



Research Paper / Makale

Micro Hole Drilling of Aerospace Materials and Regression Analysis

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Received/Geliş: 20.02.2020

Accepted/Kabul: 13.04.2020

Abstract: In this study, Electrical Discharge Micro Hole Drilling process applied to specific aerospace material of Ti-6Al-4V. Although Hole-EDM drilling uses the same principles as other EDM methods, a rotated hollow electrode and pumping of dielectric coolant fluid through the electrode tube are the two distinct features. This process has alternatively used for producing fuel injectors, holes in turbine blades and Wire-EDM starter points. In this experimental study, surface observation and the effects of machining parameters of arc on-time (T_{on}), arc off-time (T_{off}) and current (I) on performance parameters were studied. Experimental works applied with single channel, cylindrical, brass, tabular electrode. Deionized water was used for coolant where was pumping inside the electrode at high pressure. The performance parameters chosen as surface roughness (R_a), material removal rate (MRR), electrode wear ratio (EWR) which occurred under the influence of the machining parameters were analysed. The purpose of analysing, Taguchi method consulted to design of experiments. Regression mathematical model was developed and analysis of variance (ANOVA) implemented to figure out of the reliability of mathematical model results. The experimental results reveal that the 500 μ m brass electrode has comparatively better MRR and lower EW. According to ANOVA reliable mathematical models were developed with 0,9643, 0,9827 and 0,9201 R-sq.% for \varnothing 500 μ m successfully.

Key words: Aerospace materials, Electrical discharge hole drilling, Electrical discharge machining

Havacılık Malzemelerinde Mikro Delik Delinmesi ve Regresyon Analizi

Özet: Bu çalışmada havacılık malzemelerinden Ti-6Al-4V alaşımına Elektriksel Erozyon ile Mikro Delik Delme işlemi uygulanmıştır. Her ne kadar Delik-EEİ işlemi diğer EEİ yöntemleriyle aynı prensipleri kullansa da döndürülen içi boş bir elektrot ve di-elektrik soğutucu sıvısının elektrot tüpünden pompalanması ile diğerlerinden ayrılır. Bu işlem genellikle yakıt enjektörleri, türbin kanatlarındaki delikler ve Tel-EEİ başlangıç delikleri gibi delikleri üretmek için kullanılır. Bu deneysel çalışmada, yüzey pürüzlülüğü, ark açık kalma süresi (T_{on}), ark kapalı kalma süresi (T_{off}) ve akım (I) gibi işleme parametrelerinin performans parametreleri üzerindeki etkileri incelenmiştir. Deneysel çalışmalar tek kanallı, silindirik, pirinç, tabular elektrot ile gerçekleştirilmiştir. Soğutma sıvısı olarak de-iyonize su kullanılmış olup, yüksek basınçta elektrotun içine pompalanmıştır. İşleme parametrelerinin etkisi altında meydana gelen yüzey pürüzlülüğü (YP), malzeme kaldırma oranı (MKO), elektrot aşınma oranı (EAO) olarak seçilen performans parametreleri analiz edilmiştir. Analiz amacıyla Taguchi deney tasarımına başvurulmuştur. Regresyon matematiksel modeli geliştirildi ve matematiksel model sonuçlarının güvenilirliğini anlamak için varyans analizi (ANOVA) uygulandı. Deneysel sonuçlar, 500 μ m pirinç elektrotun nispeten daha iyi MKO ve daha düşük EAO'ya sahip olduğunu ortaya koymaktadır. ANOVA'ya göre \varnothing 500 μ m için 0,9643, 0,9827 ve 0,9201 %R kare ile güvenilir matematiksel modeller geliştirilmiştir.

Anahtar kelimeler: Havacılık malzemeleri, Elektro erozyon ile delik delme, Elektro erozyonla işleme

How to cite this article

Akbulut,A., Göv,K., "Micro Hole Drilling Of Aerospace Materials And Regression Analysis", El-Cezeri Journal of Science and Engineering, 2020, 7 (2); 710-723.

Bu makaleye atıf yapmak için

Akbulut,A., Göv, K., "Havacılık Malzemelerinde Mikro Delik Delme İşlemi Ve Regresyon Analizi", El-Cezeri Fen ve Mühendislik Dergisi 2020, 7 (2); 710-723.

