Performance of Powder mixed Drilling EDM on Biomedical Ti-6Al-4V Alloy

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Abstract. Titanium alloys have gained a lot of attention in biomedical due to their novel properties. In fact, their low elastic modulus and good biocompatibility have promising potential in load bearing bone replacement implants. However, a big part of successful implantation relies on proper surface treatment, which can enhance its performance. Electro discharge machining (EDM) is one of the surface treatment techniques that can be beneficial for proper surface forming. For that reason, this study investigates the machining conditions of EDM on Ti-6Al-4V titanium alloy. In details, this paper evaluates the effect of machining parameters of pulse current, time-on, time-off, gap voltage and powder on material removal rate (MRR) and overcut. Moreover, an experiment set based on L9(34) Taguchi's orthogonal array was conducted and the analysis of variance was observed. In order to investigate the optimum machining condition, grey relation analysis (GRA) and analysis of variance (ANOVA) were used. In conclusion, the best performance parameters for MRR, overcut and multiple characteristics of the orthogonal array were observed and predicted improvements are calculated in this paper.

1 INTRODUCTION

Orthopaedic application of implants is gaining more attention due to the growing number of bone replacement surgeries that demand long-term implant implantation with less harmful effects [1]. In fact, orthopaedic implant application has witnessed a lot of development throughout history. However, current biomedical implants lack proper mechanical characteristics as well as biocompatibility. Despite that, the late research novelties have brought a new class of biomedical materials, which are now one of the major interests of research in the field. These materials are β-type titanium alloys that are created by alloying β phase stabilizing elements. These alloys are distinguished by their low elastic modulus, corrosion resistance and biocompatibility [2]. One of the common alloy composition among β-type titanium alloys is Ti-6Al-4V, which possesses high strength, good fatigue resistance, and excellent fracture toughness mechanical properties.

Matching the composition of materials is vital, however, their surfaces play an important role as well. The surface of an implant is a location of interaction between the implant and body. For that reason, it must be resistant to its environment and external loads, build proper

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connections with body cells and prevent the formation of biofilm. There are several surface treatment techniques that are able to modify surface characteristics. Electro discharge machining (EDM) is one of these techniques. The demand for this method is growing in applications of hard-to-cut materials such as carbides, super alloy and titanium alloys, which would be challenging to cut with conventional machining techniques [3].

β-type titanium alloy has recently received a lot of attention in bone replacement applications. Commercially pure α-type titanium (CP-Ti) is used in dental applications due to its biocompatibility, good corrosion resistance and low elastic modulus compared to most metallic biomaterials [4]. However, in highly loaded bone replacement areas such as hips and knees, the proper elastic modulus of implant materials is crucial. Due to unmatched values of elastic modulus between an implant and an adjacent bone, resorption of bone occurs [1]. As a result of possessing very low elastic modulus, β-type titanium alloys are better suited for use in load bearing bone replacement [4].

Electro discharge machining (EDM) is a non-conventional machining process that removes material by generating electrical sparks between negatively charged electrodes and positively charged workpieces. These sparks can increase local temperatures up to 8’000 - 12’000 °C melting the machining surface of the material, which is then removed with dielectric flushing. The specific feature is that this technique allows the removal of material without physical contact [5].

