

Experimental Study of Material Removal Rate in Electrical Discharge Turning of Titanium Alloy (Ti-6Al-4V)

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Abstract. Electrical discharge turning (EDT) is a new machining process in which an external axis is added to a conventional EDM machine in order to produce precise cylindrical forms on hard and difficult to machine materials. By feeding a pre shaped tool electrode against a rotating work piece, axially symmetrical parts can be produced. The machining performance of EDT process is influenced by its machining parameters, which directly affect the quality of the machined component. This paper presents an experimental study on the effects of EDM parameters namely pulse-on time, peak current, gap voltage, spindle speed and flushing pressure on material removal rate (MRR) in electrical discharge turning of titanium alloy Ti-6Al-4V. This has been done by means of the Taguchi's design of experiment technique. A mathematical model has been developed for MRR by regression analysis and factor effects were analyzed using analysis of variance (ANOVA). Signal-to-noise ratio analysis is used to find the optimal condition.

1. Introduction

Electrical discharge machining (EDM) is largely disseminated among several industrial sectors and is no longer considered an unconventional machining process [1]. EDM machines account for about 7 percent of all machine tool sales in the world [2]. This machining method uses a series of discrete electrical sparks between a tool electrode and a work piece immersed in a dielectric fluid and subjected to an electric voltage. Literally thousands of high temperature electrical discharges per second are generated and each electrical discharge produces a tiny crater by melting and vaporization, thus work material is removed and desired shape of the tool is produced into the work piece [3]. The hardness and strength of the difficult-to-machine work-materials are no longer the dominating factors that affect the tool wear and hinder the machining process. This makes the EDM process particularly suitable for machining hard, difficult-to-cut materials [4]. The EDT process is being extended from wire electrical discharge turning (WEDT) in order to achieve a high degree of accuracy, surface finish and cylindricity in straight turning as well as in form turning of hard-to-machine material having high slenderness ratio. One of the main applications of the die-sinking EDM machine is in turning aerospace honey-comb seals where internal and external seals are machined to a burr free finish with internal or external diameters from 300mm-1400mm [5]. The concept and part machined using EDT method is shown in fig.1 and fig. 2 respectively.

The idea of employing EDM to machine cylindrical parts for manufacturing small diameter pins has been reported by Dr. Masuzawa at university of Tokyo [6]. The small pins can be utilized as a tool for micro EDM application [7]. Soni and Chakraverty conducted a comparative study of output



performance characteristics between stationary and rotary tool electrode. Their findings show improvement in material removal due to better flushing action and sparking efficiency in rotary EDM of titanium. However, this results in high surface roughness [8]. Mohan et al. perform the experimental study on Al-SiC metal matrix composite material. They showed that the rotary tool improves the material removal rate and reduce the surface roughness [9]. Y.H. Guu et al. study the influence of workpiece rotation during electrical discharge machining of AISI D2 tool steel using copper electrode. Experimental findings indicate that the surface finish improves at higher rotational speed [10]. E. Uhlmann et al. conducted a comparative experimental study of EDT, electric discharge grinding and wire electric discharge grinding to analyze the machining effect, resulted from high rotational speed of the electrodes. The experimental results make clear that the MRR growing with higher circumferential speed and discharge energy, but it causes increase in roughness of machined surface [11]. Matorian et al. established optimum process condition for electrical discharge turning process. They adopted Taguchi design method to study the influence of process parameters namely, voltage, power, pulse-on time, spindle speed and servo upon MRR while machining HSS-1.3255. Based on experimental findings, power and spindle speed were found most significant factors, that is by increasing the value of these two parameter MRR increases significantly. However pulse-on time and servo have significant and reciprocal effect on it [12]. Teimouri and Baseri introduced magnetic field in rotary EDM. Results indicate that the applying of rotational magnetic field near machining zone lead to better flushing condition and subsequently improves the material removal rate and surface finish [13]. Song et al. developed a new strip EDM turning process which performs the same function as wire in wire electric discharge turning. Experimental findings indicate that strip EDM produces nearly 74% more MRR than wire electrical discharge turning. In addition, the machined surface was found cusp free and nearly four times smoother than WEDM turned surface [14]. Janardhan et al. used pulse train data analysis to study the effect of process parameters on material removal, surface roughness and roundness [15]. Recently Aravind Krishnan and Samuel has attempted to optimize process parameters by considering the material removal and surface roughness as output parameters in wire electrical discharge turning process [16].



Figure 1. Concept of EDT process.



Figure 2. A cylindrical EDT part.

From the above literature it is found that several researchers have contributed to the development of EDT process. However, because of its stochastic nature the full potential utilization of this process is not completely solved. So the need has been felt towards the highlighting this process and explores the possible ways to adjust its parameters to enhance the process performance. This paper presents a study on straight turning of titanium alloy using preshaped solid copper electrode. This has been done by determining significant factors using ANOVA technique. Regression analysis than conducted to establish a relationship between factors and response. Finally signal to noise ratio (S/N) analysis is conducted to find the optimal settings and factor levels. Therefore optimal process parameters are verified through the confirmation experiment.