1. Introduction

Electrical discharge machining (EDM) is one of the methods where requires to process micro size holes on hard metals like titanium alloys [1-3] or would be hard to drill with conventional methods. These holes generally located on complex surfaces and bodies of parts which are widely used at Aerospace industries like turbine blades, also some specific automotive parts like diesel ejectors and dies [4, 5]. However, although wants to use EDM on every material, there is a criterion related validation. This reality requires that the materials used in the EDM must be electrically conductive. Because EDM uses a thermoelectric force to wear material from parts. This force produced via spark's heat energy. Sparks causing evaporation and melting on part local area [6]. At that point temperature raise to 8000-12000°C approximately [7]. At the same time wreckages are transferred to the outside from hole perimeter by using high pressure water. These sparks are also the main cause of some problems such as electrode removal rate, material removal rate and surface roughness, which is focused on this article. The character of hole is easily affected from sparks. The spark behaviour is not controlled easily and it causes irregularity on part. According to studies on EDM, these problems are linked with a lot of parameters such as discharge voltage, current, turn speed, pulse span [1-3, 8], electrode [9-11], workpiece characteristics. On the other hand, EDM has an advantage in terms of loads generated during machining. Comparing to conventional processes, The EDM method performs a force that is too small to be considered, irrespective of material properties such as hardness. Like this article, some studies have proposed in literature. Gov [12] researched the effect of dielectric liquid temperature on hole geometries and reached the better surface roughness was linked with decrease of liquid temperature also improved hole accuracy. Pradhan et al. [13] investigated the effects of peak current, pulse on time and rotational speed of the tool electrode as optimization of machining parameters. Workpiece has chosen as Ti-6Al-4V with brass electrode and found that higher peak current leads to higher discharge energy and raise of MRR. Also recognized that with rotating electrode higher MRR is reached. Gov [14] approached from different ways to observe the effects of different types coolant liquids on EDM responses and reached deionized water is better for Ti-6Al-4V compound, the other hand kerosene and normal water results better for Inconel 718 when compared with deionized water. Eyercioglu et al. [15] evaluated the effect of Ø2 mm electrode which has single hole and brass material on the cold working tool steel DIN 1.2080 and results show us responses were implemented such as dimensional accuracy, better finish and reasonable machining time. Gov [16] studied on the different amount of dissolved oxygen and focused on the surface roughness and machining time to increase parameters. In addition, experiments show increase of dissolved oxygen in the coolant, improved these parameters as low surface roughness and fast machining time. Some other EDM hole drilling studies were studied by Gov et al. [17-19] and the effects of EDM parameters on hole drilling process were carried out. Kalyon [20] investigated the effect of brass electrode on Aluminium 6082 alloy in the electrode discharge machine. To observe the effects of input parameters, L9 Taguchi design were used and figured out the effect of control factors on experimental results with ANOVA. According to results, pulse duration and waiting period were not significant on the average surface roughness.

2. Experimental Methods

2.1 Machine Properties and Materials

Experiments were implemented with JS EDM AD-20 (Figure 1) type hole electrical discharge machine, which is available in Mechanical Engineering Department of Gaziantep University. The sample chosen as Ti-6Al-4V (Table 1) due to widespread application on aerospace and medical sectors.

Materials prepared as 5x10x20 mm blocks (Figure 2) which were cut by wire electro discharge machine. The faces which are opposite of each other on samples were ground by using 320 to 1000 size emery papers gradually and polished by using 1 μm diamond suspension before drilling.

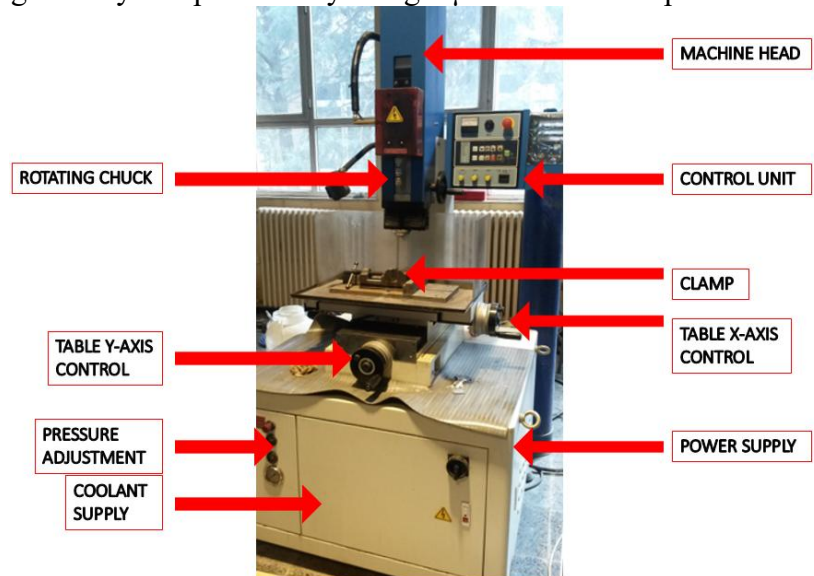


Figure 1. Electrical Discharge Machine

Table 1. Chemical Compositions of Materials (wt. %)

Ti-6Al-4V			
Ti	89,464	O	0,18
Al	6,08	C	0,02
V	4,02	N	0,01
Fe	0,22	H	0,0053

Single channel electrodes with different sizes as Ø300μm, Ø400μm and Ø500μm (Figure 3) were used for making holes which were positioned on the centre of the opposite polished faces vertically and drilled with depth of 10 mm. After process was completed, workpieces were appear as shown in Figure 4.