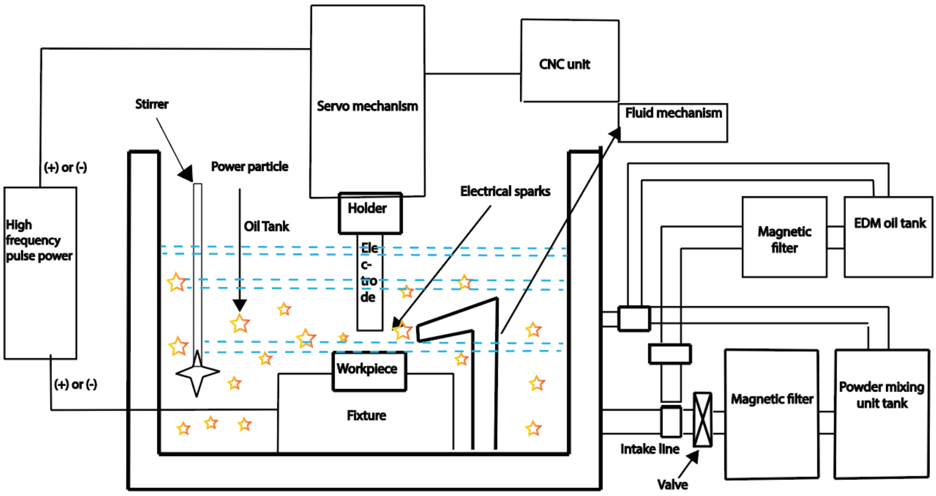

Figure 1. Powder mixed EDM schematics

Abbas et al. have done a review of future research trends with the aim of improving the process of EDM machining [6]. Kumar et al. [7] present research on the theme of surface modification phenomena utilizing EDM and their possible future applications. Moving forward, the optimization of EDM process parameters and their effect on the machining performance measures is becoming more popular among authors’ works [8, 9]. For example, Singh & Bharti [10] have conducted research using parameter optimization of EDM for Ti-6Al-4V and analyzed their response on the drilling rate (DR) and tool wear rate (TWR). They have utilized the Teaching Learning Based Optimization (TLBO) algorithm in order to discover the most optimal parameter combination. Another study on the theme of parameter optimization was conducted by Ramaswamy and Perumal [11]. They have used the response surface methodology (RSM)-based full-factorial central composite design in order to find the most optimal correlation among the process parameters for the LM13 aluminum alloy.

Moreover, they verified the optimal parameter combination using the analysis of variance (ANOVA) method. In addition, research was conducted with the addition of the tungsten powder into dielectric and MRR results were 48.43% larger in comparison with no powder addition in the dielectric [12].

A significant part of the previous studies has focused on applications, working methodologies, specimen material, machining parameters, and their influence on the output machining performances, such as material removal rate, wool wear, etc. Moreover, numerous reports on the process's advantages and drawbacks have also been made.

This paper evaluates the experimental results of drilling EDM performance on Ti-6Al-4V alloy with using hydroxyapatite powdere additive. By utilizing Taguchi's orthogonal array, the study assesses the performance of four parameters: pulse current, time-on, time-off, and gap voltage. The assessment is based on material removal rate (MRR) and overcut values. Statistical analysis, employing grey relation analysis (GRA) and ANOVA, is conducted to estimate the optimal machining conditions. Finally, the paper discusses the effects of each parameter and the optimization process.

2 METHODOLOGY

2.1 Material

The machined workpiece is a Ti-6Al-4V β-type titanium alloy. This type of alloy has advantages over currently used implant biomaterials such as low density, excellent corrosion resistance and a low elastic modulus. For these reasons, the mentioned alloy has growing interest among its class in orthopedic applications. The experiments were performed using a DD703.30A drilling EDM machine by BOFENG Machinery. The workpiece dimensions were 20 mm × 20 mm × 3 mm plate and its composition are shown in Table 1. The electrode was pure brass hollow tube with outer and inner diameters of 1 mm and 0.4 mm, respectively. Its physical properties are shown in Table 2. The dielectric fluid was distilled water.

TABLE 1. Chemical composition of workpiece.

Element		**Ti**	**Al**	**V**
%		Balance	6	4

TABLE 2. Physical properties of brass electrode.

	Density (g/cm3)	**Melting temperature (°C)**	**Thermal conductivity (W/m.k.)**
Brass	8.73	930	159

2.2 Machining parameters

The study is focused on investigating the effects of machining parameters such as time-on, time-off, peak current and gap voltage. The results are evaluated based on the effects of material removal rate (MRR) and overcut (OC). During experiments, feed rate, speed and flushing pressure were constant. Feed rate speed was set to 4 and flushing pressure was set to 10 MPa. Table 2 shows different values of machining parameters affecting machining properties. The experimental design was established by using Taguchi’s L9(34), an orthogonal array with four parameters and three levels. As a result, the number of required experiments was dropped to nine in order to evaluate the effect of each parameter.. Working current (Iw) was also changed in tandem with peak current (Ip) in order to maintain proper feedback sensitivity. The unitless values of the parameters represent the input parameters defined by the machine. The experiments were conducted three times so that the average values of measurements could be collected.

