Experimental Analysis of Electro-Discharge Machining Parameters for Minimum Tool Wear Rate on Machinability of Carbon Fiber/Epoxy Composites Using Taguchi Method

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Abstract

Electro-Discharge machining is a process of removal of material through melting or vaporization caused by high frequency spark discharge. A good selection of proper tool (electrode) material is necessary for minimum tool wear rate. Number of techniques are employed for optimization of process parameters but in this paper we used Design of experiments via Taguchi method. This method is used to determine the optimal process parameter in EDM during machining of carbon fiber/epoxy composites with copper-cadmium tool. Four major control factors named as peak current (I_p), gap voltage (V_g), pulse-on-time (T_{on}) and duty cycle (η) are considered to determine the effect on TWR. In Taguchi method for design of experiment three levels of each parameter has been taken into consideration by using standard L_9 orthogonal array and finding out optimal setting of machining parameters for minimum tool wear rate. A relationship among selected process parameters is developed by doing Response surface methodology with the help of MINITAB 15 software. Analysis of Variance (ANOVA) is also employed for obtaining the optimal process parameters.
Keywords: EDM; Taguchi Method; TWR; MINITAB; ANOVA

1. Introduction

Electro-Discharge Machining (EDM) is the process of machining electrically conductive materials by using precisely controlled sparks that occur between an ‘electrode’ and a ‘work piece’ in the presence of a dielectric fluid [1]. EDM is now become the most important accepted technologies in manufacturing industries since many complex 3D shapes can be machined using a simple shaped tool electrode. EDM is an important ‘non-traditional manufacturing method’, developed in the late 1940s and has been accepted worldwide as a standard processing manufacture of forming tools to produce plastics mouldings, die castings, forging dies and etc. New developments in the field of material science have led to new engineering metallic materials, composite materials, and high tech ceramics, having good mechanical properties and thermal characteristics as well as sufficient electrical conductivity so that they can readily be machined by spark erosion. At the present time, EDM is a widespread technique used in industry for high precision machining of all types of conductive materials such as: metals, metallic alloys, graphite, or even some ceramic materials, of whatsoever hardness. EDM technology is increasingly being used in tool, die and mould making industries, for machining of heat treated tool steels and advanced materials (super alloys, ceramics, and metal matrix composites) requiring high precision, complex shapes and high surface finish. Traditional machining technique is often based on the material removal using tool material harder than the work material and is unable to machine them economically. An EDM is based on the eroding effect of an electric spark on both the electrodes used. EDM actually is a process of utilizing the removal phenomenon of electrical-discharge in dielectric. Therefore, the electrode plays an important role, which affects the material removal rate and the tool wear rate [2].

Figure 1 illustrates the basic components of the EDM process.

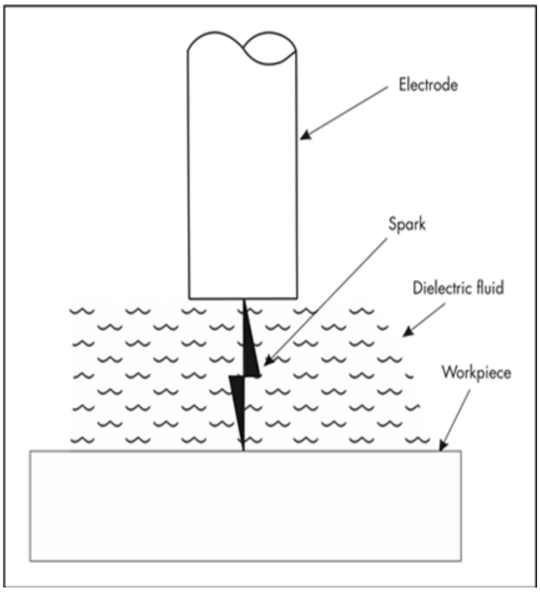

Figure 1. Component of EDM process

From the above study it is concluded that there are numbers of techniques used for optimization of process parameters but in this paper we used a Taguchi's method because of its simplicity and it gives a systematic approach to optimize the process parameters.

