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EFFECTS OF THE EDM PARAMETERS ON SURFACE ROUGHNESS OF TITANIUM ALLOY TI-6AL-4V

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Abstract. *Electrical discharge machining (EDM) is a manufacturing process which has the capacity of manufacturing complex formats and machining high-hardness materials. Ti-6Al-4V has poor machinability due to its low thermal conductivity and high strength at high temperatures. By applying EDM technology, these materials may be able to be machined efficiently. This paper investigates the effects of peak current, tool electrode polarity, pulse on time, and duty time in EDM of titanium alloy Ti-6Al-4V with graphite electrode on surface roughness. The experimental results showed that surface roughness increases as the pulse on time increases, especially when high amounts of discharging energy are involved. This is related to the depth and size of the generated crater on workpiece surface. Higher peak currents represent greater amounts of discharging energy what generates large and deeper craters on the surface resulting in greater surface roughness. Duty time variation did not exert significant influence on surface roughness for the tested range. Surface roughness values are considerably lower for the positive tool polarity when compared with the negative tool polarity all over the tested* T_{ON} *range. Probably because the discharge crater generated on the workpiece surface with positive tool polarity is smaller than that of negative tool polarity.*

Keywords: *Electrical discharge machining, titanium alloy, surface roughness*

1. INTRODUCTION

Electrical discharge machining (EDM) is a manufacturing process which has the capacity of manufacturing complex formats and machining high-hardness materials what makes it an excellent option for moulds and dies and aerospace fields.

Titanium alloys have unique properties like high strength-to-weight ratio, corrosion resistance and biological compatibility. Ti-6Al-4V is one of the most used titanium alloy in aerospace, automotive and biomedical industries. However it has poor machinability due to its low thermal conductivity and high strength at high temperatures. The heat generated during machining to dissipate from the tool edge, causing high temperatures in the cutting zone and leading to premature tool wear. By applying modern EDM technology, these materials may be able to be machined efficiently (Fonda et al., 2008).

The EDM process initiates when an appropriate voltage is developed across the tool electrode (normally anode) and the workpiece (normally cathode), the breakdown of dielectric medium between them happens due to the growth of a strong electrostatic field. Owing to the electric field, electrons are emitted from the cathode toward the anode on the electrode surfaces having the shortest distance between them. These electrons impinge on the dielectric molecules of the insulating medium, breaking these dielectric fluid molecules into positive ions and electrons. These secondary electrons travel along on the same ionization path. This event causes an increase in the electric field strength across the work surfaces and liberates a large number of electrons. It creates an ionized column in the shortest spark gap between the tool electrode and the workpiece, thereby decreasing the resistance of the fluid column and causing an electrical discharge in the shortest distance point between the tool and the workpiece. The enormous thermal energy melts and vaporizes the material from the workpiece, which creates a small crater over the work surface. There happened a collapse of the ionized column with the termination of the electrical energy by means of the switching circuit and then surrounding dielectric fluid occupies its place. The melted debris is removed by the flushing process (Jameson, 2001).

High conductivity, heat resistance and high melting point are the main desired properties for an EDM tool electrode. The most common materials used in EDM tooling are copper, graphite, tungsten and tungsten carbide. A suitable dielectric for EDM should be able to provide suitable conditions for initiation and maintenance of good effective electric discharges, cool the electrodes and to carry away the debris from the spark gap. The most common dielectric mediums used are hydrocarbon oils such as kerosene (Rajurkar et al., 2013).

Since the thermal energy produced in electrical discharge machining process is due to the applied electrical energy, it is very important to enhance the electrical process parameters to improve the process efficiency (Muthuramalingam and Mohan, 2015).The gap between the electrode and the work material should be monitored to avoid short circuit, open circuit or arcing. The presence of left over debris due to either short pulse off-time and or insufficient flushing can change the electrical conductivity at the gap and may result in non-uniform and unstable discharge process. These developments lead to arcing and unstable machining which results in damage to workpiece and tool and adversely affects the process performance (Rajurkar et al., 2013).

