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A Fundamental Study on the Influence of the pulse duration and the Interval between Pulses on the Productivity and the Electrode Wear in Sinking EDM of INCONEL 718

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Abstract. *EDM is a machining process that promotes the removal of material by applying electrical discharges. The knowledge of the parameters that allows greater productivity is important for reducing manufacturing time of a piece. At the same time, it is necessary to reduce the cost of the process by reducing the consumption of raw materials. For this, it is essential to understand how the process parameters affect the productivity and the electrode wear. In this context, this paper aims to analyze the behavior of the process with the variation in four levels of the duration of the voltage pulse (t_i) and the duration of the interval between pulses (t_o) during step EDM roughing of the alloy INCONEL 718 with respect the wear on the electrode and the removal rate of the workpiece material. For all tests, the duration of the EDM process was the same. To obtain the productivity of the process was considered the rate of removal of material from the part by measuring the mass difference before and after of the machining. Of the same way, the electrode wear was measured. The test results were processed and analyzed statistically. As result, it can be seen that there is a value for t_i which provides a higher rate of removal and a tendency towards a zero for electrode wear with the use of long t_o. Also it showed a reduction in removal rate with decreasing t_o. Some observations on the possible causes that led to the results were performed.*

Keywords: *EDM, INCONEL, removal rate, electrode wear*

1. INTRODUCTION

Heat Resistant Super Alloys (HRSA), including nickel alloy INCONEL 718, are materials able to support high temperatures without significant reduction of its mechanical resistance and oxidation. Because of its mechanical properties, conventional machining is difficult for these alloys. As an alternative for the manufacturing of some parts, the special process called Electro Discharge Machining (EDM) can be applied. In this process, the material is removed by erosive effect produced when discrete electrical discharges occur between two electrodes made of conductive materials (Ezugwu et al., 2003; Sivakumar and Gandhinathan, 2013; Amorim and Weingaertner, 2004).

There isn't a complete and definitive model to explain the phenomena involved in the EDM process. Many researchers, including Dibitonto et al. (1989), Eubank et al. (1993) and Amorim (2002) present the thermoelectric theory as the most accepted by the scientific community. According to this theory, in the EDM process it can be distinguished four consecutive phases that can be identified in Fig. (1): ignition (phase 1), plasma channel formation (phase 2), melting and evaporating of the material of both electrodes (phase 3) and ejection of the molten material which causes the formation of a microcrater (phase 4).

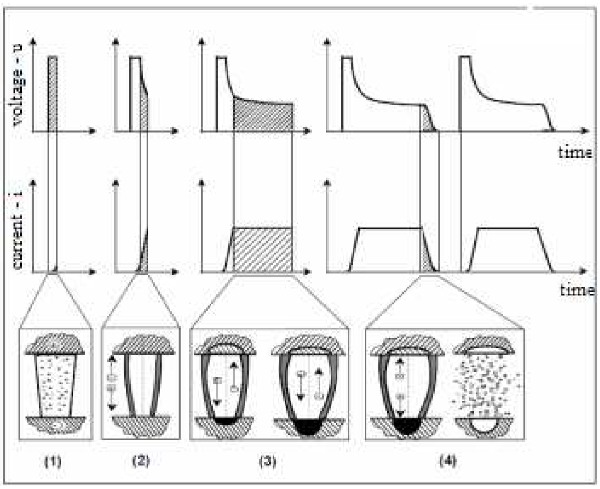

Figure 1. Phases of an electrical discharge in the EDM process (Amorim, 2002)

A significant number of articles has focused on improving process performance, such as increasing of material removal rate, decreasing electrode wear and improving the quality of the machined surface (Ho and Newman, 2003). The performance of the EDM process and its capacity to give the necessary characteristics to the part are directly connected to the electrical parameters used. In general, increasing material removal rate of the workpiece leads to increased electrode wear. Therefore, it is necessary a knowledge about how the process parameters affect productivity and the electrode wear to establish values that favors the process in these two aspects. The Table 1 shows a summary of the influence of the main electrical parameters of the EDM process with the adoption of copper electrodes and hydrocarbon as dielectric fluid.