2. Methodology

2.1. Design of Experiment

Design of Experiment methods are used in robust design for obtaining product and process conditions, which are very less sensitive to the various cause of variation to produce high quality products with low development and manufacturing cost [3].

2.2. Taguchi Method

Taguchi methods are statistical methods developed by Genichi Taguchi to improve the quality of manufactured goods, and more recently also applied to engineering, [4] biotechnology, [5][6] marketing and advertising. [7] Professional statisticians have welcomed the goals and improvements brought about by Taguchi methods, particularly by Taguchi's development of designs for studying variation, but have criticized the inefficiency of some of Taguchi's proposals. [8]

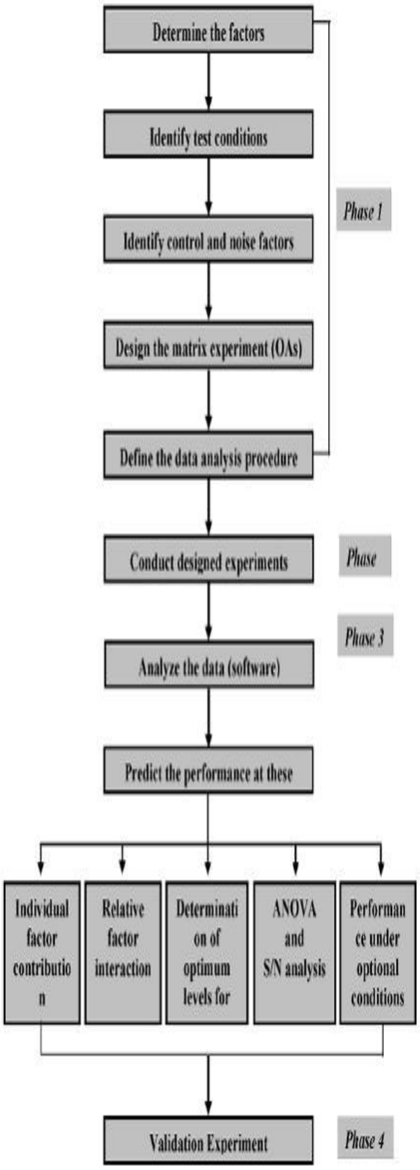

Figure 2. General Steps involved in Taguchi Method

2.3. Signal-to-noise Ratio

The experimental results are then transformed into a signal-to-noise (S/N) ratio. Taguchi recommends the use of S/N ratio to measure the quality characteristics deviating from the desired values. The S/N ratio for each level of process parameters is computed based on the S/N analysis. Generally, there are three categories of quality characteristic in the analysis of the S/N ratio, i.e. smaller-is-better, larger-is-better, and nominal-is-better.

In this paper we used smaller-is-better type quality characteristic in the analysis of the S/N ratio.

S/N Ratio for TWR using smaller-is-better,

$$\frac{S}{N} = -10 \log \left[\frac{\Sigma(yi2)}{n}\right]$$

Where n is the number of observations and y_i is the number of observed data.

2.4. Plan of Experiment

In the present study L_9 standard orthogonal array has been used which is attributed to its suitability for 3 level problems. On the basis of Taguchi method four factors with three levels of each are selected and, the L_9 array has been made for calculating the TWR. From the range of acceptable values of various selected factors we have been selected the following suitable level values of various factors.