The most important parameters in EDM are peak current, pulse on time (T_{ON}), duty time (DT) and polarity of the tool electrode. Most of the research works reveal that the peak current and pulse on time have the most influencing nature on the EDM performance measures (Muthuramalingam and Mohan, 2015). The duty time is a percentage of the on-time relative to the total cycle time. The duty time has influence on arc discharges and short-circuits formations and flushing conditions. Another important parameter is the polarity of the tool electrode (positive or negative) which is usually determined by experiments and is a matter of tool material, workpiece material, current density and pulse length combinations (Ho and Newman, 2003). According to Rajurkar et al. (2013) the surface roughness of the material increases with the pulse energy though it also depends on the material properties. The thermal action in EDM may cause micro cracks, induces residual stresses, and changes the micro hardness of the sub-surface and surface layers, results in carbon and hydrogen diffusion.

Hasçalik and Caydas (2007) investigated experimentally the EDM of Ti–6Al–4V with different electrode materials and process parameters. They concluded that the value of material removal rate, surface roughness, electrode wear and average white layer thickness tends to increase with increasing current density and pulse duration. Fonda et al. (2008) investigated the effect of Ti–6Al–4V's thermal and electrical properties on the EDM productivity and observed the optimal duty time in terms of productivity and quality. Rahman et al. (2010) proposed an optimized model to investigate the effects of peak current, pulse on time and pulse off time in EDM performance on material removal rate of Ti–6Al–4V utilizing copper tungsten as electrode. They found that the material removal rate increases with current and as well as pulse on time. Mower (2014) found that the strength degradation is correlated directly to the thickness and roughness of recast layers created by the solidification of melt material formed during EDM. He concluded that modern EDM techniques are capable of processing Ti–6Al–4V with only modest degradation of fatigue strength, in contrast to data in the literature from outdated EDM machines.

This paper investigates the effects of peak current, tool electrode polarity, pulse on time, and duty time in EDM of titanium alloy Ti-Al-4V with graphite electrode on surface roughness.

2. MATERIALS AND METHODS

The workpiece material was a titanium alloy (Ti-6Al-4V). Table 1 lists its mechanical and physical properties.

Table 1. Workpiece material properties (SAE AMS).

Workpiece material	Ti-6Al-4V
Yield strength (MPa)	870
Ultimate tensile strength (MPa)	923
Modulus of elasticity (GPa)	113.8
Density (g/cm^3)	4.42
Hardness (HRC)	36
Thermal Conductivity (W / m K)	6.7
Specific Heat (J /kg K)	560
Electrical resistivity (μΩ. m)	1.7

Graphite tool electrode used was EC14 produced by Metgraphite.

The experiments were performed on a die sinking EDM machine (ENGEMAC EDM 440 NC). Tool electrode and workpiece fixtures and flushing system were improved to ensure experimental stabilization.

The Electron hydrocarbon dielectric fluid produced by Archem Química Ltda was used in the experiments.

Figure 1 shows the experimental set-up.

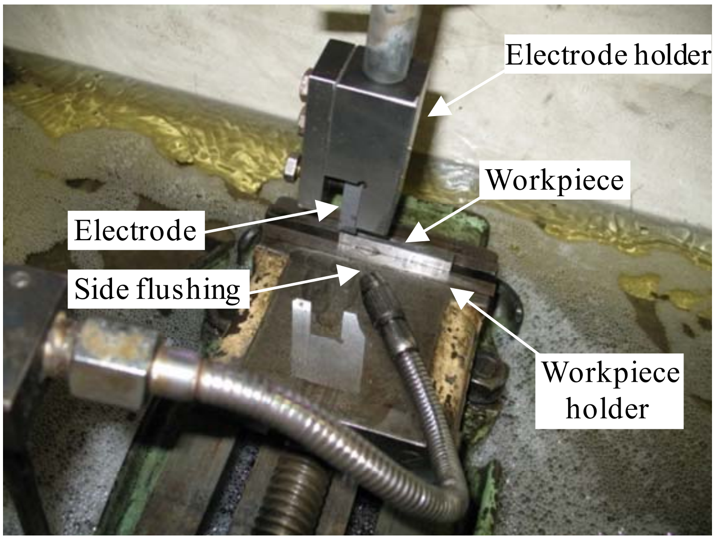

Figure 1. Experimental set-up

The workpiece surface roughness was measured by using a Taylor Hobson Precision roughness meter model Surtronic 25.

