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Effect of Electrode Materials on Electric Discharge Machining of 316 L and 17-4 PH Stainless Steels

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ABSTRACT

Electric Discharge Machining (EDM) is one of the most efficiently employed non-traditional machining processes for cutting hard-to-cut materials, to geometrically complex shapes that are difficult to machine by conventional machines. In the present work, an experimental investigation has been carried out to study the effect of pulsed current on material removal rate, electrode wear, surface roughness and diameteral overcut in corrosion resistant stainless steels viz., 316 L and 17-4 PH. The materials used for the work were machined with different electrode materials such as copper, copper-tungsten and graphite. It is observed that the output parameters such as material removal rate, electrode wear and surface roughness of EDM increase with increase in pulsed current. The results reveal that high material removal rate have been achieved with copper electrode whereas copper-tungsten yielded lower electrode wear, smooth surface finish and good dimensional accuracy.

Keywords: Electric Discharge Machining; Material Removal Rate; Electrode Wear; Surface Roughness; Stainless Steel

1. Introduction

Electric discharge machining (EDM) is one of the most widely employed non-traditional machining processes because it has been accepted as a standard process to manufacture mould and dies of aerospace, automotive, nuclear, surgical, petroleum and marine components. Since EDM does not make direct contact between the electrode and the work material, it eliminates mechanical stresses, chatter and vibration problems during machining. Hence, very hard and brittle materials can also be machined easily and also to the desired form. It removes electrically conductive materials by means of rapid, repetitive spark discharges from a pulsating direct-current power supply with dielectric flow between the work piece and the electrode. Pulse current is one of the primary input parameters of an EDM process and together with discharge duration and relatively constant voltage for the given tool and workpiece materials. Pulse current is representative of the energy per pulse expended in the spark gap region. It thus controls the material removal rate to the expected level. Considering the challenges brought by advanced technology, the EDM is one of the best alternatives for machining an ever increasing number of high strength, wear resistant and corrosion resistant materials. Further, EDM is relatively simple method to machine very complex geometry with very fine and high precision.

In EDM process the performance is determined by Material removal rate (MRR), Electrode wear (EW), Surface roughness (SR), Surface quality (SQ) and Dimensional accuracy (DA). A series of investigations has been conducted by Soni and Chakraverthi studied the surface quality, material removal rate, electrode wear rate, and dimensional accuracy of die steels and alloy steels in EDM [1]. The effect of the machining parameters on material removal rate, relative wear ratio, and surface roughness in EDM of tungsten carbide had been studied using different electrode materials and concluded that copper tungsten yields the better results than copper and brass [2]. Ho and Newman reported that research areas in EDM could be classified into three major categories: 1) Machining performance measures; 2) The effect of process parameter; and 3) Design and manufacture of electrode [3]. They also concluded that machining performance depends on the wear and surface quality. The effect of machining parameters on material removal rate, electrode wear rate, surface quality and diametric over-cut on tool steels were investigated in detail and concluded that copper and graphite electrode resulted in the best machining rate [4]. Mohd Abbas *et al.* presented the current research trends on machining and modeling techniques in predicting EDM performances [5]. Luis *et al.* had re-

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ported that the material removal rate and electrode wear in die sinking EDM of silicon carbide and conductive ceramics using copper electrode by applying design of experiments [6]. While studying the machining characteristics of tungsten carbide-cobalt composite and ceramics by EDM process, it is observed that increasing the pulse time enhances the machining instability which has significant effect on the surface finish of the workpiece [7]. Experiments which were carried out on AISI P20 tool steel as work material and copper as electrode show that the roughness of finished surface increases with an increase in the discharge voltage, pulse current, and pulse duration [8]. Wear of copper electrode was studied by employing Taguchi's standard orthogonal array in die-sinking EDM of tool steel used in moulds and dies [9]. Muttamara *et al.* investigated the effect of electrode polarities in copper, graphite and copper-infiltrated graphite electrodes in generation of conductive layer formation in EDM of alumina [10]. Jahan *et al.* experimented micro-EDM of tungsten carbide using different electrode materials of tungsten, copper tungsten and silver tungsten and reported that silver tungsten electrodes are capable of producing smooth and shiny surfaces with negligible amount of surface defects [11]. Marafona and Araujo investigated the influence of the hardness of the alloy steel on material removal rate and surface roughness of the work material [12].

