PROCESS PARAMETERS FOR FINISH EDM OF AISI H13 TOOL STEEL WITH COPPER-TUNGSTEN ELECTRODES

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Abstract. *The thermo-physical properties of the electrode and the work piece materials (e.g. thermal and electrical conductivity, thermal expansion, heat to vaporize from room temperature, melting and boiling temperatures etc) have considerable influences on the EDM performance in terms of material removal rate, electrode wear and surface integrity. There is a wide range of materials used to manufacture electrodes. Here it can be mentioned graphite and its special grades, copper, brass, tungsten carbides and copper-tungsten alloys among others. In this work a copper-tungsten alloy (30% Cu, 70% W) was used as tool electrode when finish EDM of AISI H13 tool steel work pieces. Important EDM electrical variables named discharge current i_e and discharge duration t_e were investigated. The performance EDM outputs: material removal rate Vw, volumetric relative wear ϑ and surface roughness Ra were analyzed and quantified. The paper suggests appropriate parameter settings for EDM of AISI H13 tool steel using copper-tungsten electrodes.*

Keywords: *finish EDM, copper-tungsten electrodes, AISI H13, process parameter settings.*

1. INTRODUCTION

The Electrical Discharge Machining (EDM) is one of the major manufacturing processes widely applied in die and mold making industry to generate deep and three-dimensional complex cavities in many different classes of materials in rough and finish operations, as pointed out by König & Klocke (1997). Examples include plastic injection molding tools, dies and punches etc. As explained by Van Dijck (1973) the material removal in EDM 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 2000 μs, are generated in a liquid dielectric gap separating tool and work piece electrodes. The electrical energy released by the generator creates a high-energy plasma channel, surrounded by a vapor bubble, which melts a small quantity of material of both electrodes by conduction heat transfer. Subsequently, at the end of the pulse duration, the melted pool is removed by forces which can be of electric, hydrodynamic and thermodynamic nature. This process continues until the geometry of the part 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. Examples are copper, copper-graphite, graphite and its special grades, brass, tungsten, silver, silver-tungsten alloys, tellurium-copper alloys, copper-tungsten alloys etc. Each one of those materials has its own advantages and disadvantages. However, the most common materials used as electrodes are electrolytic copper, graphite and copper-tungsten alloys.

Lascoe (1988) and Drozda (1998) observe that copper 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. 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. They also point out that graphite and its special grades can be used from rough to finish EDM particularly in steel. 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. 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 to act like a lapping compound that eventually destroys the accuracy of the machine-tool. Copper-tungsten alloy is the material recommended when fine detail and high-precision EDM operations are demanded. This material possesses high density and strength, good thermal and electrical conductivity. These properties make this material proper for EDM applications requiring smooth surface finishes.

In this work it has been investigated three important technological aspects regarding the EDM performance of AISI H13 tool steel under finish machining using a copper-tungsten alloy. The first one is the material removal rate V_w [mm^3/min], which means the volume of material removed from the work piece per minute. The second is the volumetric relative wear ϑ [%] that corresponds to the ratio between the tool electrode wear rate V_e [mm^3/min] and the material removal rate V_w. The third aspect is the surface roughness Ra of the work pieces. In order to optimize these technological aspects the electrical parameters named discharge current $\hat{\imath}_e$ [A] and discharge duration t_e [µs] were varied keeping a positive polarity to the tool electrode.

2. EXPERIMENTAL PROCEDURE

The experimental tests were conducted at the Laboratory for Research on Machining Processes - LAUS of the Pontifical Catholic University of Paraná – PUCPR. The following materials, equipment and methods were applied for the tests:

(i) *EDM Machine:* It was used a Charmilles ROBOFORM 30 CNC machine equipped with an isoenergetic generator, i.e. the discharge duration t_e can be properly controlled – among other electrical variables. The ignition delay time t_d was kept at 30% of discharge duration t_e. The time t_d elapses between applying the open circuit voltage $\hat{u}_i$ across the gap and the resulting discharge, i.e. until the current is established. This level of t_d was chosen because when finish EDM is carried out low energy $W_e = i_e \cdot t_e \cdot u_e$ [J] is applied and longer times of t_d is observed (u_e = discharge voltage). It generally happens because the contamination of the gap with micro byproducts of the erosion process is very little, which leads to longer values of ignition delay time t_d. On the other hand, when rough EDM operations are carried out lower times of t_d are used ($t_d \approx$ 15 to 20% of t_e). This means that more adequate is the contamination of the working gap and shorter is the time t_d.