The tests were performed for different values of pulse on time, peak current, and duty time and tool electrode polarity. No repetitions were performed. Table 2 shows the EDM parameters and its levels.

Table 2. EDM parameters and its levels.

Parameters	Levels
Pulse on time	10, 20, 30, 50, 80, 100, 120, 150, 200, 300, 500 and 800 µs
Peak current	3 and 15 A
Duty time	35, 48 and 60%
Electrode polarity	positive or negative

3. RESULTS AND DISCUSSIONS

Figure 2 shows the effects of pulse on time (T_{ON}) and peak current on surface roughness (R_z) for duty time 35% and negative tool electrode polarity.

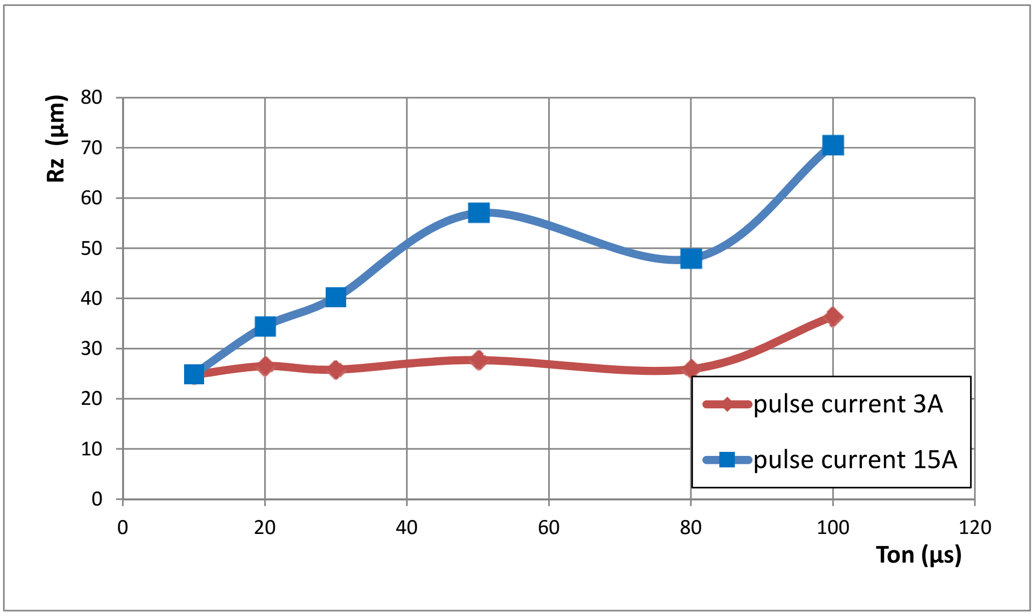

Figure 2. Surface roughness (R_z) in function of pulse on time (T_{ON}) and peak current

There is an indicative that the surface roughness increases as the pulse on time increases. This is related to the depth and size of the generated craters on workpiece surface. For lower pulse on time the craters are shallow with large diameters resulting in a smooth surface. The levels of surface roughness obtained herewith are close to results obtained by Hasçalik and Çaydas (2007). There is a significant difference between surface roughness values for peak current 3 A and 15 A for the negative tool polarity. Surface roughness values are close for peak current 3 A all over the tested T_{ON} range with exception of pulse on time 100 µs that resulted in higher value. Higher peak currents represent greater amounts of discharging energy what generates large and deeper craters on the surface resulting in greater surface roughness. Moreover, more melted material residues remaining especially around the craters contribute to form a rough surface. Thus, low peak current results in fine surface finish.