Table 1. EDM process parameters and their levels

	Machining Parameters	Level 1	Level 2	Level 3
A	Peak current in Ampere (I_p)	1	3	5
B	Gap voltage in Volts (V_g)	20	40	60
C	Pulse on time in Micro-sec (T_{on})	120	150	180
D	Duty cycle (η)	0.4	0.5	0.6

Table 2. L_9 array table for DOE based on Taguchi Method

Experiment No.	I_p	V_g	T_{on}	η
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	2	3
9	3	3	1	1

2.5. Experimental Setup

Experiments have been conducted on Super cut 3822 model Electronica. The following are the specification of the EDM machine used during the experimentation,

Table 3. Specification of EDM

Specification	Description
Maximum work piece size	400×400×200 (mm×mm×mm)
Maximum work piece weight	300 kg.
Main table traverse	300×400 (mm×mm)
Resolution	0.0005 mm
Peak current range	1-20 Ampere
Gap voltage range	10-120 Volts
Pulse duration range	0.2-500 micro-sec.
Dielectric fluid	Kerosene
Tank capacity	250 Lt.
Cooling system	2000 K-Cal.
Connecting load	10 KVA
Total heat generated	10 K-Cal./Hours

Figure 3. EDM machine used in experimentation

The material used for the tool in the experiment is 'Cu-Cd (copper-cadmium)' and widely used in industries for the tooling of EDM.

Table 4. Properties of Tool Material (Copper-Cadmium)

Properties	Description
Thermal Conductivity	391 W/m-k
Melting Point	1083°C
Electrical Resistivity	1.69×10^{-2} ohm-m
Specific Heat Capacity	0.385 J/gm.-°C
Size of Sample	Dia.-8mm, Height-30mm

The work piece material used in the experiment is 'carbon fiber' which has a very high strength to weight ratio.

Table 5. Properties of Work Piece (Carbon-Fiber)

Properties	Description
Number of Layers	48
Thickness of Each Layers	0.2 mm
Volume Fraction	70%C
Resin	LY556 (Phenolic)
Hardness	154 DDS
Epoxy	427 gm.
Solvent	Ethyl Methyl Ketone
Size of Sample	30×20×9.6(mm×mm×mm)

The dielectric fluid used in this experiment is 'kerosene'.

Table 6. Properties of Dielectric fluid (Kerosene)

Properties	Description
Dielectric Strength	14 to 22 MV/m
Dynamic Viscosity	1.64 gm./m-sec.
Thermal Conductivity	0.149 W/m-k
Specific Heat Capacity	2.16 J/g-k

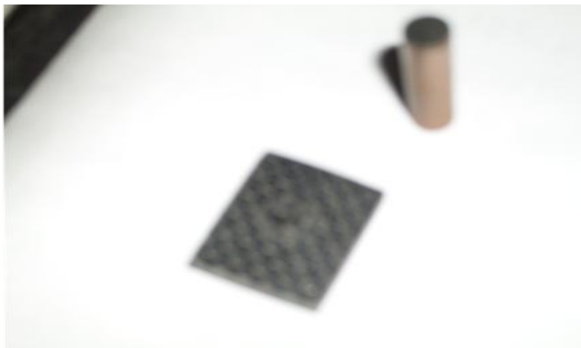

Figure 4. Tool and Work piece after machining

2.6. Mathematical Analysis

The weight loss has been calculated by weighing the electrode (Tool) before and after performing the machining. TWR can be calculated as follows,

$$\mathrm{TWR} = \frac{\text{Weight reduction on tool during machining}}{\text{Time taken in machining}}$$

3. Results and Discussion

Table 7 shows the entire experimental results about the TWR at different experiment number with different tools. The values of TWR are found to be between 0.000026 and 0.000358 gm. /minute.

Table 7. TWR for various experiments

Exp No.	Wt. before m/c	Wt. after m/c	Mat. Removed	Time of Exp.	TWR (gm./min)
1	12.0467	12.0412	0.0055	120	0.000045
2	12.0986	12.0956	0.0030	112	0.000026
3	12.1045	12.0996	0.0049	98	0.000050
4	12.1067	12.1012	0.0055	105	0.000052
5	11.9864	11.9814	0.0050	85	0.000058
6	11.9969	11.9909	0.0060	78	0.000076
7	12.1382	12.1298	0.0084	54	0.000155
8	12.1416	12.1302	0.0114	46.3	0.000246
9	12.0853	12.0731	0.0122	34	0.000358

Table 8 shows the S/N ratio of TWR in which TWR is to be considered as Smaller-is-better.