(ii) *EDM tool electrode*: Copper-Tungsten (30% Cu 70% W) cylindrical bars 100 mm long and 10 mm diameter at positive polarity were mounted axially in line with work piece samples, as shown in Fig.1.

(iii) *Work pieces samples:* It was used AISI H13 tool steel square samples 25 mm wide and 15 thick with Ra =0,42 µm on the surface to be EDM . The chemical composition of AISI H13 tool steel is the following: 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 20^0 C. The AISI H13 work pieces were quenched and tempered to an average 45 HRC.

(iv) *Flushing method:* A hydrocarbon dielectric fluid with 3 cSt at 40^0 C was used during the tests. The introduction of dielectric fluid to the gap is normally based in four methods: (a) normal flow, (b) reverse flow, (c) immersion flushing and (d) jet flushing, as reported by Drozda 1998. In this work shallow cavities of small diameters were to be EDMachined onto the work piece samples. Therefore, a jet of dielectric fluid directly against the gap and the immersion of the pair electrode/work piece into the dielectric fluid were applied as flushing technique, as depicted in Fig 1. This method was sufficient to evacuate the excess of eroded particles away from the working gap as well as to promote adequate cooling. However, this method was also sufficient to promote some contamination of the working gap accelerating the ignition of the discharge, as remarked by Schumacher (1990). 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. 2. The values of U and R were defined after pilot tests.

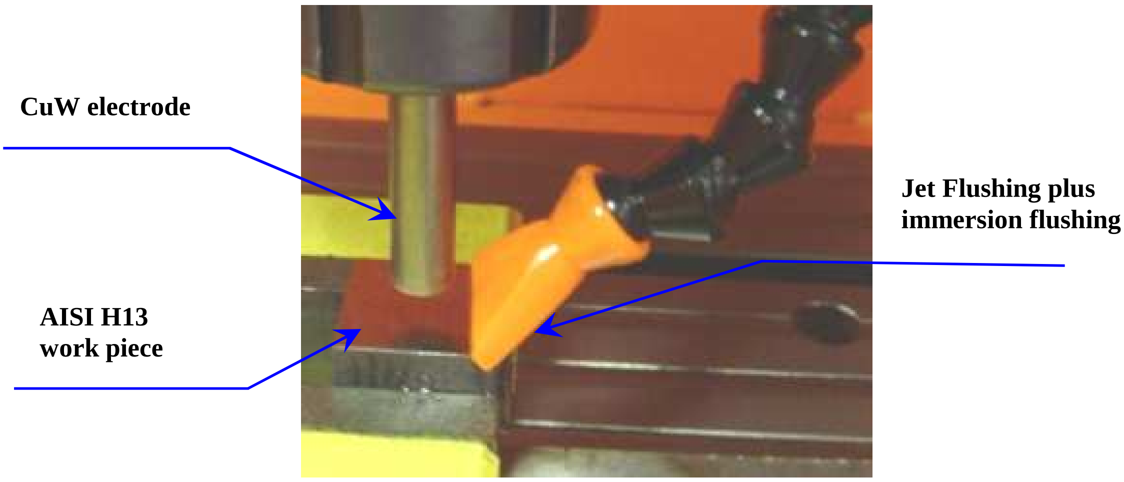

Figure 1. The picture depicts the assembly of electrode, work piece and the flushing method.

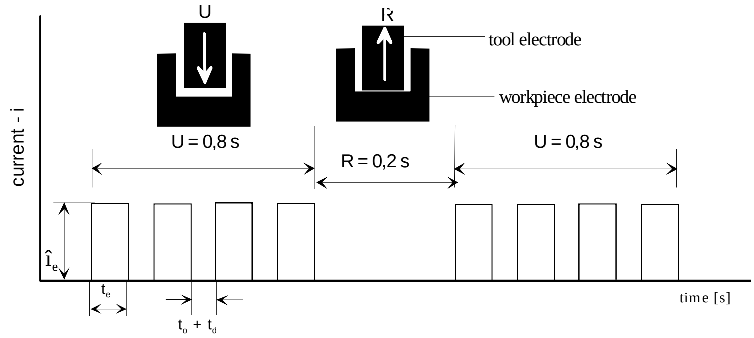

Figure 2. Series of pulses U followed by a pause time R.

(v) *Electrical variables:* The main electrical variables that influence on the performance of EDM, which are discharge current $\hat{\imath}_e$, discharge duration t_e were investigated according to the values presented in Tab.1. In order to optimize the results of V_w, ϑ and R_a, pilot tests on the variables open circuit voltage $\hat{u}_i$, discharge duration t_e, pulse interval time t_o and discharge current $\hat{\imath}_e$ were carried out. 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 work piece) before and after an average machining time of 30 minutes. The tests were done three times for each parameter settings using new electrodes and no significant differences on results were observed.