2. Experimental setup and equipments

In this research all experiments were conducted on Electronica 500×300 ZNC EDM machine. The dielectric fluid used for experiments was industrial grade EDM oil. The experiments are aimed at considering effects of several controllable factors on MRR. In these experiments, electrolytic copper tool electrode was used. The material selected for carrying out the experiments was cylindrical bar (10 mm dia. and 75 mm length) of titanium alloy. This material is a difficult-to-machine material and is extensively used in aerospace, automobiles, chemical and biomedical applications. To determine the material removal rates the specimen was weighted before (w_i) and after (w_f) machining using a precision self calibrating digital balance (AND, GR-200 e = 1mg.). The material removal rate was specified using the following equation (1):

$$MRR(mg / min .) = \frac{W_i - W_f}{t} \times 1000 \quad (1)$$

Table 1. Experimental layout using an L18 orthogonal array.

Run	Ton	IP	V	RPM	FP	MRR	S/N ratio
1	5	5	40	40	0	4.7425	13.5201
2	5	20	60	80	0.25	16.632	24.4188
3	5	35	80	120	0.5	13.052	22.3135
4	10	5	40	80	0.25	9.023	19.1070
5	10	20	60	120	0.5	24.706	27.8560
6	10	35	80	40	0	19.428	25.7685
7	15	5	60	40	0.5	7.17	17.103
8	15	20	80	40	0	17.588	24.9043
9	15	35	40	120	0.25	40.308	32.1078
10	5	5	80	120	0.25	0.344	9.2688
11	5	20	40	40	0.5	14.65	23.3167
12	5	35	60	80	0	19.456	25.7810
13	10	5	60	120	0	1.042	0.3573
14	10	20	80	40	0.25	13.96	30.2114
15	10	35	40	80	0.5	32.402	30.2114
16	15	5	80	80	0.5	5.088	14.1309
17	15	20	40	120	0	26.866	28.5840
18	15	35	60	40	0.25	28.7255	29.1653

2.1. Design of experiments

The accuracy and effectiveness of an experimental program depends on careful planning and execution of the experimental procedure. With a view to achieve the aforesaid objective, Taguchi orthogonal array (OA) $L_{18}(2^1 \times 3^7)$ was adopted for design of experiments. Thus 18 experiments were conducted at parameter levels shown in table 1. Note that the experiments were run in random order and the machining time for each experiment was fixed to 20 minute. Peak Current, pulse on-time, voltage, spindle rotation speed and flushing pressure each at three levels are adopted as a factor (variable parameters) which varies during the experiments according to the design of experiment. The commercial software MINITAB 16 was used to design and analysis the experiments. Table 1 shows the assigned orthogonal L_{18} array along with the data acquired for material removal rate. In this research only the main effect of factors are of interest and their interaction are excluded from the data analysis.

3. Data analysis

The first step in data analysis of this study is to summarize test results for each experiment performed by the use of Taguchi design of experiments technique. Figure 3 exhibits the main effect plot of pulse-on time, peak current, gap voltage, spindle speed and flushing pressure on the material removal rate. Figure 3 a-b shows the effect of applied pulse-on time and current on material removal rate. It indicates that both the parameters has most significant effect on MRR and shows direct proportion to it. That is by increasing the value of these two parameters MRR Increases significantly. Gap voltage as indicated in Figure 3 (c) is reciprocally proportional to the MRR; that is higher material removal can be obtain at the lower voltage value. The Figure 3 d-e presents the effect of spindle rotational speed and flushing pressure on MRR. As indicated none of the parameter has a significant effect on material removal. Analysis of Variance (ANOVA) was used for discussing and interpreting data. It is numerously employed by researchers because it covers the shortcomings of graphical assessment. Before any presumptions can be made based on ANOVA table, the assumptions through ANOVA have to be checked (normality error, variance consistency etc.). Figure 4 shows the normal plot of residuals for MRR. A normal probability plot is just a graph of cumulative distribution of the residuals on normal probability paper. Anderson-Darling (AD) statistic is used here to check the normal distribution of the residuals. As shown in Figure 4 the p-value calculated based on AD statistic is higher than the α -level of confidence (0.05), the error normality is considered to be valid. Table 2 indicates ANOVA table for MRR. It can be seen from table that current, pulse-on time and voltage have most significant impact on material removal rate at confidence level of 95%. So the P-values which are less than 0.05 indicate that null hypothesis should be rejected and thus the effect of respective parameter is significant.

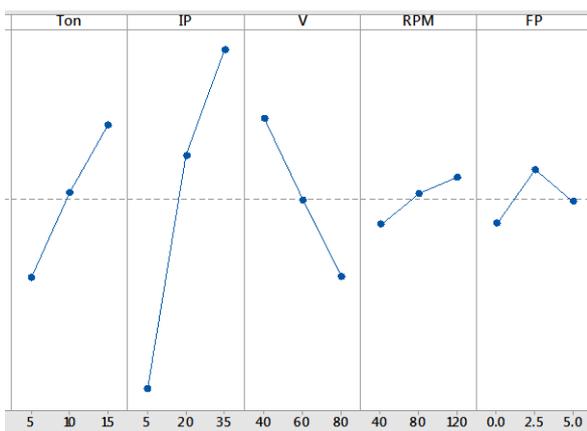


Figure 3. Mean effect plot of factors for MRR.