Table 1. Influence of the main electrical parameters on the EDM process, with the adoption of copper electrodes and hydrocarbon as dielectric fluid *

Parameter	Description	Expected Influence on the Removal Rate	Expected Influence on the Electrode Wear
Polarity	When the electrode-tool is located in the positive polo of the electric field formed between this and the piece, the polarity of the process is defined as positive	For small t_i (<10 µs): negative polarity increases the removal rate For medium and large t_i: positive polarity increases the removal rate	For small t_i (<10 µs): negative polarity reduces the electrode wear For medium and large t_i: positive polarity reduces the electrode wear
Peak Current	Maximum current applied to the process	Increasing this parameter raises the removal rate	Increasing this parameter raises the electrode wear
t_i	Process cycle time in which there is voltage	Increasing this parameter raises the removal rate up to a maximum Then, increasing t_i reduces the removal rate	Increasing this parameter reduces the electrode wear
t_o	Process cycle time in which there isn't voltage	Increasing this parameter reduces the removal rate	No information about the expected influence this parameter on the electrode wear
Voltage	Open voltage between the electrode-tool and the piece	To some extent, the increase of this parameter raises the removal rate	The increase this parameter reduces the electrode wear

* Compiled information from: Dibitonto et al., 1989; Amorim, 2002; Amorim and Weingaertner, 2005; Kunieda et al, 2005; Santos, 2007; Saha, 2008.

This article reports the results obtained about a second stage of the study that evaluated the influence of the variation of the EDM Process Parameters on the Productivity and the Electrode Wear in machining of INCONEL 718. In this stage, a total factorial experiment was performed with the variation in four levels of the pulse duration (t_i) and of the duration of the interval between pulses (t_o). Results of the first stage were presented in the article "Influence of Process Parameters Variation on the Electrode Wear and the Productivity during Roughing EDM of Alloy Stainless Steel 304 and INCONEL 718" (Neves and Souza, 2013), published on the COBEF 2013.

2. EXPERIMENTAL PROCEDURE

The tests were performed in a SA 20 ACTSpark die-sinking EDM machine. As dielectric fluid was used a hydrogenated hydrocarbon, conventionally applied for die-sinking EDM. The tool electrodes were electrolytic copper cylindrical pieces with a main section measuring 20 mm in diameter and 53 mm in length, a central hole of 4 mm in diameter for forced washing of the eroded cavity and another section with a diameter of 50.8 mm and 7 mm in length which served as basis for the System 3R (used to facilitate the fixation of the electrode on the machine). As test samples square blocks of INCONEL 718 were used with dimensions of 30 mm x 30 mm and thickness of 10 mm. Figure (2) shows the pictures of the electrode and the workpiece used in these tests.

Figure 2. Pictures of electrode and workpiece (test sample)

Before each test, the electrode and the workpiece were weighted on a precision balance (brand Bel, model Mark M503) with resolution of 1 mg and their masses were recorded. The machining time was 30 minutes for each test. After this period, the electrode without System 3R and the workpiece were submitted to drying in oven at temperature of 150 °C for 20 minutes. After cooling, they were weighted again and their masses were registered.

To obtain the material removal rate (V_w) the Eq. (1) was used and was considered the density approximate of INCONEL 718 (ρ = 8.19 g/cm³) and the difference between initial (m_i) and final (m_f) masses of the workpiece. To obtain the relative wear (ϑ) of the electrode by Eq. (2) was considered the density approximate of electrolytic copper (ρ_e = 8.92 g/cm³) and the difference between initial (m_{ie}) and final (m_{fe}) masses of the electrode.

$$V_w = \frac{(m_i - m_f)/\rho}{T} \tag{1}$$

$$\vartheta = \frac{(m_{ie} - m_{fe})/\rho_e}{(m_i - m_f)/\rho} x100 \tag{2}$$

The parameters values are shown on Tab. 2. The experiment was a full factorial multilevel, with one replication. In the Tab. 3 are presented t_i and t_o values adopted in the trials.

Table 2. Experimental Planning

Parameter	**t_i**	**t_o**
Values (µs)	50; 200; 400; 800	50; 200; 400; 800
Number of Replication	1	
Number of Tests	32	
Polarity	Positive	
Peak Current (A)	29	
Voltage (V)	125	
Erosion Time (s)	0.8	
Oscillation Mode	Iso-Frequency	

Table 3. Parameters Values of each Trial: t_i and t_o

Trial	t_{on} (μs)	t_{off} (μs)	Trial	t_{on} (μs)	t_{off} (μs)
1	800	800	**17**	800	50
2	200	50	**18**	400	200
3	400	800	**19**	200	400
4	50	200	**20**	800	400
5	50	400	**21**	400	400
6	400	50	**22**	200	800
7	800	800	**23**	800	50
8	200	50	**24**	50	200
9	50	400	**25**	50	800
10	400	800	**26**	200	200
11	400	200	**27**	200	800
12	400	50	**28**	50	50
13	800	400	**29**	800	200
14	800	200	**30**	50	50
15	50	800	**31**	200	200
16	400	400	**32**	200	400

3. RESULT AND DISCUSSION

The results obtained are shown in the Tab. 4.

