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Research Article

# Process Parameter Optimization for Maximum Material Removal Rate in High Speed Electro-Discharge Machining

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***Abstract***

*The objective of this paper is to determine the optimal combination of the process parameters in a high speed electro-discharge machining (EDM) while machining carbon fiber epoxy composite with the copper-cadmium tool. The parameters considered are peak current, gap voltage, pulse-on-time and duty cycle; whereas the response is material removal rate (MRR). The optimal setting of the parameters are determined through experiments planned, conducted and analyzed using the Taguchi method followed by regression analysis. In Taguchi's design of experiment three levels of each parameter has been taken into consideration by using standard $L_9$ orthogonal array to find out optimal setting of machining parameter for maximum material removal rate. A relationship among selected process parameters is developed doing regression analysis with the help of MINITAB 15 software.*

***Keywords:*** *EDM, Taguchi Method, MRR, MINITAB 15*

## 1. Introduction

EDM has achieved a status of being nearly indispensable in the industry because of its ability to machine any electrically conductive material irrespective of its mechanical strength. EDM is a spark erosion process involves submerging two conductive materials, the cutting tool, which is the electrode or spark, and the work piece, a hard metal which needs to be precisely bored or shaped, in a non-conductive liquid (a dielectric). The material removal in EDM mainly occurs due to formation of shock waves as the plasma channel collapse owing to discontinuation of applied potential difference. Material is removed from the work piece through localized melting and vaporization of material. EDM is commonly used in mold and die making industry and in manufacturing automotive, aerospace and surgical components. Since there is no mechanical contact between the tool and the work piece, thin and fragile components can be machined without the risk of damage. Because of the nature of EDM process, optimization of the process parameters is required, in order to achieve the desirable performance specification.

In machinability studies investigations, statistical design of experiment is used quite extensively. Statistical design of experiment refers to the process of analyzing appropriate data by statistical methods to get valid and objective conclusions. Taguchi's parameter design is totally based on statistical design of experiments. It offers a simple and systematic approach to optimize design for performance, quality and cost. Some of the previous works that used the Taguchi method as tool for design of experiment in various areas including turning, drilling, grinding are listed in refs (S.H. Lee et al., 2001; T. Masuzawa et al., 1989; P.J. Davim, 2001; W.H. Yang et al., 1998; K.N. Anand, 1999; D.C. Montgomery, 2001).

## 2. Literature Review

Haron C. et al. (2001) investigated the influence of machining parameters when machining tool steel using EDM and observed that low current was suitable for small diameter electrode and high current for big diameter electrode. Her and Weng (2002) performed a study of the electrical discharge machining of semi-conductor Barium Titanate ($BaTiO_3$) and understood that for the EDM of semi-conductor $BaTiO_3$ positive polarity machining should be selected to ensure better surface roughness, minimum surface roughness can be achieved using GA, and to avoid the work piece being broken the discharge current cannot exceed 0.25 A and the on-pulse cannot exceed 10μs. Lee et al. (2003) presented a study of the relationship between EDM parameters and surface cracks by using a full factorial design, based upon discharge current and pulse-on time parameters on D2 and H13 tool steels as materials. They found that when the pulse current is increased, the increase in material removal rate. Luis et al., (2004) has define the optimization of machining parameter for EDM of Boron carbide of conductive ceramic materials. Results shows that the intensity and

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pulse time factor were the most important in case of SR while the duty cycle factor was not significant at all. The intensity factor was again influential in case of TWR. The important factors in case of MRR were the intensity followed by duty cycle and the pulse time. Marafona et al. (2006) developed a thermal-electrical model for sparks generated by electrical discharge in a liquid media. Copper and iron are the materials used for anode and cathode, respectively. The Finite Element Analysis (FEA) results were compared with the experimental values used by other researchers. Pradhan and Biswas (2008) investigated the relationships and parametric interactions between the three controllable variables on the material removal rate (MRR) using RSM method. Experiments were conducted on AISI D2 tool steel with copper electrode and three process variables (factors) as discharge current, pulse duration, and pulse off time. The significant coefficients were obtained by performing analysis of variance (ANOVA) at 5% level of significance. It was found that discharge current, pulse duration, and pulse off time significant effect on the MRR.