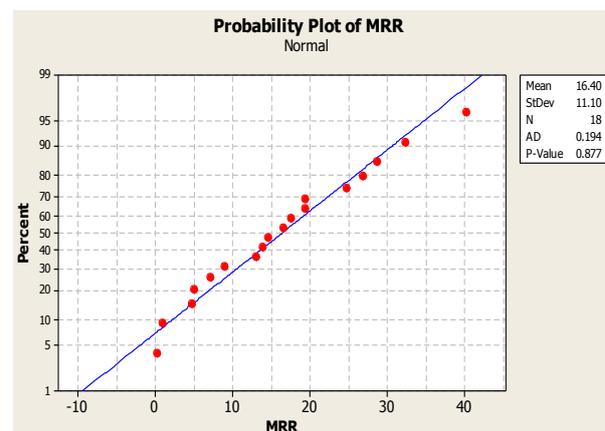


Figure 4. Normal probability plot of residual for MRR.

Table 2. Analysis of Variance for Ra, using Adjusted SS for Tests.

Source	DF	Seq SS	Aj SS	Adj MS	F	P
Ton	2	270.68	270.68	135.34	10.21	0.008
IP	2	1386.26	1386.26	693.13	52.28	0.000
V	2	285.60	285.60	142.80	10.77	0.007
RPM	2	26.74	26.74	13.37	1.01	0.412
FP	2	33.34	33.34	16.67	1.26	0.342
Error	7	92.80	92.80	13.26		
Total	17	2095.43				
S= 2.64		R-sq.= 95.57%		R-sq (adj)= 89.24%		

Equation (2) presents the relationship between factors and response, which is the outcome of multiple linear regression analysis.

$$\text{MRR} = 3.96 + 0.948 \text{ Ton} + 0.700 \text{ IP} - 0.244 \text{ V} \quad (2)$$

Table 3 indicates that the above mention regression model is the best one in comparison with the others that can be used with these parameters and parameter levels by $R^2(\text{adj.})$ test. The R^2 value indicates that the model can reasonably explain 91.1% of the variance in MRR. $R^2(\text{adj.})$ is 89.24%, which accounts for the number of predictors in the model. Both value show that the data are fitted well. S/N ratio analysis is utilized to obtain the optimal condition. The type of problem which is dealt with here is "higher the better" [17] For such type of problem η is calculated as:

$$(\text{HB}) \eta = -10 \log \left[\frac{1}{n} \sum_{i=1}^n \left(\frac{1}{y_i^2} \right) \right] \quad (3)$$

Table 4 shows the mean S/N ratios obtained for each parameter level. The purpose of the confirmation experiments is to validate the conclusions drawn during analysis. The predicted S/N ratio using the optimal level of the machining factors can be calculated as Equation (4). The results of confirmation test are presented in table 5.

$$\eta_{opt} = \eta_m + \sum_{j=1}^k (\eta_j - \eta_m) \quad (4)$$

Table 3. Table of coefficients for regression analysis for MRR.

Predictor	Coef.	SE coef.	T	P
Constant	3.956	5.153	0.77	0.458
Ton	0.9478	0.2279	4.16	0.001
IP	0.6997	0.0759	9.21	0.000
V	-0.2438	0.0569	-4.28	0.001
RPM	0.0367	0.0284	1.29	0.221
FP	2.649	4.599	0.58	0.572
S= 3.94	R-sq.=91.1%	R-sq (adj)= 87.4%		

Table 4. S/N values (dB) for MRR.

Factor level	Ton	IP	V	RPM	FP
1	16.680	9.160	24.475	21.963	19.819
2	21.033	25.330	20.782	23.092	19.738
3	24.334	27.558	16.791	16.992	22.490
Delta	7.654	18.398	7.683	6.101	2.752
Rank	3	1	2	4	5

Table 5. Results of the experimental confirmation for MRR.

Initial machining parameter	Optimal machining parameter		
Level	A2B2C2D2E2	Prediction A3B3C1D2E3	Experiment A3B3C1D2E3
MRR	16.952	57.884	57.651
S/N ratio	24.58	35.25	35.22

4. Conclusion

In this study the influence of machining parameters i.e. pulse on time, current and spindle speed over MRR was investigated. The study has been made for Ti-6Al-4V because of its growing range of applications in industry. Experiments have been designed by Taguchi's design of experiments method. Experimental findings shows that Ton, IP and V has most significant effect upon MRR. A multiple regression equation was derived and presented as Eq. 1 for MRR. An optimum parameter combination for the maximum MRR was obtained by using the S/N ratio analysis. The confirmation test results are indicated in table 5. This table evaluates the predicted and actual value of MRR. Thus, MRR is increased by 3.41 times and S/N ratio increased by 1.43 times. This confirms the success of the experiments by using estimated model and proposed statistical technique.

5. References

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