Table 8. S/N Ratio for TWR

Exp. No.	I_p	V_g	T_{on}	η	TWR (S/N)
1	1	20	120	0.4	86.93
2	1	40	150	0.5	91.70
3	1	60	180	0.6	86.02
4	3	20	150	0.6	85.67
5	3	40	180	0.4	84.73
6	3	60	120	0.5	82.38
7	5	20	180	0.5	76.19
8	5	40	120	0.6	72.18
9	5	60	150	0.4	68.92

3.1. Response effect for Signal-to-noise ratios of TWR

Table 9 shows the response effect for signal-to-noise ratio of TWR. Which is defined as the mean value of S/N ratio at each level of parameters.

Table 9. Response effect for Signal-to-noise ratio of TWR

Level	I_p	V_g	T_{on}	η
1	88.21	82.93	80.49	80.91
2	84.26	82.87	82.09	83.42
3	72.43	79.10	82.31	81.29
Delta	15.78	3.83	1.82	3.23
Rank	1	2	4	3

The difference of maximum and minimum mean S/N ratio indicates the significance of the process parameters, greater the difference, greater will be the significance.
Table 9 shows that the peak current (I_p) contributes most significantly towards TWR as the difference value is highest, followed by gap voltage (V_g), duty cycle (η) and pulse on time (T_{on}).
Process parameters setting with the highest S/N ratio always yield the optimum quality with minimum variance. So the optimum combination of process parameters is $A_1B_1C_3D_2$.

Following mean S/N ratio graphs are obtained for different process parameters using MINITAB software.

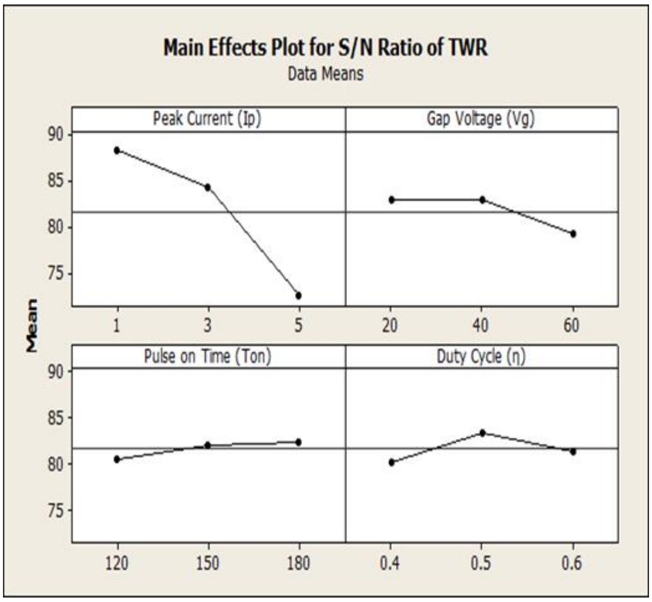

Figure 5. Mean S/N ratios graph

- As the Peak Current increases the mean S/N ratio decreases.
- As the Gap Voltage increases the mean S/N ratio is first constant, after that it decreases gradually.
- As the Pulse on Time increases the mean S/N ratio increases.
- As the Duty cycle increases the mean S/N ratio increases but after the second level it decreases gradually.

