ON THE BEHAVIOR OF PARAMETERS AND COPPER-TUNGSTEN ELECTRODE EDGE RADIUS WEAR WHEN FINISH SINKING EDM OF TOOL STEEL

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The optimization of the electrical discharge machining (EDM) parameters and the thermophysical properties of electrode and workpiece materials are among the main factors that contribute to the overall machining efficiency. In this work an experimental investigation on the performance of copper-tungsten alloy electrode when finish Sinking EDM of a heat treated tool steel has been carried out into two stages. In the first stage, effects of important EDM electrical variables on process characteristics, namely material removal rate, volumetric relative wear and surface roughness were investigated. In the second stage, the change in electrode shape was studied by measuring its edge radius wear growth as the machining time proceeds. This paper contributes with reference to the understanding of the relation between the process parameters to electrode edge radius wear as well as some analysis of the recast layer produced on the tool steel workpiece.

1 INTRODUCTION

Electrical Discharge Machining (EDM) is one of the major non-conventional manufacturing processes widely applied in industry to generate complex geometrical shapes in many different kinds of electrical conductive materials in rough and finish machining conditions. In line with EDM theory, the mechanical properties of workpiece and electrode material have few influences on the process. On the other hand, the thermo-physical properties have extensive influences on the EDM performance characteristics, as reported by Kunieda, Lauwers, Rajurkar and Schumacher (2005) /7/. Over the recent last decades, there have been increasingly more low cost EDM machine-tools delivered with standard technology tables.

However, the tests developed by the manufacturers to build these technology tables with reference to proper workpiece material removal rate, surface texture and electrode wear rate, are carried out under optimum machining conditions and using standard materials, which is not normally the case faced by the tooling industry as formerly remarked by Löttgen (1998) /10/. Consequently, for the purpose of achieving reliable results under realistic machining conditions, the customer himself has to develop further tests for each different work, i.e., concerning the cavity geometrical accuracy as well as the kinds of workpiece and electrode materials.

The aforementioned remarks are in accordance with the work of Ho & Newman (2003) /5/ about the state of the art in EDM, where they showed that a significant number of recent researches are still focused in improving EDM performance measures such as material removal rate, electrode wear rate and surface integrity. Abbas, Solomon and Bahari (2007) /1/ also reviewed the current research trends in EDM and pointed out that throughout the last decades many researchers have 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 regards to this and according to VDI - Verein Deutscher Ingenieure 3402 Blatt 1 (1990) /11/, there are four ways to analyze the electrode wear in EDM: volumetric relative wear, relative linear frontal wear, relative linear corner wear and relative linear edge wear. But, these measurements of electrode wear are normally carried out at stationary state, i.e., after ending the workpiece machining. Nowadays, in the majority of research works this is still a common practice. Conversely, the wear of the electrode proceeds throughout the machining time M_t. Consequently, to achieve high precision in workpiece geometry and tolerances, it is very important to evaluate the change of the electrode shape at the same time as the machining proceeds.

In view of that, in this study an experimental investigation on the performance of copper-tungsten (Cu-W) alloy electrode when finish Sinking EDM of AISI H13 heat treated tool steel is carried out. The Cu-W alloy was selected as electrode material because it is suitable to be used when high precision is required and the AISI H13 tool steel as for the workpiece due its wide application to the tooling industry. The focus of this study is the investigation of the influences of electrical parameters over important machining performance characteristics, connected to the understanding of the relation between the process parameters to the change in electrode shape throughout machining time M_t by measuring its edge radius growth, as well as some analysis of the recast layer produced on the workpiece.

Nomenclature:

M_t = machining time, min
t_e = discharge duration, µs
t_p = pulse cycle time, µs
t_i = pulse duration, µs
t_d = delay time, µs
t_0 = pulse interval time, µs

$\hat{u}_i$ = open circuit voltage, V
$\hat{i}_e$ = discharge current, A
R_a = surface roughness, µm
V_e = electrode wear rate, mm³/min
V_w = material removal rate, mm³/min

Greek Symbols:

ϑ = volumetric relative wear
τ = duty factor

2 EXPERIMENTAL PROCEDURES

2.1 Development of adequate parameter settings for finish EDMachining - Stage I

In order to investigate the change of electrode shape, by measuring its edge radius growth as a function of machining time M_t, it is necessary to achieve adequate EDM parameter settings. Thus, the following materials and equipment were applied:

(i) Machine-tool: the tests were carried out on a Charmilles ROBOFORM 30 CNC die-sinking machine-tool equipped with an isoenergetic generator, where is possible to set the discharge duration te. A noteworthy 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 EDM is carried out, low energy is applied and longer times of t_d are observed. This is due to the very small working gap contamination with micro byproducts of the erosion process. In the present work, taking into account the low gap contamination, the ignition delay time t_d was set as 30% of discharge duration t_e.