TABLE 2. Machining parameters.

Parameter	**Symbol**		**Levels**			**Unit**
			1	*2*	*3*	
Peak current	I_p	A	2	5	8	
Working current	I_w		2	5	8	
Time-on	T_{on}	B	2	5	8	
Time-off	T_{off}	C	2	5	8	
Gap voltage	V_g	D	2	5	8	
Fixed parameters						
Flushing pressure	P_f		5			MPa
Machining depth	h		1			mm
Servo speed	V_s		4			
High volts	HV		2			

The machining properties are evaluated in terms of MRR and OC. MRR (mm3/s) was calculated with volumetric loss over machining time. The volume loss is calculated by multiplying the machined area by the depth of the blind hole. Due to the hollow shape of the electrode, the workpiece is machined incompletely, and thus the area of the untreated surface is subtracted. The difference between the inner and outer diameters of the hole and the inner and outer diameters of the tool was used to calculate the overcut. For that purpose, three dot circles were used to estimate each diameter. In total, the mean value from four measurements was calculated. The following formulas were used to calculate MRR and overcut:

$$\boldsymbol{MRR = \frac{Volumetric\ loss\ of\ the\ material\ during\ machining\ (mm^3)}{Machining\ time\ (min)} = \frac{\left(Area\ of\ the\ hole\ (mm^2) - Untreated\ area\ (mm^2)\right) * Depth\ (mm)}{Machining\ time\ (min)}} \tag{1}$$

$$\boldsymbol{OC_{outer} = \frac{Hole\ diameter - Tool\ diameter}{2}} \tag{2}$$

$$\boldsymbol{OC_{inner} = \frac{Tool\ inner\ diameter - Diameter\ of\ untreated\ surface}{2}} \tag{3}$$

$$\boldsymbol{OC = \frac{OC_{outer} + OC_{inner}}{2}} \tag{4}$$

This whole setup was repeated with the addition of the 5g/l hydroxyapatite powder to the dielectric.

In the analysis of Taguchi's method, MRR and overcut are categorized as "higher-the-better" and "lower-the better", respectively. These results are also normalized for grey relation analysis (GRA) and by using GRA and ANOVA, the optimum combinations of parameters are predicted.

2.3 Software and Equipment Used in the Study

In order to measure the diameters of the holes, an optical microscope was used in tandem with Motic Images Plus 3.1 software. The machining time was calculated by using a 240 frame-per-seconds slow motion camera. Minitab 19 software was used for analytical estimations.

3 Results and Discussion

3.1 Powder addition

3.1.1 MRR

After conducting experiments, the effect of each machining parameter was analyzed and illustrated in relation to the MRR in tables 3 and 4.

Table 3: Response Table for Signal to Noise Ratios for 0 gram per liter hydroxyapatite powder concentration

Level	Discharge current	Time-On	Time-Off	Gap voltage
1	-19.58	-17.36	-13.15	-14.66
2	-13.63	-15.07	-16.18	-16.46
3	-13.76	-14.54	-17.65	-15.86
Delta	5.95	2.82	4.5	1.79
Rank	1	3	2	4

Table 4: Response Table for Signal to Noise Ratios for 5 gram per liter hydroxyapatite powder concentration

Level	Discharge current	Time-On	Time-Off	Gap voltage
1	-25.14	-20.95	-19.57	-22.13
2	-21.39	-22.67	-23.77	-23.52
3	-21.18	-24.09	-24.38	-22.07
Delta	3.96	3.14	4.81	1.44
Rank	2	3	1	4

Table 3 displays the results for MRR versus Discharge Current, Time-On, Time-Off, and Gap Voltage with a concentration of 0 grams per liter of hydroxyapatite powder. The highest signal-to-noise ratio was achieved at level 2 for Discharge Current, with a value of -13. 63, while level 3 had the highest signal-to-noise ratio for Time-On, with a value of -14.54. Additionally, level 1 had the highest signal-to-noise ratio for Time-Off, with a value of -13.15, and for Gap Voltage, with a value of -14.66. SN ratios here are used to maximize the MRR.