The duty factor τ = 0,5 was implemented for all the tests. The duty factor τ (t_i/t_p), represents the ratio between pulse duration t_i and pulse cycle time t_p ($t_p = t_i + t_0$). This value of τ, i.e., $t_i = t_o$, was used because the good stability normally observed for finish EDM operations. It means a few occurrence of short-circuits and arc-discharges. 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 the value of $\hat{u}_i$ the larger the working gap, according to König & Klocke (1997). 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 $\hat{u}_i$ = 200 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.

Table 1. Experimental electrical discharge machining parameter settings.

Discharge current îe (A)	Discharge duration te (µs)	Pulse interval time to (µs)	Open circuit voltage ûi (V)	Tool 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	+

3. RESULTS AND DISCUSSION

When finish EDM an important aim is to achieve a high work piece surface quality R_a and a low level of volumetric relative wear ϑ as well as keeping a good level of material removal rate V_w. Figure 3 presents the results of material removal rate V_w against the variation of discharge current $\hat{\imath}_e$ when using positive CuW electrodes. It is observed that the best material removal rate V_w is approximately 6 mm³/min for $\hat{\imath}_e$= 8 A to the optimum discharge duration t_e = 50 µs.

It is also seen that the global values of V_w obtained for $\hat{\imath}_e$ = 2 and 4 A are much lower than those achieved for $\hat{\imath}_e$ = 8 A. For the discharge current $\hat{\imath}_e$ = 4 A the maximum V_w = 0,8 mm³/min was reached for the t_e = 50 µs. This occurs because the material removal rate V_w is proportional to the energy $W_e = u_e.i_e.t_e$ [J] released into the working gap i.e., the increase of the energy W_e leads to higher values of Vw.

Concerning the behavior of material removal rate V_w for discharge current $\hat{\imath}_e$ = 8 A, it can be pointed out from Fig. 3 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 Vw starts decreasing. The explanation for this V_w behavior after its maximum point is concerned to a very high plasma diameter global expansion. This happens due to longer discharge duration t_e that diminishes pressure and energy of the plasma channel over the molten material of the electrodes, according to Dibitonto *et al.* (1989). As a consequence, this phenomenon brings instability into the process. For all three discharge currents i_e (2, 4, 8 A) tests with t_e = 100 µs promoted very little material removal rate V_w, although this result is not present in the graphs.

It is important to remark that for discharge currents i_e = 2 and 4 A the variation of discharge duration t_e from 3,2 to 50 µs did not affect significantly the material removal rate V_w. A possible explanation is related to the small working gap. Here the total molten material is not properly expelled away from the working gap. The majority amount of molten material is solidified in the recent formed crater and surroundings.

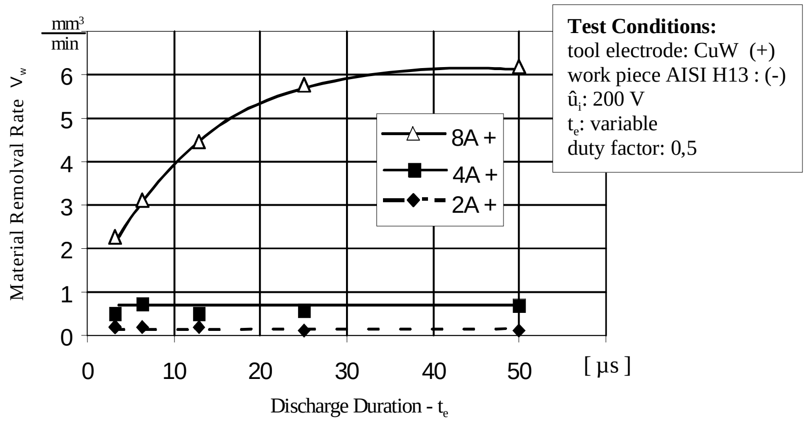

Figure 3 . Material removal rate V_w with variation of discharge current $\hat{\imath}_e$ and discharge duration t_e for EDM with positive Copper-Tungsten electrodes.

The volume of material removed from three cavities onto AISI H13 work piece samples under discharge currents i_e = 2, 4, 8 A and t_e = 50 µs after EDM are presented in Fig. 4. Generally, when EDM with copper or especially with graphite tool electrodes it is commonly observed some sort of gray to black film adhered over the bottom of the cavities after machining, as reported by Amorim & Weingaertner (2002). From evidences of visual inspections of the AISI H13 work pieces after the EDM tests with CuW electrodes it was verified that this phenomenon is almost inexistent, as can be seen in Fig. 4. This fact is an important aspect regarding the mold making production chain. Here it means that the mold polishing time can be reduced.