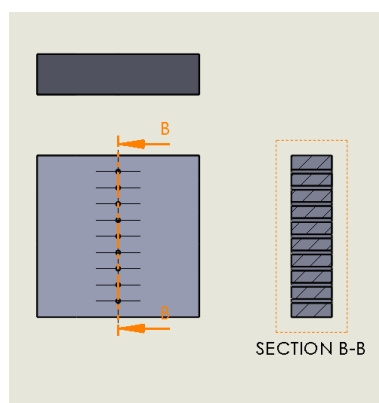


Figure 2. 3D Workpiece Illustration



Figure 3. 300 and 400 µm Diameter Brass Single Channel Electrodes

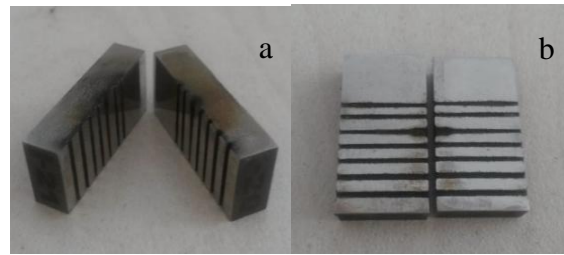


Figure 4. (a) Cross view and (b) inside view of workpiece

The electrode properties given in table 2. As coolant liquid, deionized water chosen and implemented to all experiments regularly. The operations made considering the results of preliminary experiments.

Table 2. Properties of The Electrode Material

Electrode Material	Brass
Melting point (°C)	900-940
Electrical resistivity (ohm-cm)	25659
Thermal conductivity (W/m-°K)	159
Specific heat capacity (J/g-°C)	0.380

These experiments were performed with setting the parameters (Table 3) as current (I), pulse on time (T_{on}), pulse off time (T_{off}) and remained constant the other parameters to observe the changes on the output parameters. Output parameters focused on surface roughness, material removal rate and electrode wear ratio.

Table 3. Machining Conditions

Discharge current (I)	3,4-8,8 A
Pulse-on time (T_{on})	35-44 µs
Pulse-off time (T_{off})	20-26 µs
Capacitance	104 µF
Voltage	29 V
Coolant liquid	deionized water
Dielectric flushing pressure	100 bar
Electrode rotation	200 rpm
Polarity of tool electrode	Negative (-)

2.1 Design of Experiments

With the DOE method, the amount of test required to done normally, is reduced considerably, thus eliminating a large workload, which can lead to more test results in a short time. In this context, it was decided to do experiment design with Taguchi method (Table 5) and applied as machining parameters they were selected that Current, Pulse on time and Pulse of time as shown in table 4 with 3 factor, 3 level experiment parameters A, B, C and level 1, 2, 3 respectively.

This method is one type of design methods. Taguchi method focus on design the development of superior performance, designs to deliver quality in comparison with statistical process control, which tries to control the factors that unfavourably affect the quality of product. Table 5 repeated for all electrode dimension separately. With each electrode, were implemented 9 experiments and consequently 27 experiments implemented in this article.

Table 4. Process Parameters

	A	B	C
Levels	I (ampere)	T _{on} (μs)	T _{off} (μs)
1	3,4	35	20
2	8,2	38	23
3	8,8	44	26

Table 5. L9 Taguchi Experiment Design for One Electrode Dimension

Experiment No	L9 Taguchi Design			Machine Parameters			Parameter Values		
	A	B	C	I	T _{on}	T _{off}	I ()	T _{on} (μs)	T _{off} (μs)
1	1	1	1	4	7	7	3,4	35	20
2	1	2	2	4	8	8	3,4	38	23
3	1	3	3	4	9	9	3,4	44	26
4	2	1	2	5	7	8	8,2	35	23
5	2	2	3	5	8	9	8,2	38	26
6	2	3	1	5	9	7	8,2	44	20
7	3	1	3	6	7	9	8,8	35	26
8	3	2	1	6	8	7	8,8	38	20
9	3	3	2	6	9	8	8,8	44	23

2.2 Surface Roughness Measurement

Different types of fluids pass through the created holes according to their working condition. Each fluid significantly affected by the roughness of the surface through which passes inside. At this point, if the application is to be developed, the surface roughness should be considered. Minimizing the surface roughness will turn into a benefit on fluent characteristics, which flows inside holes like air, fuel, etc. Machining parameters are playing active role on the surface roughness.