In contrast, Table 4 displays the results for MRR versus Discharge Current, Time-On, Time-Off, and Gap Voltage with a concentration of 5 grams per liter of hydroxyapatite powder. Here, the highest signal-to-noise ratio was achieved at level 1 for Time-Off, with a value of -19.57, while level 1 had the highest signal-to-noise ratio for Time-On, with a value of -20.95. Furthermore, for Discharge Current, level 3 had the second-highest signal-to-noise ratio, with a value of -21.18, and for Gap Voltage, level 1 had the lowest signal-to-noise ratio, with a value of -22.13.

Analyzing both tables, it is apparent that the highest signal-to-noise ratios are generally greater in Table 4 than in Table 3, indicating that increasing the concentration of hydroxyapatite powder may have a positive effect on the MRR. Furthermore, the rank order of the levels for each factor differs in the two tables, which suggests that the optimal settings for each factor may vary depending on the concentration of hydroxyapatite powder. These findings can be utilized to enhance the MRR process by identifying the optimal settings that lead to the highest signal-to-noise ratios for each factor at different concentrations of hydroxyapatite powder.

3.1.2 Overcut

After conducting experiments, the effect of each machining parameter was analyzed and illustrated in relation to the Overcut in the tables 5 and 6.

Table 5: Response Table for Signal to Noise Ratios for 0 gram per liter hydroxyapatite powder concentration

Level	Discharge Current	Time-On	Time-Off	Gap Voltage
1	19.08	18.95	17.98	18.01
2	18.27	18.14	17.97	18.15
3	17.07	17.33	18.48	18.26
Delta	2.01	1.63	0.51	0.25
Rank	1	2	3	4

Table 6: Response Table for Signal to Noise Ratios for 5 gram per liter hydroxyapatite powder concentration

Level	Discharge Current	Time-On	Time-Off	Gap Voltage
1	19.05	19.64	16.59	17.32
2	17.33	16.66	17.76	17.41
3	15.85	15.94	17.89	17.51
Delta	3.2	3.7	1.3	0.19
Rank	2	1	3	4

Table 5 illustrates that the largest signal to noise ratio is achieved at Level 3 for Discharge Current, Level 3 for Time-On, Level 2 for Time-Off, and Level 1 for Gap Voltage. The rank order of the factors in terms of their impact on Overcut is Discharge Current > Time-On > Time-Off > Gap Voltage. On the other hand, Table 6 shows that the highest signal to noise ratio is achieved at Level 1 for Discharge Current, Level 1 for Time-On, Level 3 for Time-Off, and Level 3 for Gap Voltage. The rank order for the factors in terms of their impact on Overcut is Time-On > Discharge Current > Time-Off > Gap Voltage. Comparing the two tables, it is evident that the optimal levels for each factor differ between the two tables, indicating that the concentration of hydroxyapatite powder plays a role in Overcut. Specifically, Discharge Current has the most significant impact in Table 5, while Time-On has the most substantial influence in Table 6. Furthermore, the difference between the highest and lowest signal to noise ratio is more significant in Table 6, suggesting that the variation in the factors has a more considerable impact on Overcut in this case. In conclusion, it can be stated that both the concentration of hydroxyapatite powder and the specific process factors significantly affect Overcut in the macro EDM process. Optimal settings for each factor may differ depending on the powder concentration, and it may be necessary to optimize each factor for each specific powder concentration to achieve the desired Overcut.