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 Taguchi Method*

Taguchi method was developed by Dr. Genichi Taguchi of Japan. The overall objective of the method is to produce high quality product at low cost to the manufacturer. The experimental design proposed by Taguchi involves using orthogonal arrays to organize the parameters affecting the process and the levels at which they should be varies. Orthogonal Arrays (often referred to Taguchi Methods) are often employed in industrial experiments to study the effect of several control factors (Taguchi, 1990).

### *2.2 Signal-to-Noise Ratio (S/N Ratio)*

The experimental results are then transformed into a signal-to-noise (S/N) ratio. Dr. Taguchi's S/N ratio, which are 'Log' function of desired output serve as objective function for optimization, help in data analysis and prediction of optimal result. 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, higher-is-better, and nominal-is-better. In the present experimental design, the higher-is-better type quality characteristics is used which is expressed as:

$$\frac{S}{N} Ratio = -10\ Log\left(\frac{1}{n}\right)\sum_{i=1}^{n}\frac{1}{y_i^2} \quad (1)$$

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

Taguchi suggested a standard procedure for optimizing any process parameters (Phadke, 1989)

The steps involved are:

- Determination of the quality characteristic to be optimized.
- Identification of the noise factors and test conditions.
- Identification of the control factors and their alternative levels.
- Designing the matrix experiment and defining the data analysis procedure.
- Conducting the matrix experiment.
- Analyzing the data and determining the optimum levels of control factors.
- Predicting the performance at these levels.

## 3. Work Plan

### *3.1 Selection of Process Parameters and Their Levels*

For the present experimental work the four process parameters each at three levels have been decided. It is desirable to have three minimum levels of process parameters to reflect the true behavior of output parameters of study. The process parameters are renamed as factors and they are given in the adjacent column. The levels of the individual process parameters/factors are given in Table 1.

**Table 1** Process Parameters and their Level

| Factors | Parameters | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|
| A | Peak Current ($I_p$) | 1 | 3 | 5 |
| B | Gap Voltage ($V_g$) | 20 | 40 | 60 |
| C | Pulse-on-time ($T_{on}$) | 120 | 150 | 180 |
| D | Duty Cycle (η) | 0.4 | 0.5 | 0.6 |

As per Taguchi experimental design philosophy a set of three levels assigned to each process parameter has two degrees of freedom (DOF). This gives a total of 8 DOF for four process parameters selected in this work. The nearest three level orthogonal array available satisfying the criterion of selecting the OA is $L_9$ having 8 DOF (Ross 1988). For each trial in the $L_9$ array, the levels of the process parameters are indicated in Table 2.

**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 | 1 | 3 |
| 9 | 3 | 3 | 2 | 1 |

## 4. Experimental Setup

### *4.1 Specification of EDM Machine*

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

- Maximum work piece size = 400×400×200 (mm × mm × mm)
- Maximum work piece weight = 300 kg
- Peak current range = 1 to 20 Amp.
- Gap voltage range = 10 to 20 Volts
- Pulse duration range = 0.2 to 500 μ sec.
- Tank capacity = 250 liter
- Cooling system = 2000 K-Cal.

**Fig. 1** EDM Machine used in Experimentation

### *4.2 Properties of Work piece Material*

The work piece material used in the experiment is ‘Carbon fiber epoxy composites’ which has a following properties,

- Number of Layers = 48
- Thickness of Each Layers = 0.2 mm
- Volume Fraction = 70%C
- Tensile Strength = 1550 MPa
- Specific Strength = 2457 KN-m/Kg.
- Thermal Conductivity = 24 W/m.K
- Size of Sample = 30×20×9.6(mm ×mm × mm)

**Fig. 2** Workpiece Material (Carbon Fiber Epoxy Composites)

### *4.3 Properties of Tool Material*

The tool used in the experiment is of ‘Copper-Cadmium’ which is widely being used in industries for tooling of EDM. The properties of ‘Cu-Cd’ are as follows,

- Thermal conductivity = 391 W/m-°K
- Melting Point = 1083 °C
- Resistivity = 0.009-0.07 ohm-cm × $10^{-4}$
- Specific heat capacity = 0.385 J/gm.-°C
- Size of sample = 8mm (Dia.), 30mm (Height)

**Fig. 3** Copper-Cadmium Tool used in Experimentation

## 5. Machining Performance Evaluation

The weight loss has been calculated by weighing the samples before and after performing the EDM. The MRR can be calculated as follows,

$$\text{MRR} = \frac{\text{Weight reduction on work piece during machining}}{\text{Time taken in machining}} \quad (2)$$

## 6. Experimental Results and Discussion

Table 3 shows the entire experimental results about the MRR at different experiment number. The value of MRR is found to be between 0.000432 to 0.002036 g/minute.