Table 4. Results Obtained of each Trial

Trial	Removal Rate (mm^3/min)	Electrode Wear (%)	Trial	Removal Rate (mm^3/min)	Electrode Wear (%)
1	25.703	-0.080	**17**	51.822	0.171
2	48.488	0.206	**18**	40.374	-0.347
3	19.541	-1.880	**19**	11.558	1.673
4	5.643	26.422	**20**	36.771	0.028
5	2.927	27.159	**21**	15.096	-0.130
6	51.543	-0.031	**22**	12.159	0.722
7	26.849	-0.567	**23**	50.879	-0.068
8	52.059	0.377	**24**	5.302	27.733
9	2.631	32.061	**25**	2.350	27.505
10	20.010	-0.191	**26**	17.392	0.440
11	33.292	-0.067	**27**	5.926	0.457
12	55.783	-0.055	**28**	22.142	20.118
13	36.758	-0.437	**29**	37.420	-0.082
14	44.630	-0.195	**30**	25.244	19.059
15	2.068	29.551	**31**	14.704	-1.411
16	28.979	-0.119	**32**	7.385	0.772

The results of tests, it is observed that there is a tendency to increase the removal rate with the increment of pulse duration (t_i), shown in Fig. 3. To check the probably influence of t_i on the removal rate, some regression curves were tested and the curve that obtained the greatest coefficient of determination or R-squared is shown in the Fig. 4. In this regression curve can be observed that raising the t_i value provides a gradual increase in removal rate until a maximum value considered optimal for the process and equivalent to the maximum removal rate achieved. Above this value of t_i, the removal rate tends to decrease. Similar behavior was presented by Amorim and Weingaertner (2005) in the EDM of AISI P20 steel.

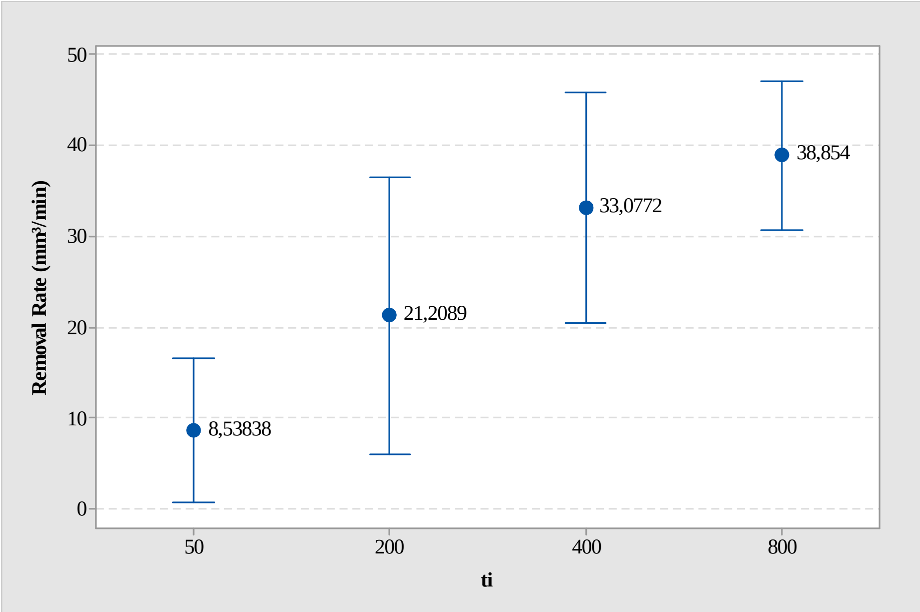

Figure 3. Removal Rate x t_i (95.0% of confidence level)