3.2 Optimal EDM Parameters

In order to analyze and estimate optimal machining parameters considering multiple types of results, grey relation analysis (GRA) is used. This technique is performed in several steps. First, normalization of each output dataset is done according to the “large-is-better” (LB) and “smaller-is-better” (SB) criteria. For the data with LB criteria, the values are normalized by the following formula:

$$\boldsymbol{y_i^*(k)} = \frac{\boldsymbol{y(k) - \min y_i(k)}}{\boldsymbol{\max y_i(k) - \min y_i(k)}}, \tag{7}$$

Whereas normalization with SB criteria is estimated by the following formula:

$$\boldsymbol{y_i^*(k)} = \frac{\boldsymbol{\max y_i(k) - y(k)}}{\boldsymbol{\max y_i(k) - \min y_i(k)}}. \tag{8}$$

There, i is the experiment number, k is the data sample number, $y_i(k)$ is the measurement value of the experiment i of data sample k, max $y_i(k)$ and min $y_i(k)$ are their maximum and minimum values. Second, the deviation sequence is calculated from the following equation:

$$\boldsymbol{\Delta_{0i}(k) = \| y_0^*(k) - y_i^*(k) \|}. \tag{9}$$

Third, grey relation coefficients (GRC) are calculated by using the following formula:

$$\boldsymbol{\zeta_i(k)} = \frac{\boldsymbol{\Delta_{min} + \zeta . \Delta_{max}}}{\boldsymbol{\Delta_{oi}(k) + \zeta . \Delta_{max}}}, \tag{10}$$

Where ζ is the identification coefficient, which, for this study, was set to 0.5, Δ_{max} and Δ_{min} are the maximum and minimum values of $\Delta_{0i}(k)$. Lastly, grey relation grade (GRG) was obtained by taking the average value of GRC for each experiment number:

$$\boldsymbol{g_i = \frac{1}{n} \sum_{k=1}^{n} \zeta_i(k)}. \tag{11}$$

By using equations (7-11), the GRG for each experiment was calculated and shown in Table 7 and 8. According to that, for no powder addition approach experiment 6 has the biggest GRG compared to the other eight experiments. Whereas for 5 g/l hydroxyapatite powder addition experiment 1 stands out among other 8 trials.

The mean S/N ratios of GRG for each experiment are shown in Table 11 and 12. By referring to these tables, the most optimal parameter set, based on GRA, is $A_3B_3C_1D_2$ for no powder addition and $A_1B_1C_1D_3$ for 5g/l powder addition.

TABLE 7. Grey relation coefficient for 0 gram/l powder addition.

No. Exp.	**Grey relation coefficient**		**Grade**
	MRR	Overcut	
1	0.3805	0.3333	0.3569
2	0.3375	0.4352	0.3864
3	0.3333	0.6088	0.4711
4	0.4276	0.4545	0.4411
5	0.5217	0.6567	0.5892
6	**1.0000**	**0.7908**	**0.8954**
7	0.3707	0.7017	0.5362
8	0.9772	0.7678	0.8725
9	0.6990	1.0000	0.8495

TABLE 8. Grey relation coefficient for 5 gram/l powder addition.

No. Exp.	**Grey relation coefficient**		**Grade**
	MRR	Overcut	
1	**0.5982**	**1.0000**	**0.7991**
2	0.3403	0.6868	0.5136
3	0.3333	0.6251	0.4792
4	0.5644	0.9161	0.7403
5	0.4384	0.5036	0.4710
6	0.5371	0.3636	0.4503
7	0.4593	0.6793	0.5693
8	1.0000	0.3333	0.6667
9	0.4186	0.3445	0.3815

TABLE 9. S/N response for GRG for 0 g/l.

Level	**Pulse current**	**Time-on**	**Time-off**	**Gap voltage**
1	0.4048	0.4447	0.7083	0.5985
2	0.6419	0.6160	0.5590	0.6060
3	0.7527	0.7387	0.5321	0.5949
Delta	0.3479	0.2939	0.1761	0.0075
Rank	1	2	3	4
Optimal	0.7527	0.7387	0.7083	0.6060

TABLE 10. S/N response for GRG for 5 g/l

Level	**Pulse current**	**Time-on**	**Time-off**	**Gap voltage**
1	0.5973	0.7029	0.6387	0.5506
2	0.5539	0.5504	0.5451	0.5111
3	0.5392	0.4370	0.5065	0.6287
Delta	0.0581	0.2659	0.1322	0.1177
Rank	1	2	3	4
Optimal	0.5973	0.7029	0.6387	0.6287

Meanwhile, Table 11 shows the results of GRA based on ANOVA. It demonstrates that for 0 g/l powder addition pulse current has a significant influence on multiple characteristics and performance, accounting for 50.6077 % of the contribution. However, for 5 g/l powder concentration, time-on has a significant effect with 66.123%.