Figure 3 shows the effects of pulse on time (T_{ON}) and duty time on surface roughness (R_z) for peak current 15 A and negative tool electrode polarity. The horizontal axis is in logarithmic scale because of the wide range of T_{ON}.

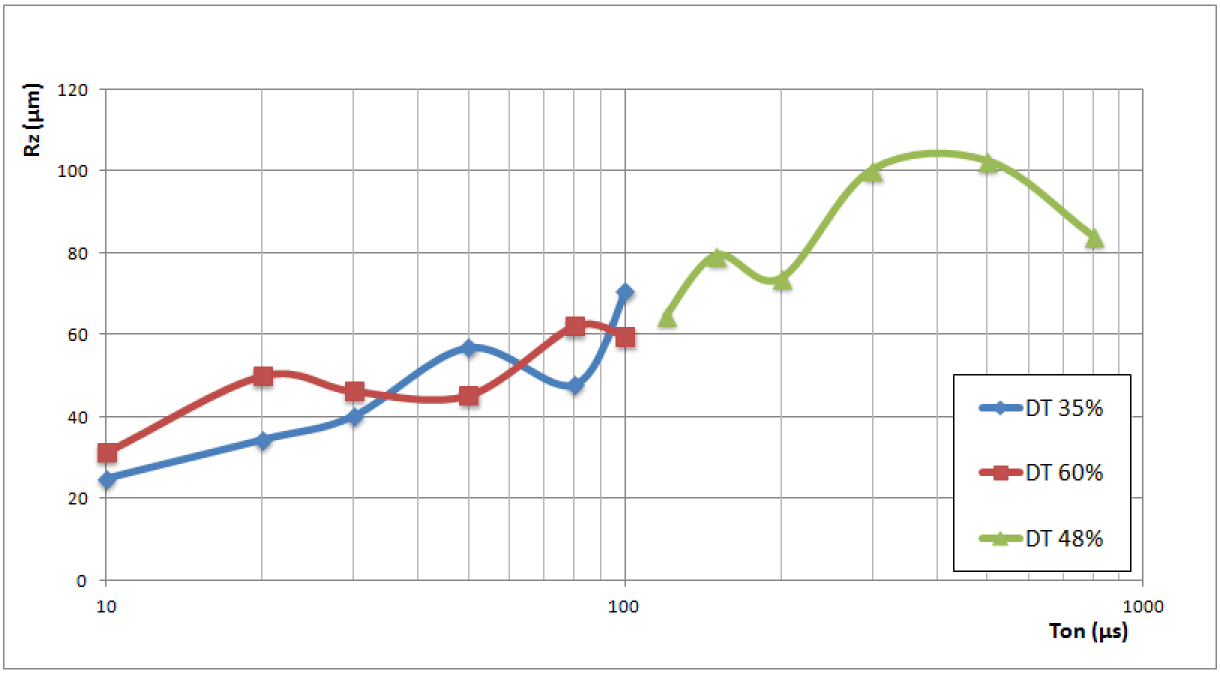

Figure 3. Surface roughness (R_z) in function of pulse on time (T_{ON}) and duty time

The curve representing duty time 60% shows an initial increase (10 to 20 µs) followed by a small decrease (20 to 50 µs), then the surface roughness increases again (50 to 80 µs). The curve for duty time 48% shows a tendency of increasing until T_{ON} 500 µs, then the surface roughness decreases for T_{ON} 800 µs. Fonda et al. (2008) have observed blending of individual discharge craters for higher duty factors, which is most likely caused by elevated material temperatures that do not allow sufficient time for the discharge craters to solidify and cool before the next discharge occurs.

At extended pulse on time durations the pulse duration affect the surface roughness negatively except for 200 µs. According to Hasçalik and Çaydas (2007) this particular surface roughness improvement is due to decreasing in the discharge spots because of the expansion of the plasma channel.

Figure 4 shows the effects of pulse on time (T_{ON}) on surface roughness (R_z) for duty time 35%, peak current 15 A and positive tool electrode polarity.