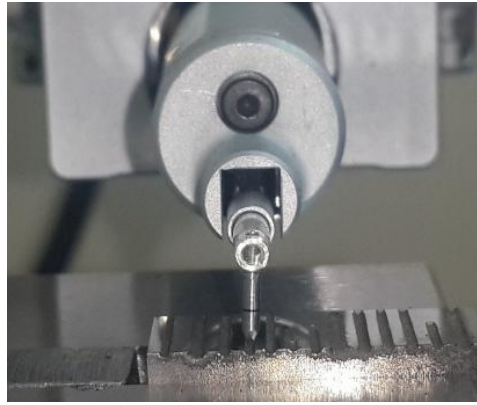


Figure 5. Roughness Measurement

The experiment surfaces measured with Mitutoyo SJ 401 Stylus type surface roughness measuring machine, evaluation length chosen as 4 mm respectively and all measurements applied with three repetitions.

2.3 Material Removal Rate

Material removal rate calculated with weighing of workpieces. Workpieces weighted before drilling operations and after drilling operation regularly. Each part of workpiece's weight recorded separately then weights summed to understand how much weight loses. In order to understand effect of parameters, weights rated per minute (Equation 1). All weight measurements performed with SHIMADZU AUX220 respectively and electronic timer used to measure drilling time.

$$\text{MRR} \left(\frac{\text{mg}}{\text{min}} \right) = \frac{\text{Initial weight of material} - \text{final weight of material}}{\text{Machining Time}} \quad (1)$$

2.4 Electrode Wear Ratio

During the EDM operation, spark, which occurred on head of electrode, reached to high temperatures. These sparks melt the workpiece's surface and separate material via pressurized water. While operating this process, electrode also melts and remove tiny parts from head of electrode at the same time. This situation named as electrode wear. It is important for improve the EDM process performance. Electrode wear effects the performance of EDM with inverse ratio. Small electrode wear ratio means low electrode cost and low manufacturing cost also. To understand that, electrode weights measured before and after operation. Obtained data used to calculate EWR as shown in equation (2).

$$\text{EWR} \left(\frac{\text{mg}}{\text{min}} \right) = \frac{\text{Initial weight of electrode} - \text{final weight of electrode}}{\text{Machining Time}} \quad (2)$$

3. Experimental Results

3.1 Effects on Surface Roughness

Surface roughness can be described as deformation on surface under working condition of machining. These conditions occur with the result of sparks, which were producing on the tip of electrode. These sparks melt the material and remove them by coolant liquid.

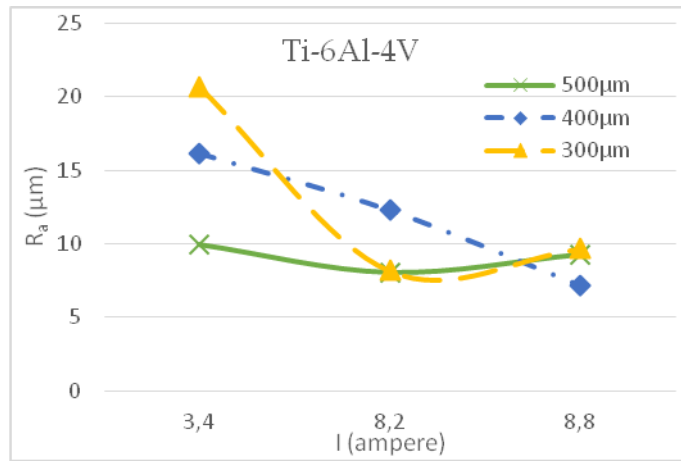


Figure 6. Surface Roughness (Ra) vs I

The molten materials create some cavities on the surface behind them. These geometric irregularities are unwelcome characteristic results of EDM. According to the result of surface roughness inspection (Figure 6-8), when current increases roughness decreases also. The worst roughness values observed when current parameter chosen as 3,4 A and best result obtained at 8,8 A. If we only observed Ø500 µm holes, we can say the effect of current is not significant on roughness. Pulse-on time also not significant on surface roughness even if change the diameters, as shown in figure 7. Only for Ø300 µm was small change occurred between 8,2 A and 8,8 A.