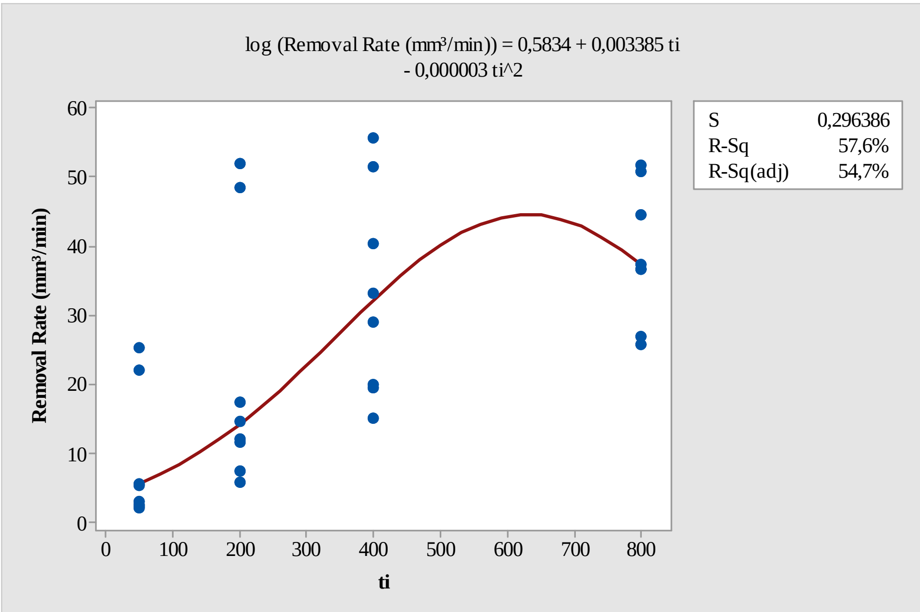

Figure 4. Quadratic Regression of Removal Rate x t_i: with logarithmic in y

The behavior of this curve is explained by increasing the diameter of the plasma channel until to achieve optimum dimension (when pulse duration is the optimum, too). After this, there is an increasing the energy losses by conduction to the dielectric and the electrodes, in addition to energy losses by irradiation, that it leads to a reduction in the rate of melting material during discharge and a reduction of the specific removal rate using pulse durations above the optimal value. According to the curve in the Fig. 4, a higher removal rate can be obtained when t_i is approximately equal 650 µs.

In relation to the electrode wear behavior with the increase of t_i, Fig. 5 shows that there was no significant difference between the standardized effects for the three largest levels of t_i. Fig. 6 exhibits the regression curve of the electrode wear with the variation of the t_i, where there is the abrupt reduction of relative wear with the increase of pulse duration. Similar trend was also observed by Kang and Kim (2003) in EDM of another nickel superalloy. This behavior can be explained considering of the phenomena involved in the formation and maintenance of the plasma channel: with the prolongation of the pulse duration, the increase of the plasma channel in the anode region causes a decrease in the energy flow into this cavity with consequent decrease in the amount of melting material. With the prolongation of pulse duration, part of molten material begins to solidify. So, there is optimum pulse duration of material removal in the anode region that occurs before the optimum point of material removal in the cathode region.

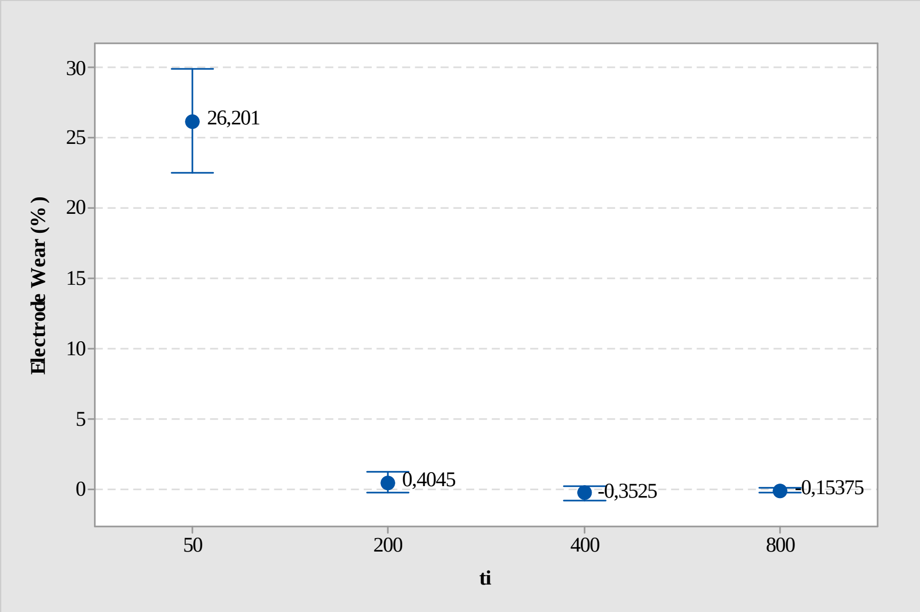

Figure 5. Electrode Wear x t_i (95.0% of confidence level)