(ii) Electrode: Copper-Tungsten cylindrical bars 100 mm long and 10 mm in diameter with positive polarity were mounted axially in line with workpiece samples, as shown in **Fig. 1**. The properties of CuW electrodes used in this work are presented in **Tab.1**.

Material	**CuW**
Density (g/cm³)	14,18
Electrical Resistivity (μΩ.cm)	3,59
Thermal Conductivity (W/mK)	160
Linear Expansion Coefficient ($x10^{-6}$ /K)	10,77
Melting Point (°C)	3410
Specific Heat (J/KgK)	214
Hardness (HRC)	37

Table 1: Properties of copper-tungsten (30%Cu 70%W)

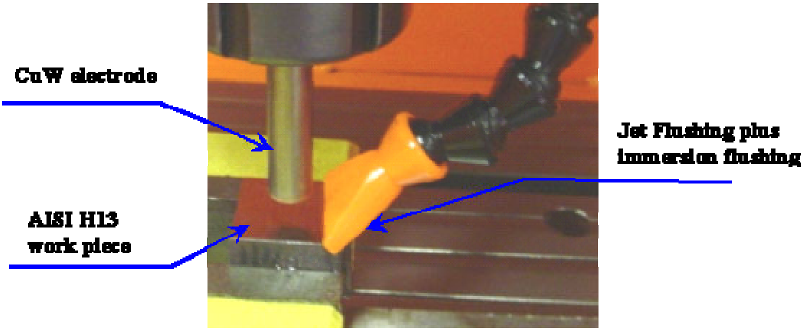


Figure 1: Assembly used to determine the adequate parameter settings for finish EDMachining: a cilindrical CuW electrode, the workpiece sample AISI H13 and the flushing method; mounted on a Charmilles ROBOFORM 30 CNC machine-tool. A hydrocarbon with 3 cSt at 400 C was used as dielectric fluid.

(iii) Workpiece samples: AISI H13 tool steel square samples 25 mm wide and 15 mm thick with Ra = 0,42 μm where prepared by Wire EDM. This material is widely applied by the die and mold-making industry. The chemical composition of AISI H13 tool steel is as follows: 0,40% C, 1,0% Si, 1,0% Mn, 5,2% Cr, 1,5% Mo, 0,9% V and 0,00765 g/mm³ density at 200 C. The workpieces were quenched and tempered to an average 45 HRC.

(iv) Flushing method: A hydrocarbon dielectric fluid with 3 cSt at 400 C, flash point of 134 oC and 0,01 wt.% of aromatic contents were used for the tests.

According to Boothroyd and Winston (1989) /3/, the introduction of dielectric fluid to the gap is normally based on four methods: (a) normal flow, (b) reverse flow, (c) immersion flushing and (d) jet flushing. In view of the shallow cavities of small diameter to be machined, a jet plus an immersion flushing of dielectric fluid was applied, as shown in **Fig. 1**. This flushing method was sufficient to remove the excess of eroded particles away from the working gap as well as to promote adequate cooling. In addition, this method also maintained some contamination of the working gap reducing the ignition delay time t_d. The flushing efficiency was also improved by alternating the machining period U [s] and the electrode retraction period with no discharges R [s], as shown in **Fig. 2**. The values of U = 0,8 s and R = 0,2 s were defined after pilot tests.

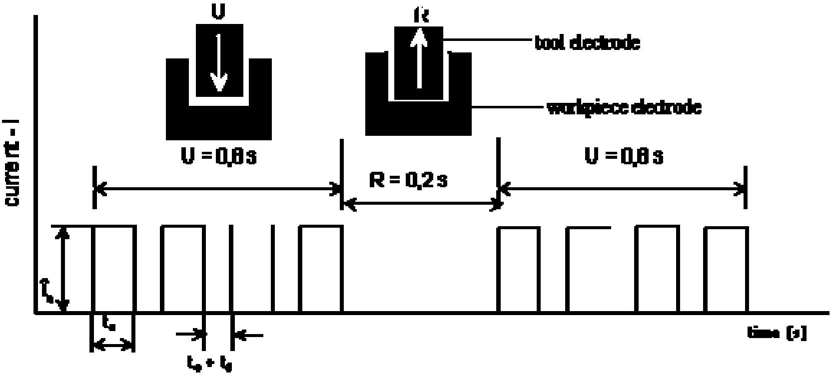


Figure 2: Series of pulses U = 0.8 s followed by a pause time R = 0.2 s

(v) Electrical variables: Tests about the influence of discharge duration t_e and discharge current $î_e$ with reference to the workpiece material removal rate V_w [mm3/min], the surface roughness Ra [m] and the volumetric relative wear $\vartheta = V_e/V_w$ (V_e is the electrode wear rate [mm3/min]) were carried out under the conditions showed in **Tab.2**. The quantification of V_w and ϑ was performed considering the mass of electrode and workpiece before and after a 30-minute machining time. Three tests were done for each parameter setting, using new electrodes, with no significant differences among results. A balance with 0,0001 g resolution was used to quantify the mass. A proper duty factor τ was implemented for all the tests. The duty factor $\tau = t_i / t_p$ represents the ratio between pulse duration t_i and pulse cycle time t_p ($t_p = t_i + t_o$).