From the earlier investigations, it has been observed that no extensive work has been carried out to study the effect of pulse current using copper, copper tungsten and graphite electrode materials on the corrosive resistant stainless steels as work material. Therefore, this research envisage to investigate the effect of various electrode materials and pulse current on material removal rate, electrode wear rate, diameteral overcut and surface roughness in EDM of 316 L and 17-4 PH stainless steels. The above said work materials have been chosen by considering its wide range of applications in chemical processing industries, refineries, petroleum, shipping and nuclear industries due to its superior corrosion resistance. The main objective of this study is to identify better electrode material which results in greater MRR and lower EW, lower surface roughness and good dimensional accuracy.

2. Experimental Details

2.1. Machine Tool

The experiments were performed on Roboform 40 die-sinking EDM supplied by Charmilles Technologies which is shown in **Figure 1**. It is energized by a 64 A pulse generator. A commercial grade EDM Oil (SAE 30) was used as dielectric fluid during the experiments. An impulse jet flushing system was used to flush away the eroded material from the sparking zone is shown in **Figure 2**.

2.2. Work Piece Material

The work materials used in this study are stainless steel 316 L and 17-4 PH. The chemical composition of the work materials are given in **Table 1**. The dimensions of the work materials are 25 mm in diameter and 20 mm in length.

2.3. Electrode Material

The prime requirement of any electrode material is that it must be electrically conductive and maintain less electrode wear. In principle, the materials best suited should have a very high melting point and a very low resistance to electricity. Electrode tool materials perform with varying degree of success on different workpiece materials. The selection of particular electrode material depends primarily upon the specific cutting application and upon the material being machined. In EDM of steels, copper, copper-tungsten and graphite electrodes are most widely used [2]. The electrodes of 10 mm diameter were selected for the purpose of this research. The physical properties of all the electrode materials are given in **Table 2**.

Figure 1. Die-sinking EDM machine used to carry out the experiments.

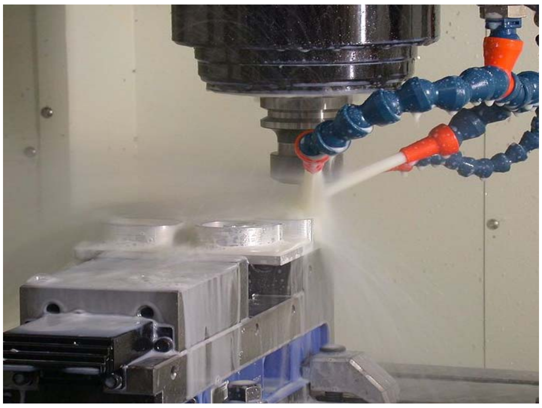

Figure 2. Impulse jet flushing system used.

Table 1. Chemical composition (wt%) of work materials.

Elements	316 L (wt%)	17-4 PH (wt%)
C	0.026	0.06
Si	0.37	0.81
Mn	0.16	0.30
Cr	16.55	17.22
Cu	0.16	3.01
Ni	10.0	3.91
Nb	-	0.16
P	0.029	0.023
S	0.027	0.03
Mo	2.02	0.76
N	0.036	-
Fe	Balance	Balance

Table 2. Physical properties of electrode materials.

Material	Graphite	Copper	Copper tungsten
Composition	100%	99.9%	75% tungsten, 25% copper
Density (g/cm^3)	1.811	8.96	15.2
Melting point (˚C)	3675	1084	3410
Electrical resistivity (μΩ·cm)	14	9	5.5
Hardness	HB 10	HB 100	HB 200

2.4. Experimental Procedure

The pulse current is normally selected on the basis of the maximum removal rate possible within the allowable mean current, electrode wear and surface integrity. The experiments were carried out for a depth of cut of 2 mm for all electrode materials with five different pulse current settings of 6 A, 12 A, 18 A, 24 A and 30 A. Material removal rate (MRR) is expressed as the ratio of difference of weight of the work piece before and after machining to the machining time [13].

$$\text{MRR} = \left(w_{jb} - w_{ja}\right)/t \quad (1)$$

where w_{jb} and w_{ja} are weights of the work piece before and after machining, and t is the machining time. Electrode wear rate (EWR) is expressed as the ratio of difference of weight of the tool electrode before and after machining to the machining time [13].

$$\text{EWR} = \left(w_{eb} - w_{ea}\right)/t \quad (2)$$

where w_{eb} and w_{ea} are weights of the tool electrode before and after machining, and t is the machining time. Percent electrode wear is calculated as the ratio of volume of material eroded from the tool electrode per unit time to the volume of material eroded from the work piece in the same time [2].

$$\text{EW}(\%) = (\text{EWR}/\text{MRR}) \times 100 \quad (3)$$

Since there exists many ways of measuring MRR and EW, in this work the material removal rate and electrode wear values have been calculated by weight difference of the work material and the electrode before and after machining using a digital weighing scale and recorded. The density values of work materials 316 L and 17-4 PH and electrode materials of graphite, copper and copper tungsten were used to calculate the MRR and EW [6].