Figure 4 shows the workpiece material after machining. Precision balance was used to measure the weight of the workpiece. This machine capacity is 300 gram and accuracy is 0.001 gram and Brand: SHINKO DENSHI Co. LTD, JAPAN, Model: DJ 300S. (Figure 5)

**Fig. 4** Workpiece Material after Machining

**Fig. 5** Electronic Balance weight machine

**Table 3** MRR for Various Experiment Number

| Exp. No. | Wt. before m/c | Wt. after m/c | Material Removed (In gram) | Time of exp. (In min.) | MRR (gm./min) |
|---|---|---|---|---|---|
| 1 | 5.8755 | 5.8219 | 0.0536 | 124 | 0.000432 |
| 2 | 7.1171 | 7.0633 | 0.0538 | 110 | 0.000489 |
| 3 | 6.0917 | 6.0350 | 0.0567 | 95 | 0.000597 |
| 4 | 6.4796 | 6.4215 | 0.0581 | 82 | 0.000710 |
| 5 | 6.1350 | 6.0716 | 0.0634 | 74 | 0.000860 |
| 6 | 5.7759 | 5.7092 | 0.0667 | 61.5 | 0.001085 |
| 7 | 6.2713 | 6.2063 | 0.0650 | 49 | 0.001327 |
| 8 | 6.0092 | 5.9474 | 0.0618 | 38.66 | 0.001599 |
| 9 | 6.3130 | 6.2482 | 0.0648 | 32 | 0.002036 |

Table 4 shows the S/N ratio of MRR in which MRR is to be considered as Higher-is-better type characteristics.

**Table 4** S/N Ratio for MRR

| Exp. No | $I_p$ | $V_g$ | $T_{on}$ | η | MRR(S/N) |
|---|---|---|---|---|---|
| 1 | 1 | 20 | 120 | 0.4 | -67.29 |
| 2 | 1 | 40 | 150 | 0.5 | -66.21 |
| 3 | 1 | 60 | 180 | 0.6 | -64.48 |
| 4 | 3 | 20 | 150 | 0.6 | -62.97 |
| 5 | 3 | 40 | 180 | 0.4 | -61.31 |
| 6 | 3 | 60 | 120 | 0.5 | -59.29 |
| 7 | 5 | 20 | 180 | 0.5 | -57.54 |
| 8 | 5 | 40 | 120 | 0.6 | -55.92 |
| 9 | 5 | 60 | 150 | 0.4 | -53.82 |

*6.1 Response Effect for Signal-to-Noise Ratio of MRR*

A greater value of S/N ratio is always considered for better performance irrespective of the category of performance characteristics. 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 5 shows that the peak current (Ip) contributes most significantly towards MRR as the difference value is highest, followed by gap voltage (Vg), duty cycle (η) and pulse on time (Ton).

**Table 5** Response effect for Signal-to-noise ratio of MRR

| Level | $I_p$ | $V_g$ | $T_{on}$ | η |
|---|---|---|---|---|
| 1 | -65.99 | -62.60 | -60.83 | -60.80 |
| 2 | -61.19 | -61.14 | -61.00 | -61.01 |
| 3 | -55.76 | -59.19 | -61.11 | -61.12 |
| Max-Min | 10.23 | 3.41 | 0.28 | 0.32 |
| Rank | 1 | 2 | 4 | 3 |

*6.2 Effect on MRR*

In order to see the effect of process parameters on MRR, experiments were conducted using $L_9$ OA (Table 2).

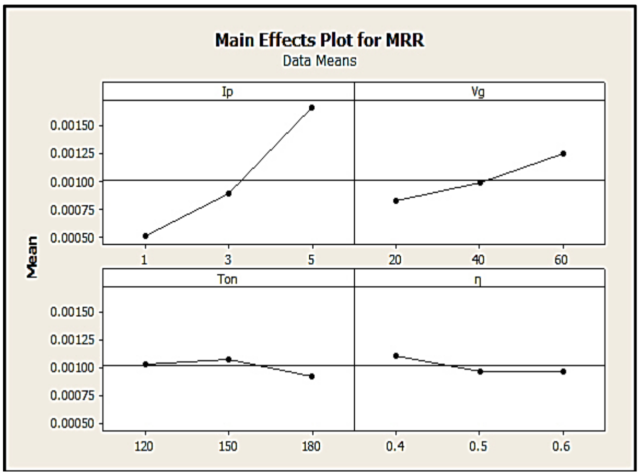


**Fig. 6** Main Effect Plot for MRR (Raw Data)

The experimental data is given in Tables 3. The average values of MRR for each parameter at levels 1, 2 and 3 for raw data and S/N data are plotted in Figures 6 and 7 respectively.