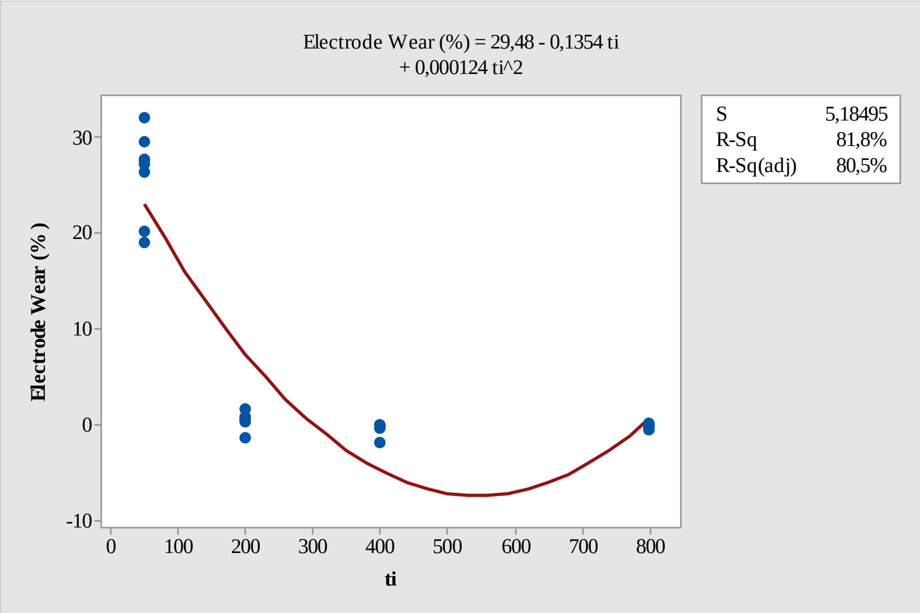

Figure 6. Quadratic Regression of Electrode Wear x t_i

Figure 7 represents the influence to the modification of interval pulses on removal rate and the Fig. 8 shows the regression curve to these data. It can be seen that there is a trend of decreasing removal rate with the increase of interval pulses duration (t_o). During the occurrence of t_o, there isn't removal material. So, the decrease of this time leads to a reduction of the unproductive time of the process and, consequently, more removal of material in the total time.

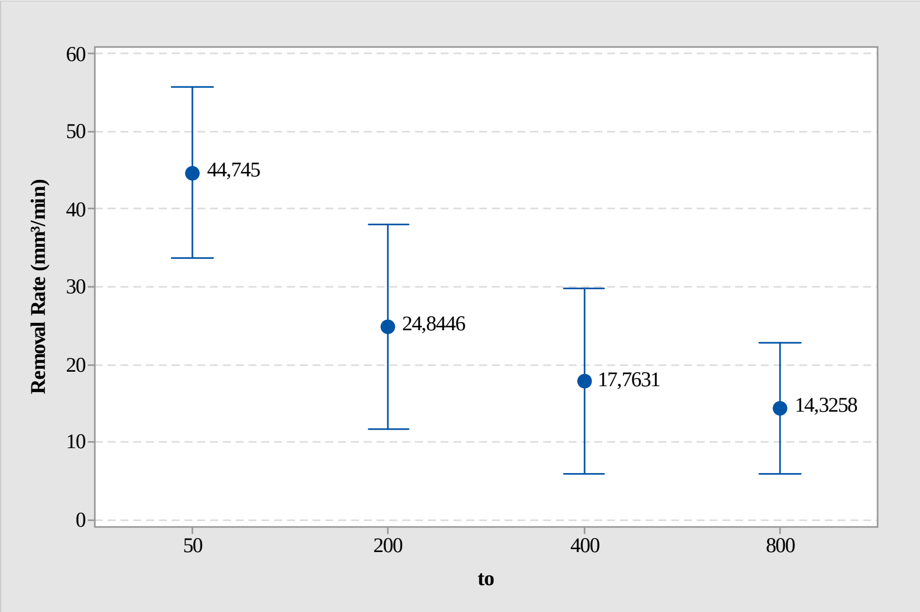

Figure 7. Removal Rate x t_o (95.0% of confidence level)