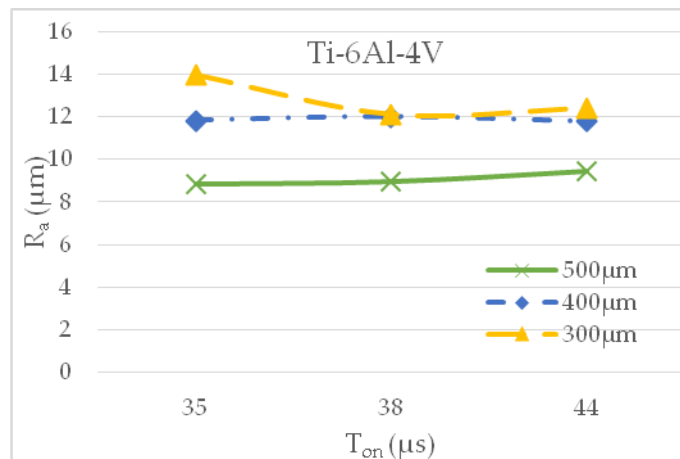


Figure 7. Surface Roughness (Ra) vs Ton

When we observed the pulse-off time effect (Figure 8), general view occurred irregular and independent from each other. While increasing the T_{off} from 20 to 23 µs, the Ra value for 300µm and 500µm diameter experiment results decreased as shown. 400µm diameter result reached to the peak value of itself. According to these results, we reached Pulse-off time is not significant on roughness directly.

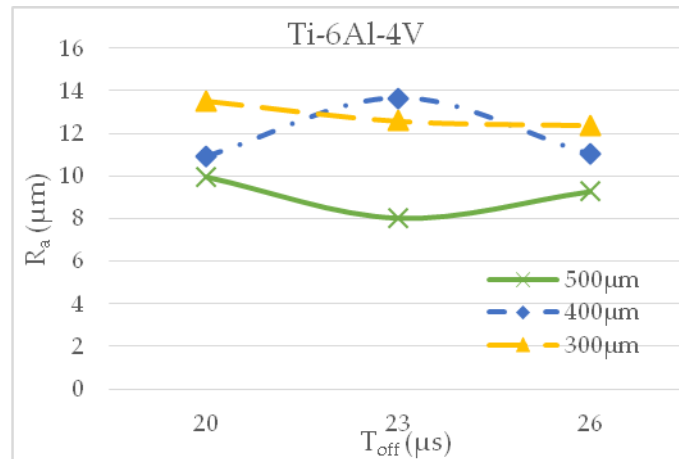


Figure 8. Surface Roughness (R_a) vs T_{off}

3.2 Effects on MRR

EDM process works with the principle of melting the workpiece's contact surface with electrode and remove the molten material from the workpiece. The amount of molten material is figure out MRR. Generally, MRR shows parallel behaviour with discharge current. When discharge current increase, it means the energy of spark increase and it causes more melting and vaporizing on the workpiece. According to figure 9, there was a slight increase in the MRR for Ø300 µm and considerable rise at Ø500 µm and linear increasing observed at Ø400 µm. Ampere highly effected on MRR considerably.

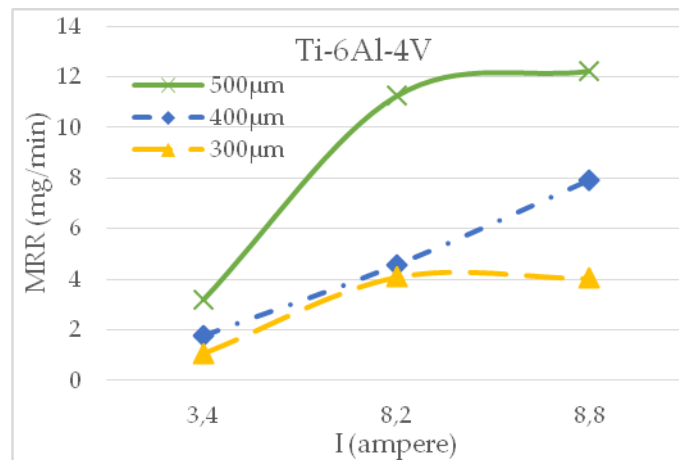


Figure 9. MRR vs I

The effect of pulse on-time (T_{on}) on MRR was shown in Figure 10. The increment of T_{on} caused some changes on MRR for all electrode diameter. While increasing T_{on} from 35 µs to 38 µs, MRR decreased for Ø500 µm. At the same time, MRR increased for Ø400 µm. That means there is no logical relation between T_{on} and MRR.