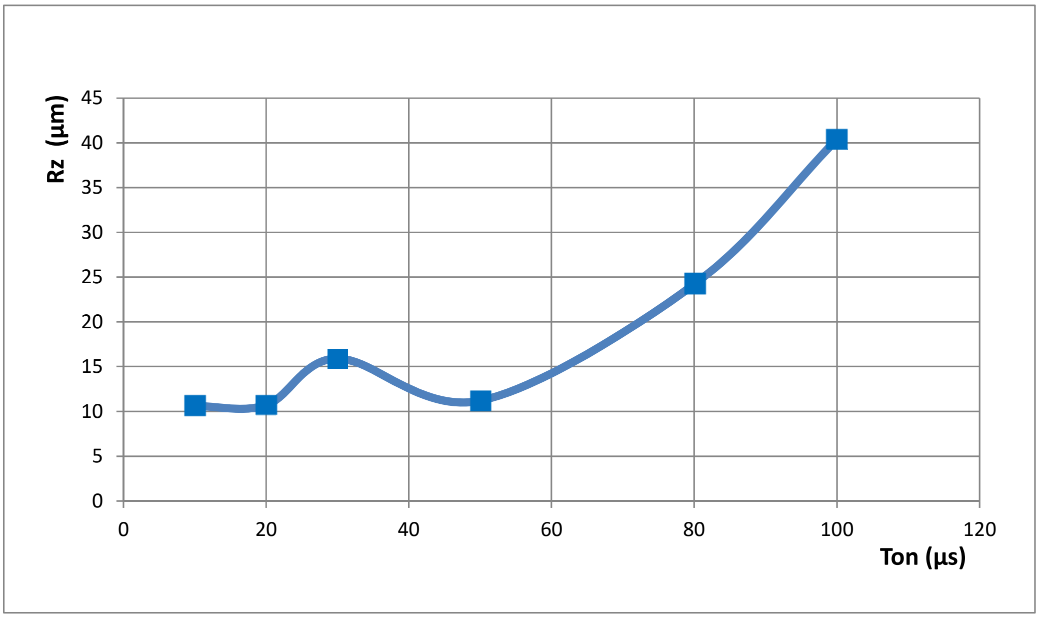

Figure 4. Surface roughness (R_z) in function of pulse on time (T_{ON}) for positive electrode polarity

Surface roughness values are considerably lower for the positive polarity when compared with the negative polarity all over the tested T_{ON} range. The use of positive polarity resulted in low surface roughness until pulse on time 80 µs when the value jumped to 24.2 µm. According to DiBitonto et al. (1989), melting of the cathode is delayed in time by one or two orders of magnitude beyond that of the anode due to the lower mobility of the positive ions. Moreover, because it is emitting electrons, the plasma radius at the cathode is also much smaller, thereby approximating a point heat source for conduction into its interior. The discharge energy distributed to the anode is normally greater than that to the cathode (Xia et al., 1996). Thus the melting zone at the discharge spot is narrower and the discharge crater generated on the cathode surface is smaller than that on the anode. In the studies of Han et al. (2006) the surface obtained by positive tool polarity was found to be smoother than that using negative polarity, what coincides with the result where the discharge crater generated on the workpiece surface with positive polarity is smaller than that of negative polarity. Moreover, according to Lin et al. (2001) in EDM of Al–Zn–Mg aluminum with tool positive polarity, some melted material solidifies on the crater center to form a bulging droplet, whilst for negative polarity, most of the melted material in the crater center is flushed away to form a deeper hollow in the center and a higher ridge around the crater. Lloyd and Warren (1965) have found that the anode craters take the form of a circular depression independent of crystal orientation and characterized by a raised circumferential lip resulting from the upheaval of metal during the liquid dispersion time. In addition, they observed that the crater diameter is approximately constant for the same spark condition. The cathode craters, on the other hand, were not found to be truly circular but tend to reflect the symmetry of the crystal faces on which they occur. The different geometry of the craters, shallow saucer for the anode and hemispherical cavity for the cathode, can provide some differences in the plasma flushing efficiencies (DiBitonto et al., 1989). The effect of polarity on EDM performance is conflicting for different workpiece material and it is difficult to draw a general conclusion about the effect of polarity on electric discharge machining performance. The results presented in Fig. 4 show that better surface finish is achieved by using positive tool polarity in EDM of Ti-6Al-4V.