To allow a good stability for finish EDMachining operations, the pulse duration t_i and the pulse interval time t_0 were set to be equal. This condition leads to a duty factor of $\tau = 0,5$ and provides few occurrences of short-circuits and arc-discharges. The open gap voltage $\hat{u}_i$ has an intrinsic relation with the size of the working gap, i.e., the distance between the electrode and workpiece during the spark. As reported by König & Klocke (1997) /8/ the higher the value of $\hat{u}_i$ the larger the working gap. The magnitude of $\hat{u}_i$ assures a proper dispersion of sparks along the frontal area of the pair electrode/workpiece, improving the flushing conditions. Therefore, in finishing EDMachining it is recommended that higher values of $\hat{u}_i$ should be established in order to promote a more adequate working gap. In this study, the value of $\hat{u}_i$ = 200 V was established after a series of pilot tests.

Discharge current i_e [A]	**Discharge duration t_e [μs]**	**Pulse interval time t_o [μs]**	**Open Circuit Voltage $\hat{u}_i$ [V]**	**Electrode polarity**
2	3,2; 6,4; 12,5; 25; 50	3,2; 6,4; 12,5; 25; 50	200	+
4	3,2; 6,4; 12,5; 25; 50	3,2; 6,4; 12,5; 25; 50	200	+
8	3,2; 6,4; 12,5; 25; 50	3,2; 6,4; 12,5; 25; 50	200	+

Table 2: Experimental parameters for the development of adequate finish sinking EDMachining settings at Stage I

2.2 Evaluation of electrode edge radius wear - Stage II

Here in stage II, the change in electrode shape by measuring its edge radius growth as a function of machining time M_t was carried out using the best EDM parameter settings achieved in stage I. **Tab. 3** presents the EDM process parameters, machine-tool and materials established for the experimental conditions.

EDM machine tool	**Charmilles ROBOFORM 30 CNC**
Machining dielectric fluid	Arclean Hydrocarbon fluid with 3 cSt at 40 ^{0}C
Electrode material	Copper-Tungsten (30% Cu 70% W)
Work piece material	Quenched and tempered AISI H13 tool steel (45 HRC)
Polarity of electrode	Positive
Discharge current i_e	8 A
Discharge duration t_e	50 µs
Open circuit voltage $û_i$	200 V
Flushing method	Jet plus immersion flushing
Duty factor	0,5

Table 3: Experimental tests for the evaluation of electrode edge radius wear at Stage II

Suitable electrode geometry was selected to facilitate the measurement of edge radius growth throughout the machining time M_t. **Fig. 3** shows a schematic representation of the copper-tungsten square bar electrode 70 mm long and 7 mm wide. The faces of the electrode were generated by wire EDM from rough machining to four trim cuts providing a surface roughness Ra = 0,3 µm, which was then followed by polishing. The electrode to be analyzed was thus produced with an initial edge radius rei 11 µm. Afterwards, the electrode was installed at a high accuracy EROWA tool-holder which was mounted directly to the EDM machine headstock, as shown in **Fig. 4**. This method provided an easy removal of the whole assembly. As result the measurement of the electrode edge radius growth has been done without losing the repositioning accuracy of the electrode to the EDM machine. This method assured both an adequate continuation of the EDM operation and an accurate analysis of the electrode wear.

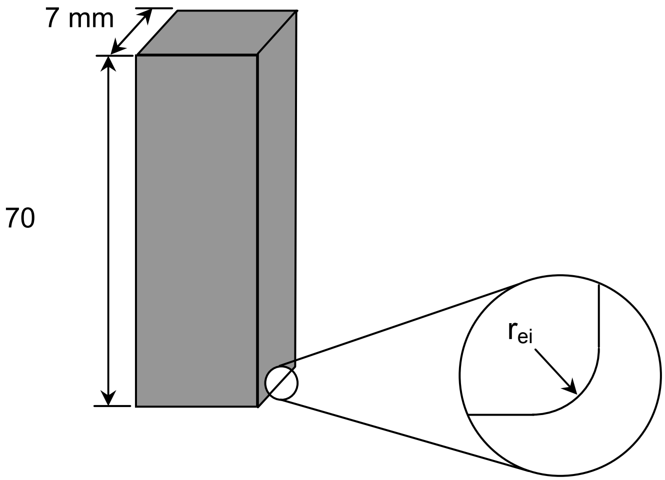


Figure 3: Schematic representation of the electrode geometry depicting the initial electrode edge radius r_{ei} 11µm