The machined cavity will always be larger than the electrode and the difference between the electrode and the work material gap is called the "overcut", or "diameteral overcut" as shown in **Figure 3**. The diameteral overcut (DOC) are due to the presence of side sparks found to occur in the work material (Sing *et al.*, 2004). The amount of overcut will vary according to the amount of pulse current, pulse on time, type of electrode and work material. The primary factor that affects the DOC is the quantity of pulse current that exists in the gap and pulse duration [13]. The DOC is always measured per side. The DOC is expressed as the difference of diameter of the hole produced to the tool diameter as stated in Equation (4).

$$\text{DOC} = d_{je} - d_e \quad (4)$$

where d_e is the diameter of the tool electrode and d_{je} is the diameter of the hole drilled. An optical microscope was used to measure the diameter of the eroded hole. The parameter used for surface roughness is R_a, which is the arithmetic mean of the departures of the roughness profile from the mean line [2]. A surface roughness tester (Kosaka Surfcoder SE 1200) was used to measure the R_a values.

The same experiment was repeated with all three electrode materials. During experiments, pulse current was raised by keeping the voltage at 40 V, pulse duration at

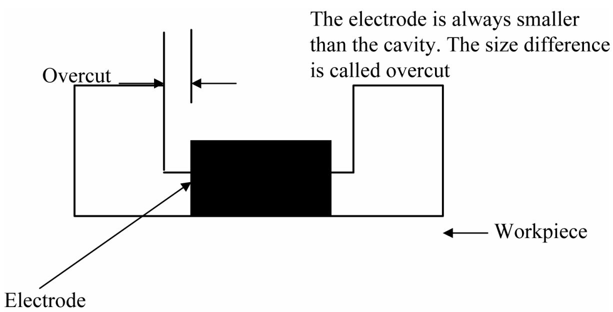

Figure 3. The diameteral overcut.

25 µs, pulse interval at 200 µs, and dielectric fluid pressure at 20 kPa for all machining conditions and the values are presented in **Table 3**. The polarity of electrode materials copper, graphite and copper tungsten were negative [6].

3. Results and Discussion

3.1. Effects Pulse Current on Material Removal Rate

Figure 4 shows the effect of pulse current on MRR of 316 L work material. The trend shows that as the pulse current increases, the MRR also increases and similar trend has been observed for all the three electrode materials. The copper electrode yields the highest MRR of 27.95 mm^3/min followed by graphite of 22.46 mm^3/min and copper tungsten of 18.62 mm^3/min for 316 L stainless steel. The increase in MRR with the increase in pulse current is due to the enhancement of spark energy that facilitates the action of melting and vaporization. More so, this action results in advancing the impulsive force in the spark gap and thereby increasing the MRR.

Figure 5 reveals similar trend of increasing MRR while increasing the pulse current for 17-4 PH. However, there is a significant increase in MRR between the pulse current ranges 18 A - 30 A for all the three electrode materials compared to 6 A and 12 A. This is because of the higher pulse current that causes rapid erosion of work material which has low hardness value. Therefore 17-4 PH material gives higher MRR as compared to 316 L.

3.2. Effects of Pulse Current on Electrode Wear

Electrode wear is mainly due to high density electron impingement generated during machining from work and electrode materials. The electrode wear vs pulse current for 316 L material is shown in **Figure 6**. Copper has the highest EW of 50.74% as against 39.62% for graphite and 17.86% for copper tungsten. In copper electrode, the EW increases as the pulse current is increased due to its low melting point where as in graphite and copper tungsten the EW is less because of their high melting point. For all the three electrode materials, it shows that the trend of EW graph remains relatively constant after about 24 A. The EW of copper tungsten is very low when compared with other two electrode materials because of its high resistance to spark.

Table 3. Experimental machining conditions.

