open circuit voltage $u_{i..}$ The volumetric relative wear ϑ for rough machining gets higher with the rise of the open circuit voltage $u_{i,}$ but their values for finish regime are not affected.

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