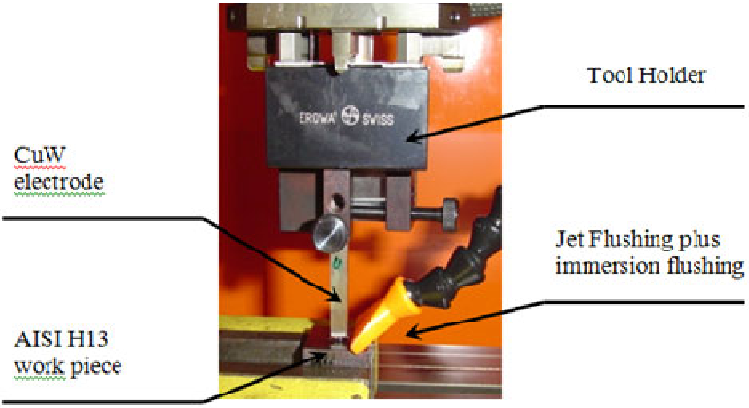


Figure 4: The assembly method of the copper-tungsten electrode in an EROWA tool-holder provided an easy removal without losing the repositioning accuracy of the electrode to the EDM machine

A procedure was implemented to investigate correctly the electrode edge radius wear growth while the machining time M_t proceeded. The measurements were accomplished for M_t through 5, 10, 20, 30, 40, 60, 80 and 100 minutes from the initial edge radius rei 11 m. After each one M_t the process was interrupted and the electrode/tool holder assembly was drawn from the machine-tool headstock. This assembly was then properly positioned on the working table of a NIKON MM40 optical microscope equipped with measuring software (**Fig.5**). This software captures ten points on the electrode edge and then calculates and presents the value of the electrode edge radius. Three measurements have been done for each one of the four edges of the electrode. This procedure continued until the total machining time M_t was performed.

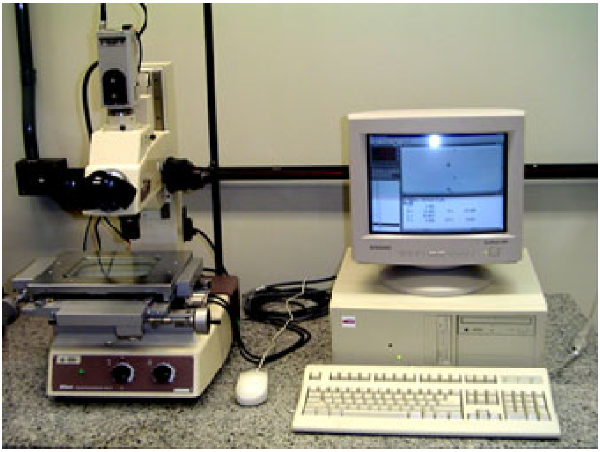


Figure 5: NIKON MM40 optical microscope (resolution = 1μm) used to measure the electrode edge radius growth

3 RESULTS AND DISCUSSIONS

3.1 Development of adequate parameter settings for finish EDMachining - Stage I

In finish EDMachining, an important aim is to achieve high workpiece surface quality R_a and low level of volumetric relative wear ϑ, while keeping a good level of material removal rate V_w. **Fig. 6** presents the volume of material removed from three cavities of AISI H13 workpiece samples under discharge currents $\hat{i}_e$ = 2, 4, 8 A with t_e = 50 s. In general, after EDMachining operations using copper or especially with graphite electrodes, a sort of gray to black film adhered to bottom of the cavities is observed. From visual inspections of AISI H13 workpieces after the tests with copper-tungsten electrodes, it has been verified that this phenomenon is almost non-existent, as seen in **Fig. 6**. It represents a good result with reference to the mold making production chain, because the existence of such material adhered to the cavity would introduce a time-consuming removal operation when polishing the mold.

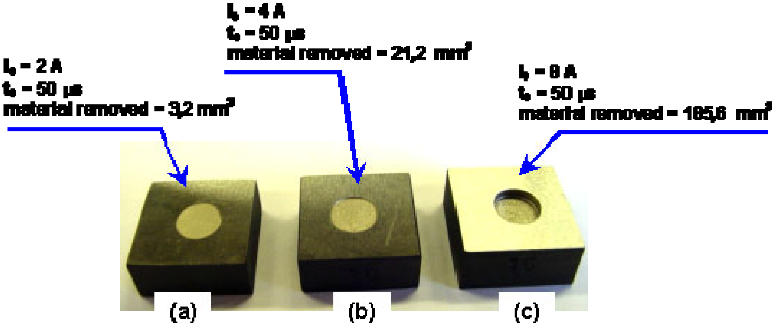


Figure 6: AISI H13 samples after EDM with positively charged CuW tool electrodes under $\hat{i}_e$ = (a) 2 A (b) 4 A and (c) 8 A at optimum t_e = 50 applying isoenergetic generator mode.