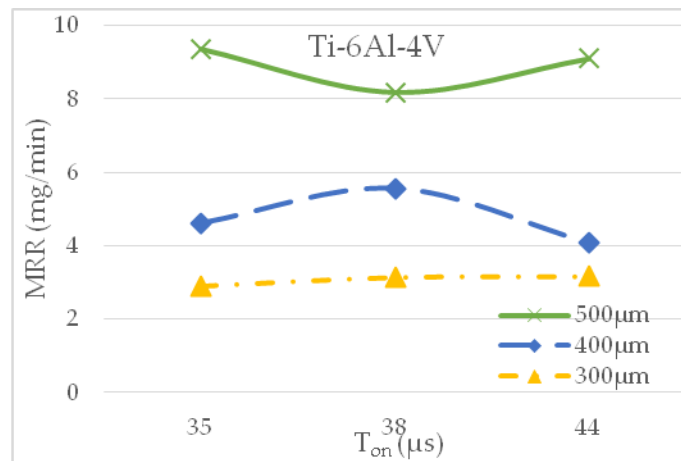


Figure 10. MRR vs T_{on}

The effect of Pulse off-time (T_{off}) on MRR was shown in Figure 11. MRR decreased slightly when the T_{off} increased from 23 μs to 26 μs for Ø500 μm. Also increment of T_{off} didn't affected on MRR for Ø400 μm and Ø300 μm. Results keep going on horizontally. So, the increase in T_{off} not significant on MRR as shown in Figure 11.

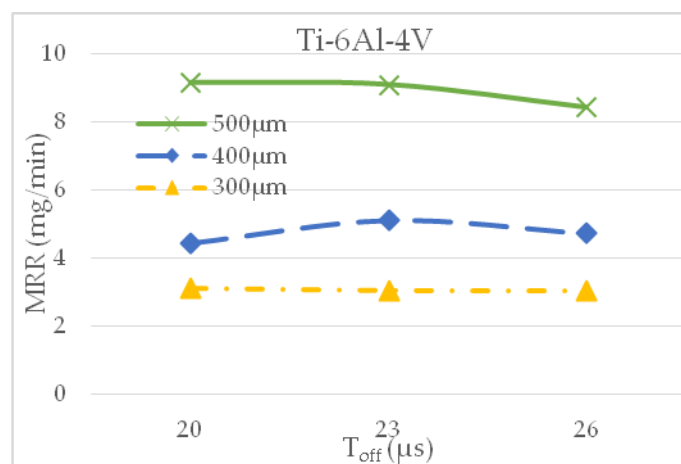


Figure 11. MRR vs T_{off}

3.3 Effects on EWR

Sparks on the tip of electrode erodes the workpiece and remove parts from materials. At the end of that there is occurs hole on the material. Beside melting workpiece, electrode is consumed by melting due to high volume energy expand on electrode tip. Electrode wear is related with the electrical parameters of EDM and electrode materials [21]. In this article capacitance (C) and voltage (V) were taken constant and the effects of current, pulse on time and pulse off time on the electrode wear were investigated. For all different diameters, ampere (I) had significant effects on EWR obviously (Figure 12). For Ø500 μm, EWR was dramatically increase at the range of 3,4 A-8,2 A and continuous with slight rise. The other side, Ø400 μm was increase with linear and constant slope. For Ø300 μm, firstly increase the EWR with rising ampere, but after reach the maximum value, EWR decreased again.

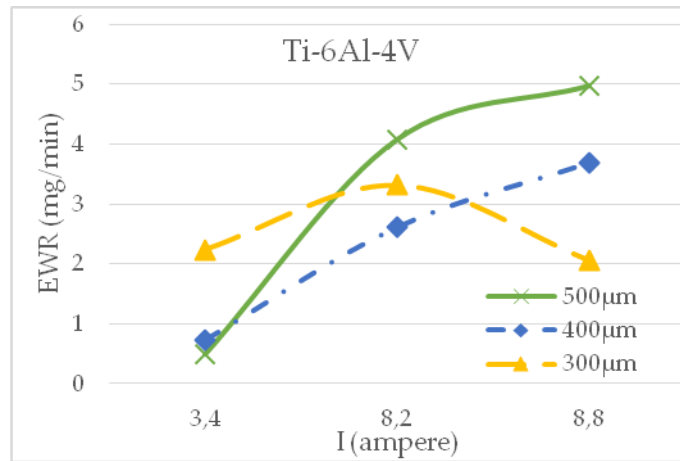


Figure 12. EWR vs I

When the effect of T_{on} was observed (Figure 13), for all diameter value, pulse-on time was same values at 38 µs, but when T_{on} was increase, slightly down the EWR values except Ø500µm results.