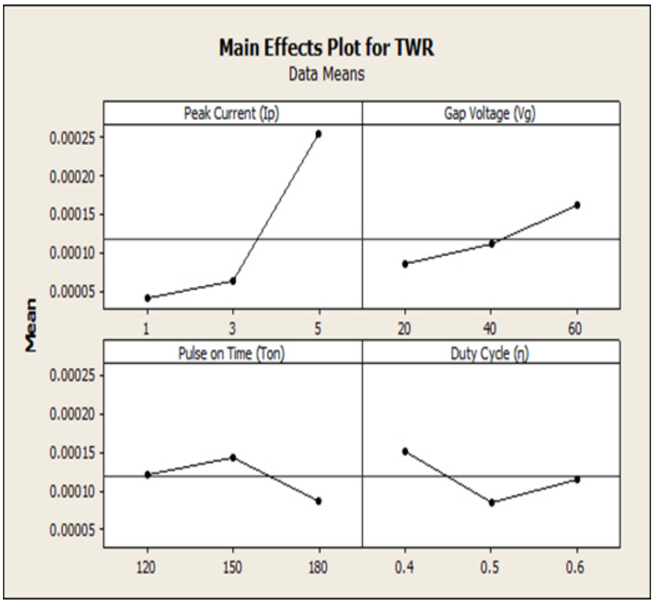

Figure 6. Main effect plot for TWR

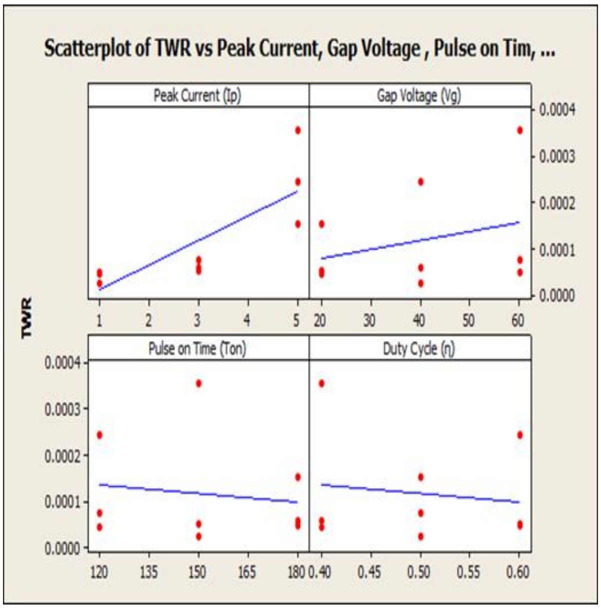

Figure 7. Scatter plot of TWR with four variables

From the scatter plot of TWR it is clear that TWR increases with the increase in the value of Peak Current and Gap voltage. And TWR decreases with the increase in the value of Pulse on Time and Duty Cycle.