3.1.1 Material removal rate V_w

The results of the material removal rate V_w against the variation of discharge duration t_e with discharge current ie = 2, 4 and 8 A for positive copper-tungsten electrodes are summarized in **Fig. 7**. The global values of V_w obtained for $\hat{i}_e$ = 2 and 4 A are much lower than those achieved for $\hat{i}_e$ = 8 A. This occurs because the material removal rate V_w is dependent on the energy We= ue.$\hat{i}_e$.t_e [J] released into the working gap, i.e., the increase of the energy We leads to higher values of V_w.

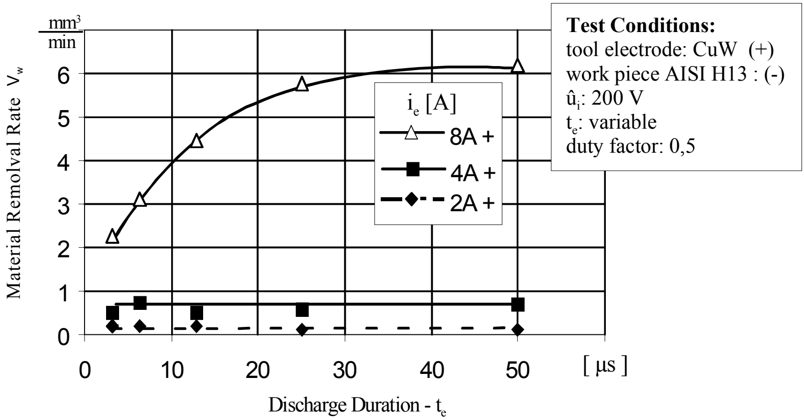


Figure 7: Influence of discharge current $î_e$ and discharge duration on material removal rate V_w for EDM with positive Copper-Tungsten electrodes.

From **Fig. 7** when EDM with discharge current ie = 8 A it is clearly seen 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 best material removal rate V_w is approximately 6 mm³/min to the optimum discharge duration t_e = 50 µs. Beyond this point V_w starts decreasing. This happens because longer discharge duration t_e reduces the pressure and energy of the plasma channel over the molten material of the electrode and the workpiece, which owes to the very high plasma diameter global expansion. As a consequence, this phenomenon brings instability to the process reducing the material removal. To verify the influence of higher values of t_e than that of the optimum one, tests with t_e = 100 µs were performed for the discharge currents $î_e$ = 2, 4 and 8 A, presenting very little material removal rate V_w. For discharge currents $î_e$ = 2 and 4 A, the variation of discharge duration t_e from 3,2 to 50 s 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 away from the gap. As a result, the molten and vaporized material solidifies in the recently formed crater and surroundings.

3.1.2 Volumetric relative wear ϑ

The volumetric relative wear ϑ (V_e/V_w) represents the ratio between the electrode wear rate V_e [mm3/min] and the workpiece material removal rate V_w [mm3/min]. From **Fig. 8** it is observed that independently of the value of discharge current $î_e$ a decrease of volumetric relative wear ϑ occurs when increasing the discharge duration t_e. An explanation to this may be given by the longer discharge durations t_e that promote more melting of material of the workpiece and solidification of the molten material of the electrode during the spark. Consequently the V_w increases and the V_e decreases, reducing the level of volumetric relative wear ϑ (V_e/V_w).

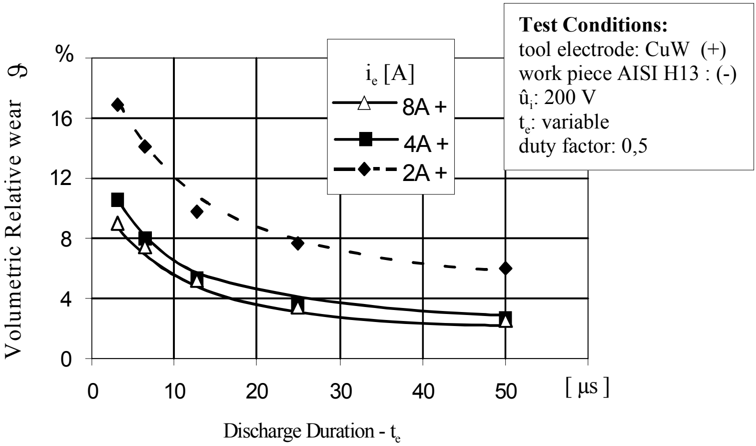


Figure 8: Results of volumetric relative wear ϑ against the variation of discharge duration t_e and discharge current $\hat{i}_e$ for EDM with positive Copper-Tungsten electrodes.