TABLE 11. ANOVA estimation for GRG for 0 g/l.

Factor	Level 1	Level 2	Level 3	DOF	Sum of squares	Variance	Contribution, %
Pulse current	0.4048	0.6419	0.7527	2	0.1896	0.0948	50.6077
Time-on	0.4447	0.6160	0.7387	2	0.1308	0.0654	34.9170
Time-off	0.7083	0.5590	0.5321	2	0.0540	0.0270	14.4240
Gap voltage	0.5985	0.6060	0.5949	2	0.0002	0.0001	0.0513
Error				0			
Total				8	0.3746		

TABLE 12. ANOVA estimation for GRG for 5 g/l.

Factor	Level 1	Level 2	Level 3	DOF	Sum of squares	Variance	Contribution, %
Pulse current	0.5973	0.5539	0.5392	2	0.0055	0.0027	3.3945
Time-on	0.7029	0.5504	0.4370	2	0.1068	0.0534	66.1228
Time-off	0.6387	0.5451	0.5065	2	0.0277	0.0139	17.1606
Gap voltage	0.5506	0.5111	0.6287	2	0.0215	0.0108	13.3221
Error				0			
Total				8	0.1615		

4 CONCLUSION

This study investigated drilling EDM machining parameters on Ti-6Al-4V titanium alloy. By examining machining parameters such as pulse current, time-on, time-off and gap voltage, the following observations were carried out:

From the experiments, it was observed that the performance of MRR is directly proportional to pulse current and time-on. Meanwhile, it is indirectly proportional to time-off and gap voltage.

Pulse current and time-on are major parameters that increase MRR with a contribution of 50.67% and 34.92%, respectively. However, with the addition of the 5 g/l hydroxyapatite powder into dielectric the contribution value of Pulse current parameter decreases up to 3.3945. The increase in pulse current leads to an increase in discharge energy, while the increase in time-on lengthens pulse duration. These result in a higher rate of material removal. However, with that addition of the powder, the time-on/off and gap voltage parameters takes a leading role on the performance.

Increasing the concentration of hydroxyapatite powder in PMEDM positively affects the Material Removal Rate (MRR).

Optimal settings for factors influencing Overcut in the macro EDM process vary depending on the concentration of hydroxyapatite powder, emphasizing the need for factor optimization specific to each powder concentration.

For 0 g/l powder concentration time-off and gap voltage were found to have less influence on performance and have contributions of 14.42% and 0.0513%, respectively. However, contribution of the gap voltage parameter increased up to 13.3221 with the addition of 5 g/l powder hydroxyapatite concentration.

The lower values of time-off and gap voltage parameters increase the performance of MRR. When time-off period is reduced, idle time duration is reduced, resulting in more frequent sparking. By increasing the gap voltage, discharge energy increases, resulting in a higher MRR. However, the spark gap is increased, which leads to a reduction in energy density, which, in turn, reduces MRR. In contrast, a low sparking gap results in earlier dielectric breakdown, hence increasing the efficiency of material removal.

The overcut is less at lower time-on and time-off, higher gap voltage and medium pulse current values.

Time-on and time-off are two main parameters that change overcut performance. A small value of the time-on parameter makes the spark duration short, which results in a smaller amount of energy emitted for a single spark.

Based on GRA, time-on and pulse current has a big effect on multiple performance characteristics compared to the other three parameters. Despite this, the optimal machining performance for 0 g/l can be obtained with parameters of pulse current “8”, time-on “8”, time-off “2” and gap voltage “5”. On the other hand optical machining performance for 5 g/l can be achieved with parameters of pulse current “2”, time-on “2”, time-off “2” and gap voltage “8”.

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