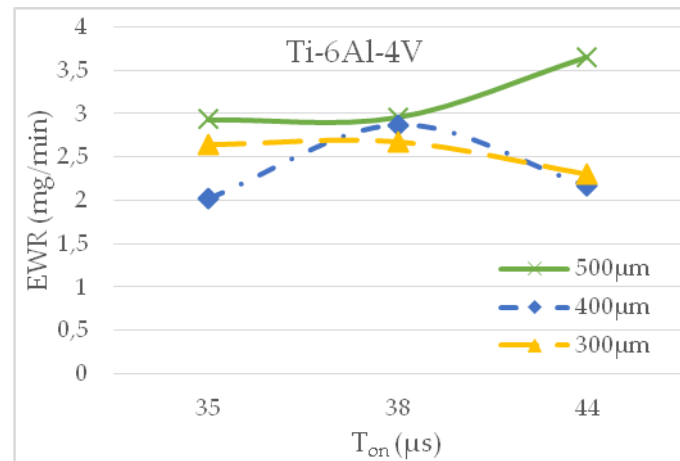


Figure 13. EWR vs T_{on}

T_{off} effects EWR slightly for all diameters. While drilling with Ø500 µm hole, changing the pulse-off time had small effect on EWR response. Between 20 µs and 26 µs EWR decreased slightly. Ø300 µm slope was increased and decreased again. So EWR and pulse-off time not proportional at Ø300 µm. Unlike others, Ø400 µm slightly increase with increasing pulse-off time. Even Ø400 µm has bigger dimensions according to Ø300 µm, general electrode consumptions less than Ø300 µm.

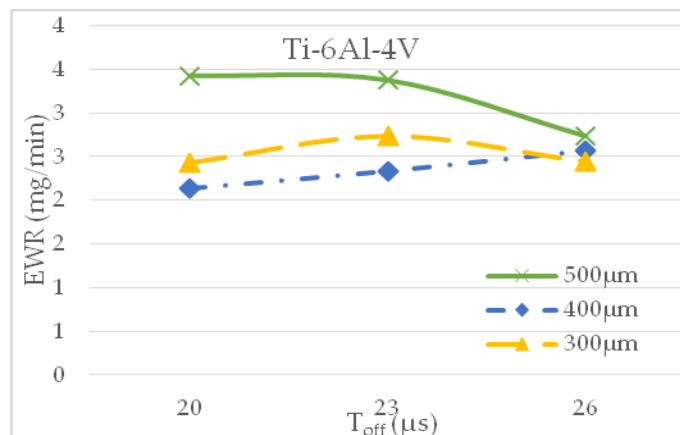


Figure 14. EWR vs T_{off}

3.4 Regression analysis

Regression analysis was applied to construct a model to predict experiment results. The model fit is usually linear, sometime non-linear models such as log linear models are also constructed. In this work multiple regression analysis was implemented for better understanding of the effects of the input parameters on the response parameters and a linear regression equation (3) is also figure out for the prediction of the output parameters. Therefore, we used MINITAB software and followed the consequent process. First, a linear model was developed on MINITAB to analyse the data of Ø500 µm as demonstration. The other experiments Ø400 µm and Ø300 µm which were experimented not shown here with details. Just Ø500 µm experiment results revealed. The fitness characteristic is shown by the following as:

$$Response\ Parameter = b_0 + b_1A + b_2B + b_3C + (\epsilon) \tag{3}$$

where b_1 , b_2 , and b_3 were estimate of the process parameters, and ϵ is error. An empirical equation is then derived to illustrate the functional correlation between response parameters and process parameters. A, B, and C as follows:

For Ø500µm hole;

$$MRR = 0,31 + 1,679 I - 0,0033 T_{on} - 0,118 T_{off} + (\epsilon) \tag{4}$$

R-sq 96,43%

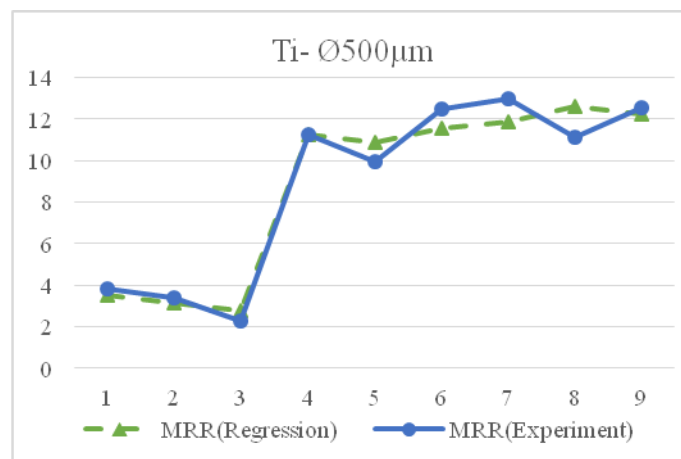


Figure 15. Comparison of mathematical model and experiment results of MRR for Ø500µm