Fig. 8 also shows that for EDMachining with copper-tungsten electrodes the higher the discharge current $\hat{i}_e$ the lower the volumetric relative wear ϑ, regardless of the discharge duration t_e. In part, this event can be explained as follows: the Cu-W alloy used as electrode material is composed of 30% Cu and 70% W, where the element tungsten has a melting point of 3410 0C; consequently, the high concentration of tungsten promotes better resistance of the electrode against the thermal wear degradation during machining. The result is a lower electrode wear rate V_e and higher material removal rate V_w. This causes a decrease of volumetric relative wear ϑ (V_e/V_w) when the discharge current $\hat{i}_e$ increases. At the optimum time t_e = 50 µs, the volumetric relative wear ϑ is about 2,0% and 2,6% respectively for $\hat{i}_e$ = 8 and 4 A. For the discharge current $\hat{i}_e$ = 2 A with t_e = 50 µs, the level of ϑ goes up to 6%. Here it is important to remark that according to Klocke and Karden (1999), for EDMachining using pure copper as electrode material, an opposite phenomenon occurs, i.e., increasing the discharge current $\hat{i}_e$ increases the volumetric relative wear ϑ. The lower melting point (1083 0C) of copper partly accounts for this.

3.1.3 Surface roughness R_a

As shown in **Fig. 9** an increase of surface roughness R_a is detected as the discharge duration t_e rises from 3,2 to 50 s for EDM with discharge currents $\hat{i}_e$ = 4 and 8 A. It may be explained by the fact that the surface roughness in EDM depends on the material removal rate V_w, which is governed by the discharge energy We = ue . ie . t_e [J]. In this equation the variables that really affect the material removal rate and thus the surface roughness are the discharge duration t_e and the discharge current ie; whilst the discharge voltage ue is uncontrollable and generally considered constant, not much influencing the process performance. In consequence, as the discharge duration t_e increases, for a given value of discharge current ie, the energy supplied into the working gap becomes higher. This implies more material removal rate, producing deeper and larger craters on the workpiece surface, i.e., poorer surface roughness.

One can also see in **Fig. 9** that the surface roughness R_a is not considerably altered by the variation of discharge duration t_e from 3,2 to 50 s for $\hat{i}_e$ = 2 A. This has to do with the fact that very long discharge duration t_e causes an over-increase of diameter of the plasma channel, reducing the pressure of the plasma over the molten pools of the electrode and workpiece materials. For that reason and also due to the small working gap the eroded particles are not properly evacuated away, but is instead accumulated in the crater and surroundings when the plasma collapses at the end of discharge duration.

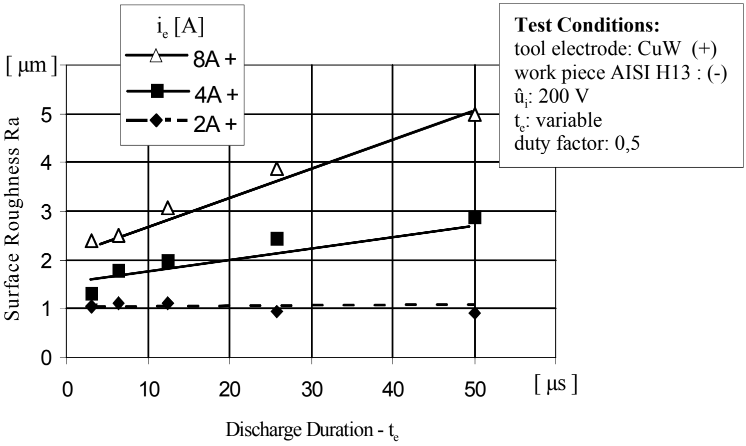


Figure 9: Results of surface roughness R_a as a function of discharge duration t_e for discharge currents ie = 2, 4 and 8 A when EDM using Copper-Tungsten electrodes at positive polarity.

3.2 Evaluation of electrode edge radius wear - Stage II

3.2.1 Edge radius wear and workpiece cavity depth as the machining time M_t proceeds

Fig. 10 shows the results of the CuW electrode edge radius wear growth as the machining time M_t goes through 5, 10, 20, 30, 40, 60, 80 to 100 minutes, using the best results reached in Stage I. It is observed that for the first 20 min of machining the edge radius wear increases abruptly from its 11 µm initial value to about 200 µm. As the machining time M_t proceeds through 20 to 40 min the edge radius wear growth is not so much intensive, increasing from 200 µm to approximately 275 µm.