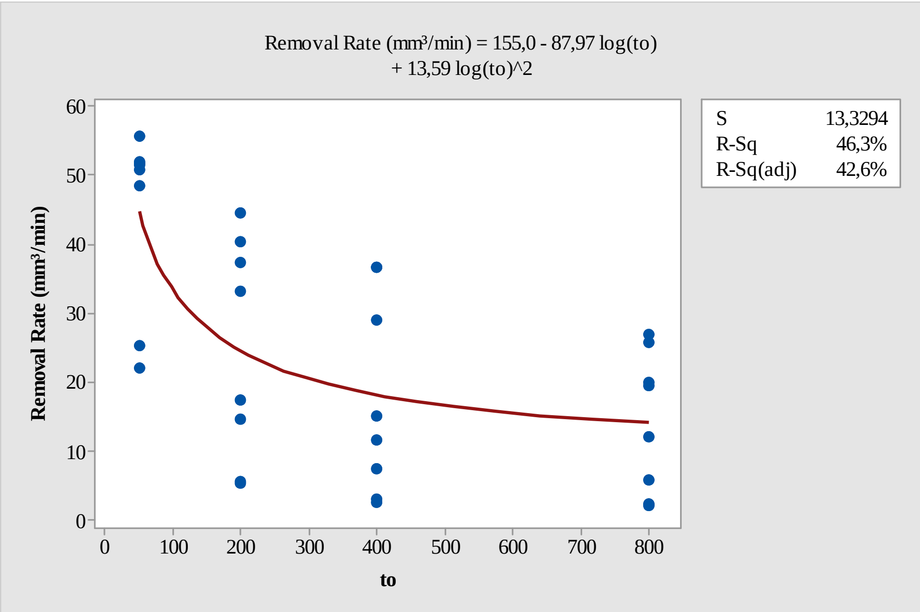

Figure 8. Quadratic Regression of Removal Rate x t_o: with logarithmic in x

Figure 9 represents the influence of t_o on the electrode wear. Due to the overlapping confidence intervals, this chart did not allow a definition of this influence.

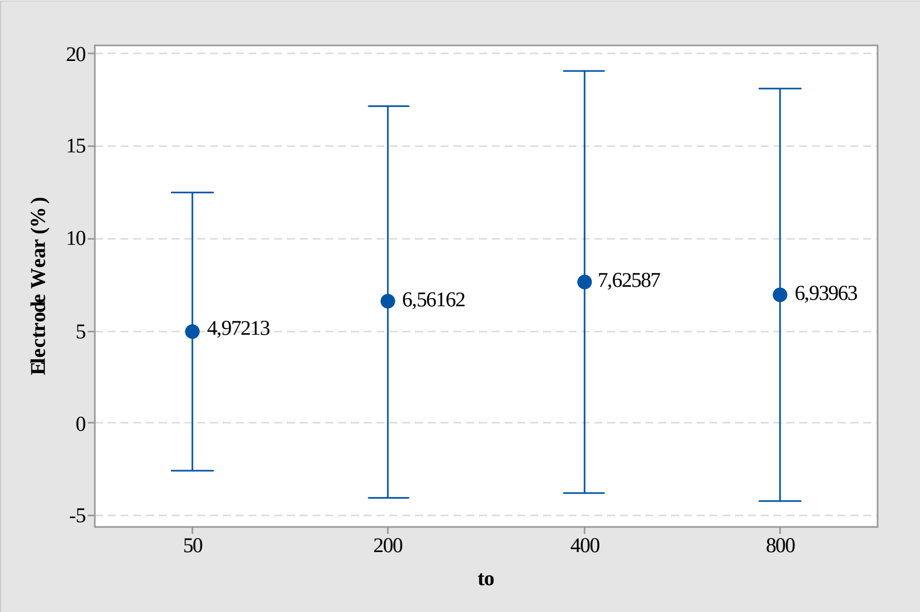

Figure 9. Electrode Wear x t_o (95.0% of confidence level)

4. CONCLUSIONS

From the experiment carried out in this study the following conclusions may be drawn:

- There is a trend in increasing removal rate with the use of larger values of t_i, besides the existence of an optimum value of this parameter that provides a higher removal rate. The curves obtained in the regressions of the analyzed data indicates to a maximum removal rate by adopting t_i = 650 µs and t_o = 50 µs, considering the process parameters used;
- There is a trend to obtain nulls electrode wear with the use of larger values of t_i;
- The results also show that the use of long t_o affect the process with regard to the productivity, reducing removal rate. However, the influence of t_o on electrode wear indicates that this parameter doesn't affect the process performance under the conditions adopted in these tests.

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