The peak current (Ip) is directly proportional to MRR in the range of 1 to 3A. This is expected because an increase in peak current produces strong spark, which produces the higher temperature, causing more material to melt and erode from the work piece. Besides, it is clearly evident that the other factor does not influence much as compared to Ip and similar conclusions were shown by Ghoreishi and Tabari. However, MRR decreases monotonically with the increase in duty cycle (Ghoreishi et al. 2007)

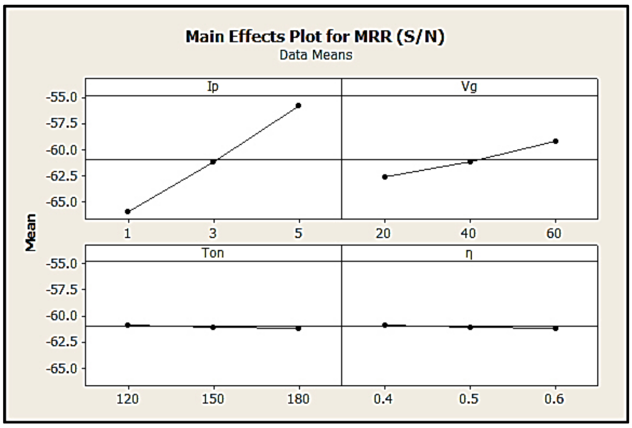


**Fig. 7** Main Effect Plot for S/N ratio of MRR

Figure 8 shows the scatterplot of MRR with peak current, gap voltage, pulse-on-time and duty cycle. MRR increases with increase in the value of peak current and gap voltage and it decreases with increase in the value of pulse-on-time and duty cycle.

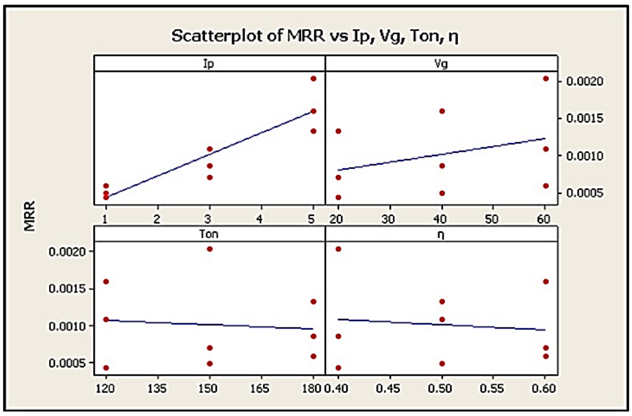


**Fig. 8** Scatter Plot of MRR

Figure 9 shows the four plots viz. Normal probability plot, residual vs fit, histogram and residual vs order. This layout is useful to determine whether the model meets the assumptions of the analysis.

The residual plots in the graph and the interpretation of each residual plot indicate below:

- Normal probability plot indicates the data are normally distributed and the variables are influencing the response.
- Residuals versus fitted values indicate the variance is constant and a nonlinear relationship exists as well as no outliers exist in the data.
- Histogram proves the data are not skewed and not outliers exist.
- Residuals versus order of the data indicate that there are systematic effects in the data due to time or data collection order.