Sparking voltage	40 V
Discharge current in steps	6 A, 12 A, 18 A, 24 A, 30 A
Servo system	Electro hydraulic
Electrode polarity	Positive
Dielectric used	Commercial grade EDM oil
Dielectric flushing	Jet flushing system

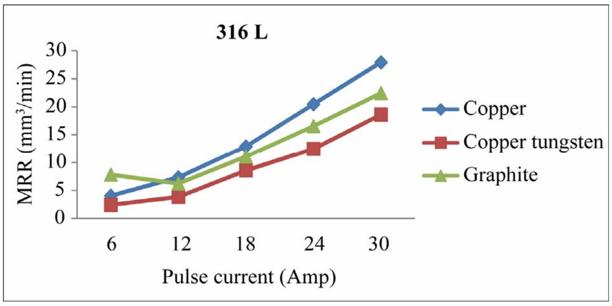

Figure 4. Effect of pulse current on material removal rate of 316 L.

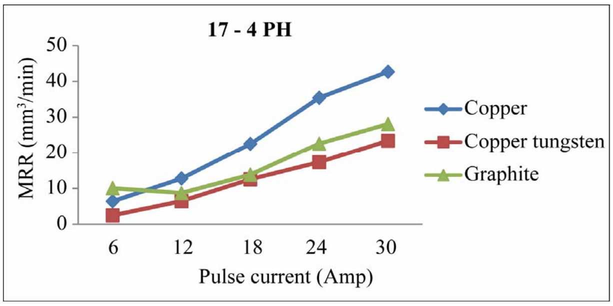

Figure 5. Effect of pulse current on material removal rate of 17-4 PH.

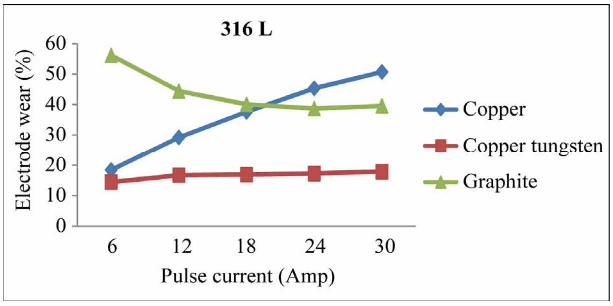

Figure 6. Effect of pulse current on electrode wear of 316 L.

Figure 7 shows the effect of pulse current on electrode wear for 17-4 PH work material similar to 316 L stainless steel, copper has the highest EW 62.08% while comparing with graphite (44.18%) and copper tungsten (16.36%) for 17-4 PH as well. The behavior of the three electrode materials remains same as that of 316 L work material.

3.3. Effects of Pulse Current on Surface Roughness

Figures 8 and **9** depict the effect of pulse current on the surface roughness of the work materials 316 L and 17-4 PH respectively. It has been observed that as the pulse

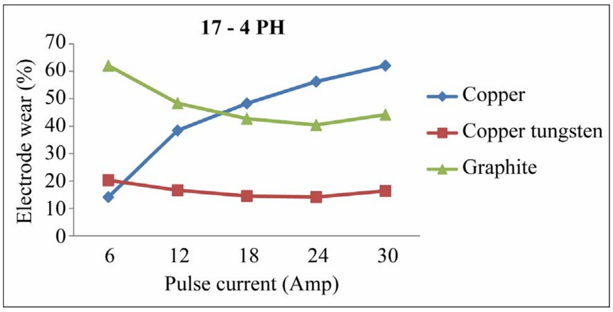

Figure 7. Effect of pulse current on electrode wear of 17-4 PH.

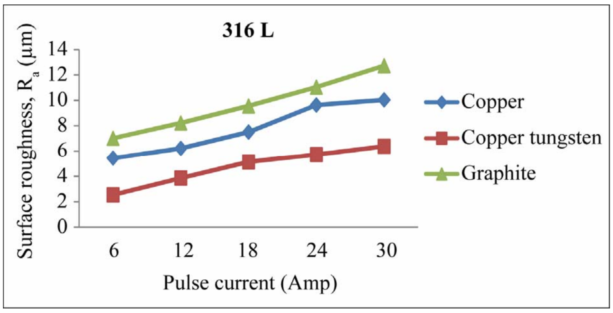

Figure 8. Effect of pulse current on surface roughness of 316 L.