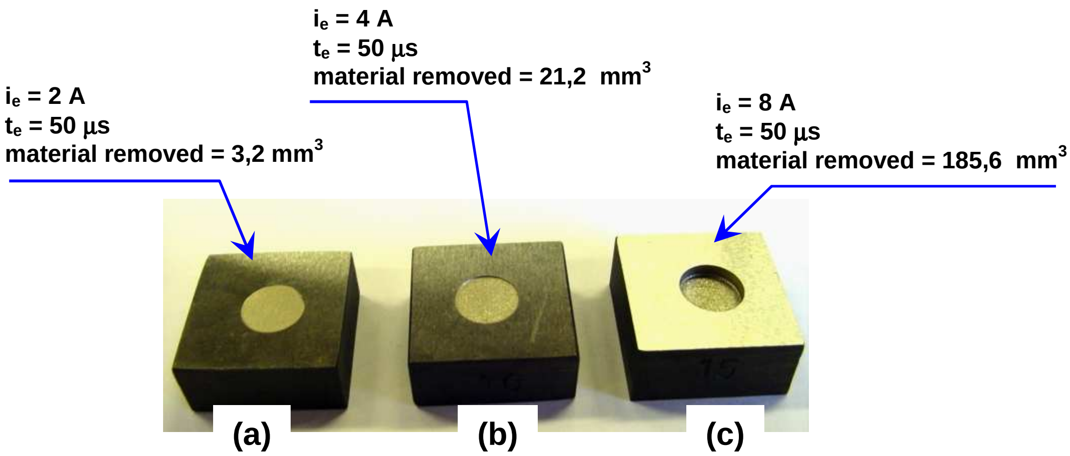

Figure 4. AISI H13 samples after EDM with positively charged CuW tool electrodes under $\hat{\imath}_e$ = (a) 2 A (b) 4 A and (c) 8 A at optimum t_e = 50 applying isoenergetic generator mode.

The volumetric relative wear ϑ represents the ratio between the electrode wear rate V_e [mm³/min] to the work piece material removal rate V_w [mm³/min]. The performance of ϑ [%] against the variation of discharge duration t_e for discharge currents i_e = 2, 4, 8 A is shown in Fig. 5. For all three values of i_e increasing the discharge duration t_e a decrease of ϑ is observed. This occurs because longer times t_e promote more melting of material in the work piece and the solidification of the molten material of the tool electrode, as described by König and Klocke (1997). Thefore, V_w increases and V_e decreases which diminishes the volumetric relative wear ϑ (V_e/V_w).

From Fig. 5 it is seen that the volumetric relative wear ϑ is about 2.0% and 2,6% respectively for $\hat{\imath}_e$ = 4 and 8 A at the optimum time t_e = 50 µs. However for the discharge current $\hat{\imath}_e$ = 2 A and t_e= 50 µs, the level of ϑ is about 6%. It means that higher the discharge current i_e lower the volumetric relative wear ϑ (V_e/V_w) when EDM with CuW electrodes. It also happens independently of the value of discharge duration t_e.

In part, this phenomenon can be explained as follows: the Cu-W alloy used as material for the tool electrode is composed by 30% Cu and 70% W. The element tungsten has a melting point of 3410 ^{0}C. Consequently, this elevated concentration of tungsten promotes a higher resistance of the tool 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. On the other hand for EDM using pure copper as tool electrode material occurs an opposite phenomenon i.e. increasing the discharge current i_e increases the volumetric relative wear ϑ, as remarked by Amorim & Weingaertner (2004). At the same way it is also explained, in part, by the lower melting point (1083 ^{0}C) of copper.

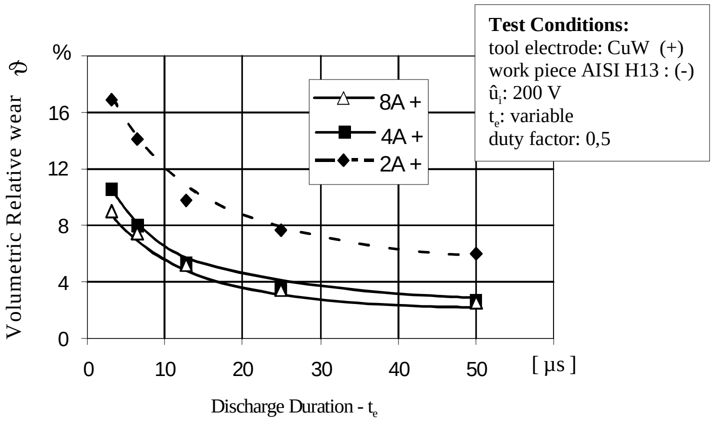

Figure 5. Volumetric relative wear ϑ with the variation of discharge current $\hat{\imath}_e$ and discharge duration t_e for EDM with positive Copper-Tungsten electrodes.