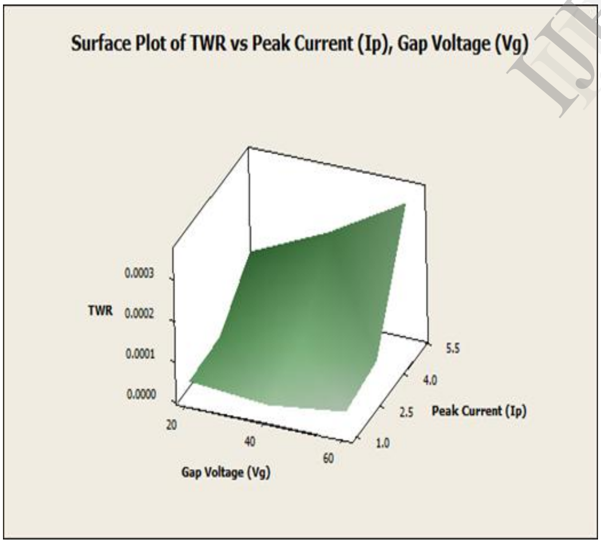

Figure 8. Surface plot of TWR with Peak Current and Gap Voltage

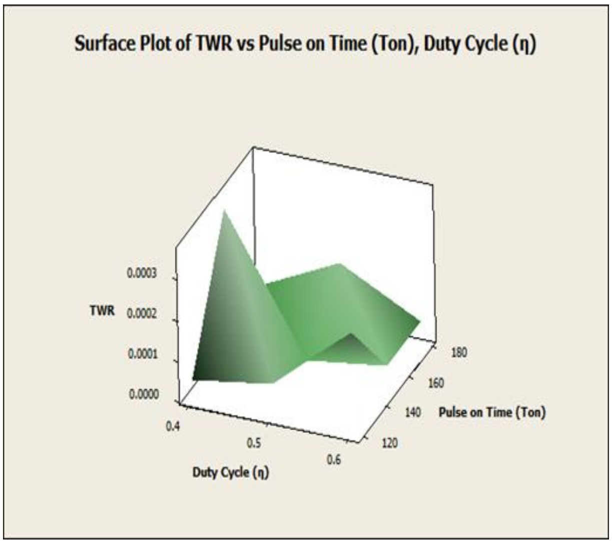

Figure 9. Surface plot of TWR with Pulse on Time and Duty Cycle

3.2. Response Surface Methodology

Response Surface Methodology is a hybrid mathematical and statistical method in which a response of interest is affected by several variables and the objective is to optimize this response [9].
The response factors can be associated with the process parameters by the following relationship:

$$Y = B_0 + B_1X_1 + B_2X_2 + B_3X_3 + B_4X_4 + \delta + \ldots + B_nX_n$$

Here,
Y = the predicted value
$B_0, B_1, B_2 \ldots B_n$ = Model coefficients
$X_1, X_2, X_3 \ldots X_n$ = several variables in the experiment

In this study, a second order polynomial was selected to develop empirical equations to represent responses in term of controllable variables,

$$Y = B_0 + B_1X_1 + B_2X_2 + B_3X_3 + B_4X_4 + B_5X_1X_2 + B_6X_2X_3 + B_7X_3X_4 + B_8X_1^2 + B_9X_2^2 + B_{10}X_3^2 + B_{11}X_4^2 + \delta \ldots$$

$$TWR = 0.000048 + 0.000106\, I_p + 0.000039\, V_g - 0.000017\, T_{on} - 0.000019\, \eta + 0.000085\, I_p^2 + 0.000013\, V_g^2 - 0.000040\, T_{on}^2 + 0.000049\, \eta^2$$

3.3. Analysis of Variance (ANOVA)

This method was developed by Sir Ronald Fisher in the 1930s as a way to interpret the results from agricultural experiments. ANOVA is a statistically based, objective decision making tool for detecting any differences in average performance of groups of items tested. The purpose of the ANOVA is to investigate which design Parameters significantly affect the quality characteristic. An ANOVA table consists of sum of squares, corresponding degree of freedom, the F ratio corresponding to the ratio of two mean square and the contribution proportions from each of the control factors. Table 10 shows the results of the ANOVA for TWR. From the ANOVA analysis it is clear that parameters Peak Current (I_p) has significant effect on TWR at 95% confidence level.

Factor Symbol	Parameters	DOF	Sum of Square	Mean Square	F	Contribution (%)
A	I_p	2	0.0000000821	0.00000004105	2.66	69.22
B	V_g	2	0.0000000092	0.00000000460	0.29	7.75
C	T_{on}	2	0.0000000050	0.00000000250	0.16	4.21
D	η	2	0.0000000069	0.00000000345	0.22	5.81
	Error	4	0.0000000154	0.00000000385		12.98
	Total	8	0.0000001186			

4. Conclusion

In this experiment it is planned to study the effect of parameters like Peak Current, Gap Voltage, Pulse on Time and Duty Cycle and their interaction for minimization of TWR using Taguchi Method.
Following conclusions can be derived based on the obtained results:

- From Table 9 the optimal combination of process parameter is $A_1B_1C_3D_2$ and peak current (Ip) contributes most significantly towards TWR as the difference value is highest, followed by gap voltage (Vg), duty cycle (η) and pulse on time (Ton).

- From the ANOVA analysis it is clear that parameters Peak Current (Ip) has significant effect on TWR at 95% confidence level.

5. References

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