$$EWR = -2,85 + 0,7951 I + 0,0839 T_{on} - 0,1151 T_{off} + (\epsilon) \tag{5}$$

R-sq 98,27%

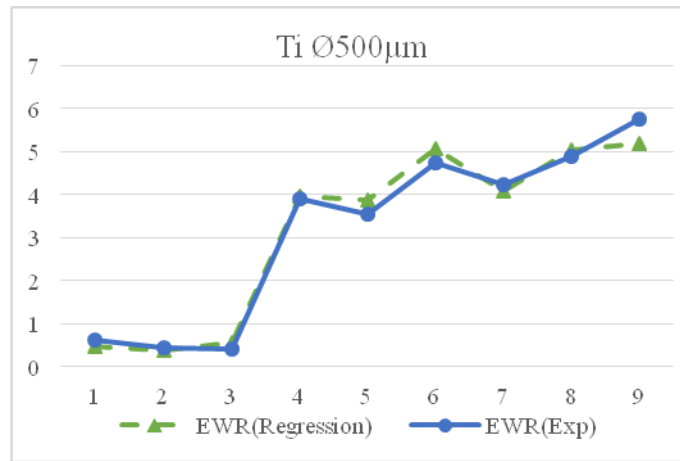


Figure 16. Comparison of mathematical model and experiment results of EWR for Ø500µm

$$R_a = 20,56 - 1,707 I + 0,071 T_{on} - 0,113 T_{off} + (\epsilon) \tag{6}$$

R-sq 92,01%

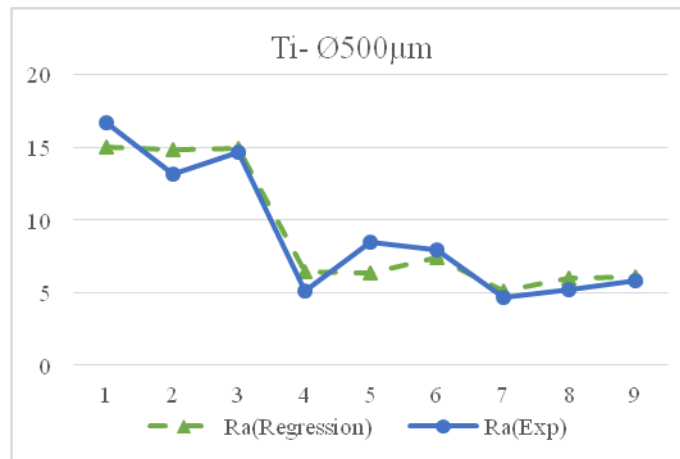


Figure 17. Comparison of mathematical model and experiment results of Ra for Ø500µm

First, the analysis of variance (ANOVA) of the regression model is considered for the reliability of the formulation and is considered to find the relationship between the variables within the statistical model. The experimental data were used to develop linear models, and analysis of the models was figure out through ANOVA.

Table 6. R-sq(%) for Ø500/400/Ø300 µm ANOVA results

Ø500 µm		Ø400 µm		Ø300 µm	
MRR	96,43	MRR	98,17	MRR	97,94
EWR	98,27	EWR	98,64	EWR	91,90
R _a	92,01	R _a	88,24	R _a	91,44

As a consequential parameter R², which is called R-sq, is the correlation coefficient and should fall between 0.8 and 1. In this study, R² was found to be 0,9643, 0,9827 and 0,9201 for Ø500 µm holes MRR, EWR and R_a respectively. As a result, the multiple regression model for response parameters matches very well with the experimental data.

4. Conclusions

Modelling of the EDM hole drilling process and the optimisation attempts were the main tasks in the work. To do so, statistical techniques were used to generate mathematical models, reveal the relations of EDM process parameters with outputs and optimisations. In this article, micro hole EDM process investigated under condition which are designed with Taguchi method and output's reliability has been proven with Analysis of Variance. The surface roughness, MRR and EWR were chosen as experiment responds. Input parameters, which combined with Taguchi, current, pulse on time, pulse off time respectively. Regression analysis were used to compare experiment results with the mathematical results. From the analysis, the following may be concluded.

- The tests results reached in this experiment (for Ø300/400/500 µm single-hole brass electrode) show that the lower discharge currents ($I < 4$ A) are not enough to evaporate the molten material properly and according to result, occurred very low MRR (less than 4 mg/min). The increment of discharge currents and pulse on-times, improves the rate of melting and evaporation, so that MRR increased as a result. Increment of discharge currents cause very high electrode wear and very rough surfaces (R_a greater than 7 µm) thanks to bigger molten metal crater on the workpiece.
- Although minimal pulse off-time is required to increase MRR value, a sufficient amount of pulse off-time is necessary to remove the molten metal between electrode and workpiece by the pressurized water.
- The logical response function designed by regression analysis and analysed with ANOVA, experiment results proved as reliable with these results for Ø500/400/300 µm electrode dimension respectively 0,9643, 0,9827 and 0,9201 terms of R^2 .

Acknowledgement: I would like to express my deepest appreciation to organizing committee of TICMET19 in the selection of my study which was presented in the conference organized on 10-12 October, 2019 in Gaziantep University

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