The results of surface roughness Ra versus discharge duration t_e are depicted in Fig.6. The lowest Ra = 0,9 was reached for discharge current i_e = 2 A and t_e = 3,2 µs. However, two important characteristics can be noticed:

(a) When EDM with discharge currents i_e = 4 and 8 A it is detected an increase of the surface roughness as the time t_e is raised. It is explained by the higher energy $W_e = u_e.i_e.t_e$ [J] released in the working gap i.e., the increase of the energy W_e leads to elevated values of V_w. Therefore, deeper and larger craters are generated on the surface of the work piece samples;

(b) The second characteristic is that for i_e = 2 A the variation of the time t_e from 3,2 to 50 µs did not change considerably the values of the surface roughness Ra. It can be related to fact that very long discharge duration t_e causes an over-increase of the plasma channel diameter, which decreases the pressure of the plasma over the molten cavities. As a result, due to the small working gap the eroded particles are not properly evacuated but, instead of this, it is accumulated in the crater and surroundings. This phenomenon may produce a smoother surface roughness on the work piece, as presented by Amorim & Weingaertner (2005).

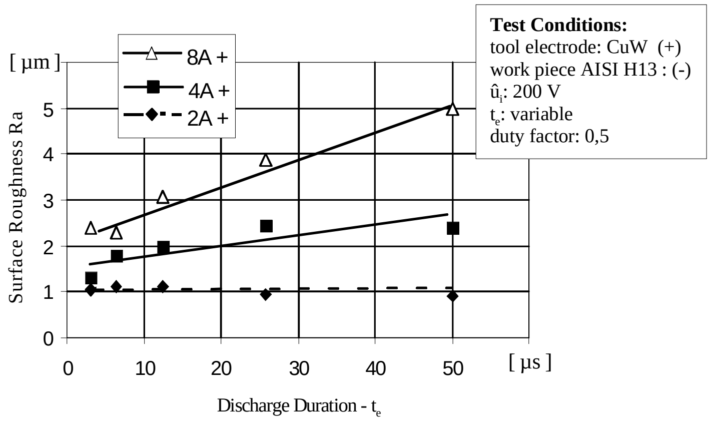

Figure 6. Results of surface roughness Ra when EDM using Copper-Tungsten electrodes at positive polarity.

4. CONCLUSIONS AND FINAL REMARKS

This work has developed an experimental investigation on the performance of Copper-Tungsten (30% Cu 70% W) tool electrodes when EDM quenched and tempered AISI H13 tool steel work pieces under finish process conditions. It has been investigated some important EDM electrical variables (discharge current $\hat{\imath}_e$, discharge duration t_e). From the results of this work the following conclusions can be presented:

(a) The maximum material removal rate (V_w= 6 mm³/min) was obtained for a discharge current $\hat{\imath}_e$= 8 A and discharge duration t_e= 50 µs using the tool electrode positively charged and the generator under the isoenergetic mode. For discharge currents i_e = 2 and 4 A the variation of t_e from 3,2 to 50 µs did not influence the values of V_w. However, the time t_e higher than 50 µs is not recommend for any of the tested discharge currents i_e.. It is because it promotes instability of the process in the form of arc discharges and short circuits. It caused the decrease of V_w.

(b) The minimum average surface roughness Ra = 0,9 µm was reached for discharge current $\hat{\imath}_e$= 2A and discharge duration t_e= 3,2 µs, when EDM with a positive tool polarity under isoenergetic generator mode.

(c) As the discharge current i_e increases the volumetric relative wear ϑ decreases. The lowest volumetric relative wear $\vartheta \approx$ 2,6 to 2,6% for discharge currents i_e = 4 and 8 A and t_e = 50 µs was reached.

(d) The adhesion of EDM byproducts on the bottom of cavities is almost inexistent.

Some tests with the tool electrode negatively charged were carried out but have shown very low levels of material removal rate V_w. In further research work more profound experiments will be developed about other EDM process variables to understand the occurrence of this phenomenon.

5. ACKNOWLEDGMENTS

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