4. CONCLUSIONS

There is an increase in surface roughness as the pulse on time increases especially when high amounts of discharging energy are involved. This is related to the depth and size of the generated crater on workpiece surface. For lower pulse on time the craters on the workpiece surface are shallow with large diameters resulting in a smooth surface.

Higher peak currents results in higher surface roughness due to greater amounts of discharging energy that generates large and deeper craters on the workpiece surface. Moreover, more melted material residues remaining especially around the craters contribute to form a rough surface.

Duty time variation did not exert significant influence on surface roughness for the tested range.

Surface roughness values are considerably lower for the positive tool polarity when compared with the negative tool polarity all over the tested T_{ON} range. Probably because the discharge crater generated on the workpiece surface with positive tool polarity is smaller than that of negative tool polarity.

5. REFERENCES

DiBitonto, D.D., Eubank, P.T., Patel, M.R. and Barrufet, M.A., 1989. "Theoretical models of the electrical discharge machining process I: a simple cathode erosion model". *Journal of Applied Physics*, Vol. 66, No. 9, p. 4095–4103.

Fonda, P., Wang, Z., Yamazaki, K. and Akutsu, Y., 2008. "A fundamental study on Ti-6Al-4 V's thermal and electrical properties and their relation to EDM productivity". *Journal of Materials Processing Technology*, Vol. 202, No. 1–3, p. 583–589.

Han, F., Yamada, Y., Kawakami, T. and Kunieda M., 2006. "Experimental attempts of sub-micrometer order size machining using micro-EDM". *Precision Engineering*, Vol. 30, p. 123–131.

Hasçalik, A. and Çaydas, U., 2007. "Electrical discharge machining of titanium alloy (Ti–6Al–4V)". *Applied Surface Science*. Vol. 253, p. 9007–9016.

Ho, K.H. and Newman, S.T., 2003. "State of the art electrical discharge machining (EDM)". *International Journal of Machine Tools & Manufacture*. Vol. 43, p. 1287–1300.

Lloyd, H. K. and Warren, R.H., 1965. "Metallurgy of spark-machined surfaces". *Journal of Iron and Steel Research*. Vol.3, p. 238–247.

Jameson, E.C., 2001. *Electrical Discharge Machining*. Society of Manufacturing Engineers, Michigan, 1st edition.

Lin, Y.C., Yan, B.H. and Huang, F.Y., 2001. "Surface modification of Al–Zn–Mg aluminum alloy using combined process of EDM with USM". *Journal of Materials Processing Technology*. Vol.115, p. 359–366.

Mower, T. M., 2014. "Degradation of titanium 6Al–4V fatigue strength due to electrical discharge machining". *International Journal of Fatigue*, Vol. 64, pp. 84–96.

Muthuramalingam, T., Mohan, B., 2015 "A review on influence of electrical process parameters in EDM process". *Archives of Civil and Mechanical Engineering*, Vol. 15, p. 87-94.

Rahman, M.M., Khan, M.A.R., Kadirgama, K., Noor, M.M. and Bakar, R.A., 2010. "Optimization of Machining Parameters on Tool Wear Rate of Ti-6Al-4V through EDM Using Copper Tungsten Electrode: A Statistical Approach", *Advanced Materials Research*, Vol.152-153, p. 1595–1602.

Rajurkar, K.P., Sundaram, M. M. and Malshe, A. P., 2013. "Review of Electrochemical and Electrodischarge Machining". *Procedia CIRP*, Vol. 6, p. 13 – 26.

Xia, H., Kunieda, M. and Nishiwaki, N., 1996. "Removal amount difference between anode and cathode in EDM process". *International Journal of Electrical Machining*, Vol.1, p. 45–52.

6. RESPONSIBILITY NOTICE

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