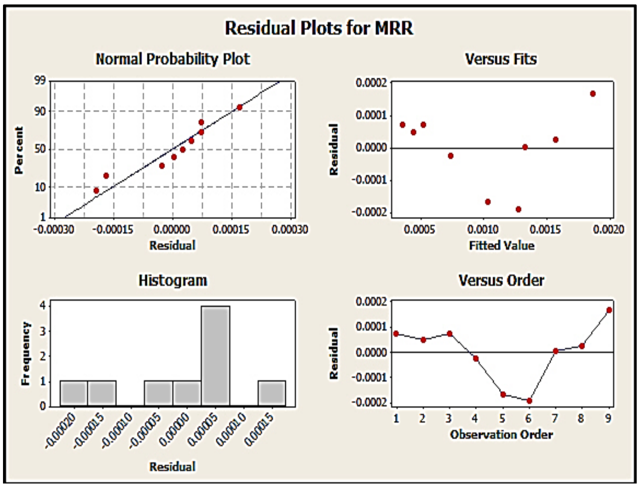


**Fig. 9** Residual Plot of MRR

*6.3 Selection of Optimal Level*

In order to selection of optimal levels of the process parameters towards MRR, the response table was employed. The response tables (Table 5) show the average of each response characteristic (S/N data, means) for each level of each factor. The tables include ranks based on delta statistics, which compare the relative magnitude of effects. The delta statistic is the highest minus the lowest average for each factor. Minitab assigns ranks based on delta values; rank 1 to the highest delta value, rank 2 to the second highest, and so on. The ranks indicate the relative importance of each factor to the response. The ranks and the delta values show that peak current have the greatest effect on MRR, followed by gap voltage, duty cycle and pulse-on-time in that order.

As MRR is the 'Higher is better' type quality characteristic, it can be seen from Figure that the third level of peak current ($A_3$), third level of gap voltage ($B_3$), first level of pulse-on-time ($C_1$), and first level of duty cycle ($D_1$) provide maximum value of MRR in EDM process.

*6.4 Regression Analysis of MRR*

In this work the functional relationship between the process response (MRR) and four machining parameters (Peak current, Gap voltage, Pulse-on-time and Duty cycle) is established using regression analysis. The linear functional relationship between the process response and different machining parameters is predicted from the MINITAB 15 statistical software using the experimental data. The multiple linear regression equation for MRR is given as,

$$MRR = 0.000366 + 0.000287\, I_p + 0.000010\, V_g - 0.000002\, T_{on} - 0.000703\, \eta$$

The developed mathematical models are checked for their adequacy using ANOVA and normal probability plot of residuals.

*6.4.1 Model Analysis of MRR*

The coefficients of model for MRR are shown in Table 6. The parameter $R^2$ describes the amount of variation observed in MRR is explained by the input factors. $R^2$ = 95.4 % indicate that the model is able to predict the response with high accuracy. Adjusted $R^2$ is a modified $R^2$ that has been adjusted for the number of terms in the model. If unnecessary terms are included in the model, $R^2$ can be artificially high, but adjusted $R^2$ (=90.9 %.) may get smaller. The standard deviation of errors in the modeling, S= 0.000165206. Comparing the p-value to a commonly used α-level = 0.05, it is found that if the p-value is less than or equal to α, it can be concluded that the effect is significant (shown in bold), otherwise it is not significant.

**Table 6** Estimated Model Coefficients for MRR

| Predictor | Coef. | SE Coef. | T | P |
|---|---|---|---|---|
| Constant | 0.0003660 | 0.0005088 | 0.72 | 0.512 |
| $I_p$ | 0.00028700 | 0.00003372 | 8.51 | **0.001** |
| $V_g$ | 0.00001041 | 0.00000337 | 3.09 | **0.037** |
| $T_{on}$ | -0.00000184 | 0.00000225 | -0.82 | 0.458 |
| η | -0.0007033 | 0.0006745 | -1.04 | 0.356 |
| S = 0.000165206 | R-Sq = 95.4% | | R-Sq(adj) = 90.9% | |

The analysis of variance (ANOVA) indicates that both the variance ratio (F) and P value are used to measure the significance of the regression under investigation. On comparing the p-value to a commonly used α-level = 0.05, it is found that the p-value for regression is less than 0.05. So, on the basis of this p-value, it can be concluded that there is a good correlation between the predicted and the experimental values.

**Table 7** Analysis of Variance

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Regression | 4 | 2.28491E-06 | 5.71227E-07 | 20.93 | 0.006 |
| Residual Error | 4 | 1.09172E-07 | 2.72931E-08 | - | - |
| Total | 8 | 2.39408E-06 | - | - | - |

*6.4.2 Predictive Performance of the Developed Model*

On comparing the experimental and regression values of MRR, it is found that there is a good correlation between the predicted and the experimental values.
Figure 10 shows the comparison of results for MRR. The average error percentage for MRR is 12.18 %.