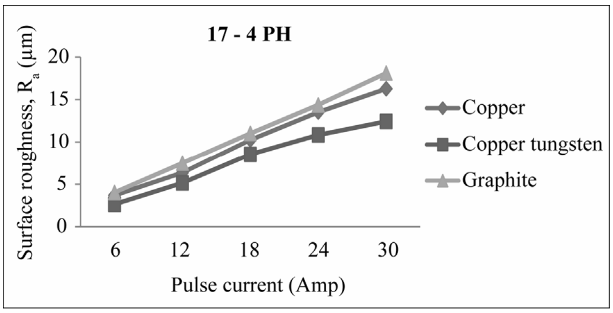

Figure 9. Effect of pulse current on surface roughness of 17-4 PH.

current is increased the surface roughness increased. The results of the above mentioned two work materials indicate that for the range of pulse current used *i.e.*, between 6 A and 30 A, copper tungsten exhibits better surface finish while the graphite shows the poorest. The surface roughness value of copper electrode is in between the graphite and copper tungsten. The surface roughness of copper and graphite are high due to the fact that higher MRR is accompanied by larger and deeper craters. This causes low pulse currents and spark energy which leads to the formation of small craters on the machined surface and thereby improving surface finish [14]. Therefore, formation of small craters results in good surface finish. The only difference between these two materials is that for same pulse currents values, 316 L offers better surface finish than 17-4 PH because of higher MRR in 17-4 PH material than 316 L.

3.4. Effects of Pulse Current on Diameteral Overcut

Dimensional accuracy becomes more important when close tolerance components are required to be produced in aerospace industries, marine industries, and also in tools, dies and moulds for press work, plastic molding and die casting. The diameteral overcut is low at low pulse current and hence the erosion is low. **Figures 10** and **11** show the diameteral overcut of work materials 316 L and 17-4 PH respectively. The copper tungsten electrode gives low and consistent diameteral overcut of 0.1 mm for both materials at high pulse current. In contrast, graphite electrode yields the poor dimensional accuracy which results in higher diameteral overcut for both materials at higher pulse current. The diameteral overcut of copper is between 0.12 mm (316 L) and 0.16 mm (17-4 PH) in the pulse current range of 12 A to 24 A and good dimensional accuracy also has been obtained. The graphite results in high overcut due to its high spark dispersing effects. The overcut not only depends on the pulse current and also depends on gap voltage and chip size.

4. Conclusions

An experimental study has been conducted to investigate the effect of electrode materials on machining characteristics in EDM of corrosive resistant stainless steels 316 L

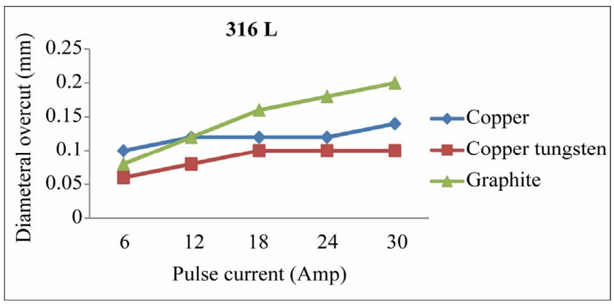

Figure 10. Effect of pulse current on diameteral overcut 316 L.

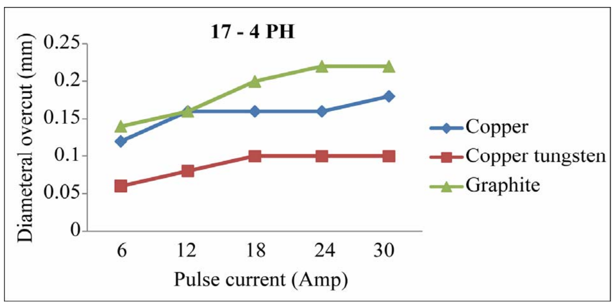

Figure 11. Effect of pulse current on diameteral overcut of 17-4 PH.

and 17-4 PH. The following inferences are arrived at:

1) For 316 L and 17-4 PH work materials copper electrode gives the better MRR than graphite whereas the copper-tungsten yields the lowest MRR value. The MRR obtained by three electrodes in 17-4 PH is higher than 316 L because of its low hardness;

2) Copper-tungsten offers comparatively low electrode wear for the tested materials whereas the performances of copper and graphite electrodes are high and almost similar;

3) Graphite and copper electrodes produce comparatively high surface roughness for the tested materials at higher values of pulse current. The copper-tungsten electrode offers low values of surface roughness at high discharge current which yields good surface finish for both work materials;

4) Copper-tungsten and copper electrodes performed consistently at high values of pulse current and copper-tungsten offers low diameteral overcut and good dimensional accuracy than copper;

5) Copper electrode has been preferred for higher MRR whereas copper-tungsten is preferred for low electrode wear, good surface finish and good dimensional accuracy.

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