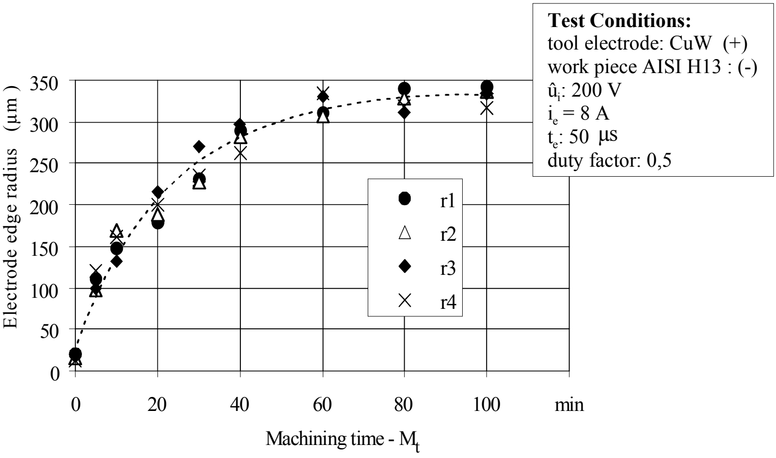


Figure 10: Electrode edge radius wear growth at the four edges (r1, r2, r3, r4) of the electrode as the machining time M_t proceeds from 5 min up to 100 min.

On the other hand, for machining time M_t from 40 to 100 minutes the electrode edge radius wear growth is not significantly affected, varying from 285 µm to 325 µm. An explanation to this phenomenon is related to the precipitation of carbon over the edge radius of the electrode as the machining time M_t advances. This carbon is released by the pyrolysis of the hydrocarbon dielectric fluid and part from the melted and vaporized tool steel workpiece material. The carbon precipitation ends up working as a protective layer against the wear and is most prominent for longer machining time M_t. It happens because at the beginning of machining the electrode edge radius is very sharp avoiding the precipitation of carbon and thus accelerating the edge radius wear growth. At longer machining time the sharp electrode edge changes to a larger circular arc edge facilitating the precipitation of carbon; which then provides stability to the edge radius growth.

As presented in **Fig. 10** slight differences can be seen in the radius wear at the four edges of the electrode (r1, r2, r3, r4). This is expected to be associated to the hydrodynamic behavior of the dielectric fluid as the cavity becomes deeper. An explanation is that during the EDM operation the dielectric fluid is in random agitation along the working gap and the sides of the cavity, causing different debris concentration. This phenomenon causes variations in the material removal of the electrode, promoting different values of its edge radius.

Fig. 11 shows the depth of workpiece cavity with the progress of the machine time M_t. It is seen that the penetration of the electrode into the workpiece cavity linearly increases as M_t proceeds from 5 to 100 min. This is due to the stability of the EDM operation with CuW electrodes, meaning that flushing is adequate and few arc discharges and short circuits takes place. The high resistance of copper-tungsten (30% Cu and 70% W) against the thermal wear degradation is probably the key factor to explain this occurrence. The linear progression of workpiece cavity depth as machining time M_t proceeds denotes that copper-tungsten electrode promotes very good conditions for finish EDM operations.

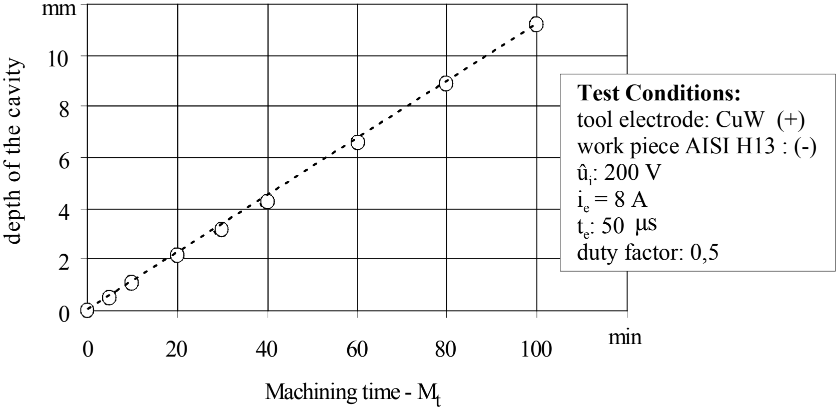
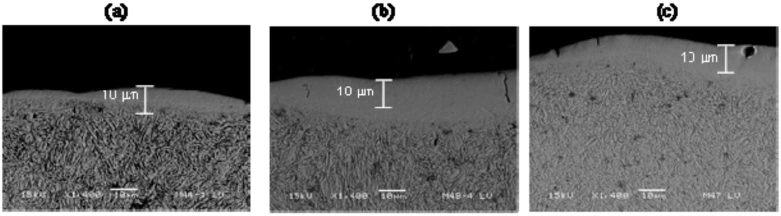


Figure 11: Results of the AISI H13 tool-steel cavity depth as the machining time M_t proceeds from 5 to 100 min.