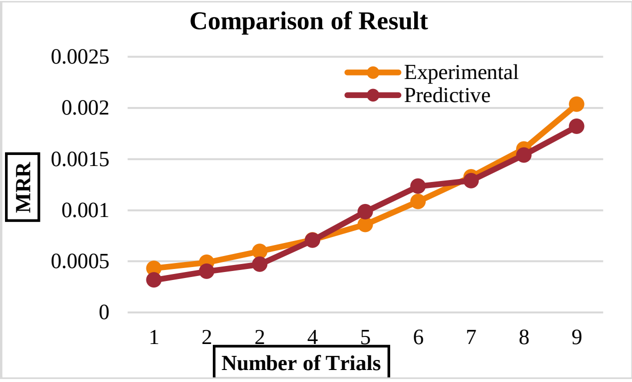


**Fig. 10** Comparison of Results for MRR

## Conclusions

Taguchi method provides a systematic and efficient methodology for the parametric design with far less effort than would be required for most optimization techniques.
Based on the experimental results, the following conclusion can be drawn:

- Optimal Combination of process parameter is $A_3B_3C_1D_1$.
- Peak current ($I_p$) contributes most significantly towards MRR as the difference value is highest, followed by gap voltage ($V_g$), duty cycle (η) and pulse on time ($T_{on}$).
- In the residual plot of MRR, the residuals spread on a straight line implies that the errors are distributed normally.
- Scatterplot shows that MRR increases with increase in the value of peak current and gap voltage and it decreases with increase in the value of pulse-on-time and duty cycle.
- Form the ANOVA for regression (Table 7), it is found that the p-value for regression is less than 0.05. So, on the basis of this p-value, it can be concluded that there is a good correlation between the predicted and the experimental values.
- On comparing the experimental and regression values, the average error percentage for MRR is 12.18%.

## References

S.H. Lee, X.P. Li, (2001), Study of the effect of machining parameters on the machining characteristics in electrical discharge machining of tungsten carbide, *Journal of Material Processing Technology*, Vol. 115, pp. 344-358.

T. Masuzawa, C.L. Kuo, M. Fjino, (1989), Deep micro-holes by EDM, *Ann. CIRP*, Vol. 38, pp. 195-198.

W.H. Yang., Y.S. Tarng, (1998), Design optimization of the cutting parameters for turning operation based on the Taguchi method, *Journal of Material Processing Technology*, Vol. 84, pp. 122-129.

K.N. Anand, (1999), Development of process specifications for improving the surface finish in the steel grinding operation, *Total Quality Management*, Vol. 10, pp. 1169-1177.

D.C. Montgomery, (2001), Design and analysis of experiment, *John Wiley & Sons. Inc. 5 edition*.

G. Taguchi, (1990), Introduction to quality Engineering, *Asian productivity organization, Tokyo*.

C. Haron, Md. B. Deros, A. Ginting, (2001), Investigation on the influence of machining parameters when machining tool steel using EDM, *Journal of Materials Processing Technology*, Vol. 116, pp.84-87.

M. Her, F. Weng (2002), A study of the electrical discharge machining of semi-conductor BaTiO3, *Journal of Materials Processing Technology*, Vol.122, pp.1-5.

H.T. Lee, T.Y. Tai, (2003), Relationship between EDM parameters and surface crack formation, *Journal of Materials Processing Technology*, Vol. 142, pp.676-683.

I. Puertas, C.J, Luis, (2004), A study of optimization of machining parameters for electrical discharge machining of boron carbide, *Materials and Manufacturing Processes*, Vol. 19, pp.1041-1070.

J. Marafona, J.A.G. Chousal, (2006) A finite element model of EDM based on the Joule effect, *International Journal of Machine Tools & Manufacture*, Vol. 46, pp.595-602.

M.K. Pradhan., C.K. Biswas, (2008), Modeling of machining Parameters for MRR in EDM using response surface methodology, *Proceedings of NCMSTA' 08 Conference (National Conference on Mechanism Science and Technology, from Theory to Application)*, NIT Harripur, India.

S.M. Phadke, (1989), Quality engineering using robust design, *Englewood Cliffs, N.J: Prentice Hall*.

P.J. Ross, (1988), Taguchi techniques for quality engineering, *McGraw-Hill Book Company, New York*.

M. Ghoreishi, C. Tabari, (2007). Investigation into the effect of voltage excitation of pre-ignition spark pulse on the electro-discharge machining (edm) process. *Materials and Manufacturing Processes*, Vol. 22, pp. 833–841.