3.2.2 The white or recast layer

Barash (1965) /2/, Jutzler (1982) /6/, Kruth, Stevens, Froyen, and Lauwers (1995) /9/ showed that when machining a workpiece with EDM, a multilayered heat affected zone is created on the workpiece surface. Furthermore, according to VDI - Verein Deutscher Ingenieure 3402 Blatt 4 (1990) /12/, the heat affected zone created by EDM is constituted of an upper layer, known as either white layer or recast layer, followed by the phase transformation zone and the conversion zone.

Fig. 12 shows scanning electron microscope cross-sectional views of the AISI H13 tool steel recast layer for different machining times M_t. It is observed that the structure of the recast layer is formed by superimposed strata derived from melted and resolidified workpiece material. It consists mainly of iron carbides in acicular or globular form distributed within an austenite matrix. The increase in carbon content in the recast layer is intrinsically related to the pyrolysis product that follows the cracking of the dielectric and is very confined to the melted and resolified workpiece material forming iron carbides. The high tensile surface stresses caused by the EDM phenomena also create pores and micro cracks restricted to the recast layer and perpendicular to the surface, as can be seen in **Fig.12 (b)** and **Fig.12 (c)**. One can also see in **Fig.12 (a)** and **Fig.12 (b)** that, as the machining time M_t advances from 5 min to 40 min, a recast layer width enlargement is produced. However, the increase of recast layer width is almost negligible to M_t from 40 min up to 100 min.



Machining time: M_t = 5 min
I_e = 8 A
t_e = 50 µs

Machining time: M_t = 40 min
I_e = 8 A
t_e = 50 µs

Machining time: M_t = 100 min
I_e = 8 A
t_e = 50 µs

Figure 12: SEM cross-sectional view of AISI H13 for Machining time M_t = 5, 40 and 100 min depicting the recast layer width, micro cracks and pores.

4 CONCLUSIONS AND FINAL REMARKS

In this study, the influence of some important EDM electrical variables on the process machining characteristics were investigated, as well as the change of the electrode shape by measuring its edge radius wear growth while the machining time M_t proceeded. From the results the following conclusions can be drawn:

4.1 Development of adequate parameter settings for finish EDMachining - Stage I

The influence of discharge duration t_e over the material removal rate is most prominent for higher values of discharge current i_e; once an enhancement of material removal rate is clearly observed. For low discharge currents the variation of discharge duration does not alter significantly the removal rate. Tests with CuW electrode negatively charged showed very low levels of material removal.

- The volumetric relative wear reduces when increasing the discharge duration t_e, regardless of the value of discharge current $\hat{i}_e$. For EDM with CuW electrodes the higher the discharge current the lower the volumetric relative wear; which is attributable to the high concentration of tungsten leading to higher resistance of the electrode against the thermal wear degradation during machining.
- The surface roughness R_a is considerably influenced by the variation of discharge duration t_e when high value of discharge current i_e is applied. For very low discharge current the surface roughness is not considerably altered by the variation of discharge duration; due to the small working gap that hinders a proper evacuation of eroded particles, but instead accumulated them in the crater and surroundings when the plasma collapses at the end of discharge duration.
- The adhesion of process byproducts onto the machined workpieces was almost non-existent when EDM with CuW electrodes. This represents a good result with reference to the mold making production chain, because the existence of such material adhered to the cavity would introduce a time-consuming removal operation when polishing the mold.

4.2 Evaluation of electrode edge radius wear - Stage II

- At the beginning of machining the electrode edge radius growth is very high, reaching an equilibrium state for longer machining times M_t. This occurs because the precipitation of carbon over the edge radius, providing the formation of a protective layer against the wear, is easier when the electrode changes from a sharp edge to a rounded edge radius.
- The machining time M_t promotes little influence on the width of workpiece recast layer. The structure of the recast layer when EDM the AISI H13 tool steel with CuW electrode is formed by superimposed strata derived from melted and resolidified workpiece material. Pores and micro cracks restricted to the recast layer and perpendicular to the surface are observed; which owes to the high tensile surface stresses caused by the rapid heating and cooling of material, intrinsic to EDM process.
- The depth of workpiece cavity linearly increases with the progress of the machine time $M_{t,}$ meaning that flushing is adequate and few arc discharges and short circuits takes place. This denotes that CuW electrode promotes very good conditions for accurate finish EDM operations.

5 REFERENCES

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