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Optimisation of CNC wire EDM process parameters and establishment polynomial process model for multiple performance characterestics

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ABSTRACT

CNC Wire Electric Discharge Machining is the process of material removal using electrical discharge erosion action, with a wire electrode travelling longitudinally through the work piece. The work piece and wire electrode both are immersed in a dielectric fluid. The relative moving passage between the wire electrode and work piece is controlled by a CNC system that is pre-programmed. The Wire Electrical Discharge Machining performance mainly depends on various machining parameters like generator parameters, drawing parameters and user parameters. But the most prominent parameters are generator parameters as they are very important for sparking principles. Reference Voltage (V), Pulse on-time (T_{on}), Pulse off-time (T_{off}) fluid injection pressure mode (Inj), Wire tension (WB), Wire velocity (WS) are the crucial machining process parameters which has influence on the machining performance characteristics such as Material Removal Rate (MRR), Surface Roughness (R_a), Spark Gap (SG) and Dimensional Deviation (DD) while processing / slicing of ingot. Variation in machining performances causes both functional, profit and loss for any manufacturing organisation. Hence, an attempt has been made to study and optimize these machining parameters for minimizing the variations in multiple machining performances and process model (empirical relationship/regression model) between the process parameters (V, T_{on}, T_{off}, Inj, WB, WS) and the performance characteristics (MRR, R_a, SG and DD) has been developed. These process model can predict the level of performance that the machine would render for a given set of process parameters, thereby providing prior knowledge of desired machining performance before actually producing the part. The process model is able to show the dependency of machining performance on process parameters, which will be useful for both machine designers and the machine users.

Introduction

Industries have witnessed a rapid growth in the development of harder and difficult to machine materials such as hastalloy, nitralloy, carbides, stainless steel and many other high strength temperature resistant alloys (HSTR). These materials find wide applications in aerospace, nuclear engineering and other industries owing to their high strength to weight ratio, hardness and heat resisting qualities. For such materials, the conventional edged tool machining is difficult, time consuming and sometimes impossible. Considering the seriousness of the problem, Merchant in 1960s emphasized the need for the newer concepts in metal machining called Electrical Discharge Machining (EDM). EDM is the process of material removal from any electrically conductive material by the initiation of rapid and repetitive (Non Stationary) electrical sparks between a tool and work piece connected in an electrical circuit and separated by a flowing dielectric medium. The fundamental capabilities of EDM are possible to machine any conductive material irrespective of its hardness and toughness. Thus, hard metals and alloys which cannot be machined by conventional machine can be machined by EDM. One of the types of EDM is Wire EDM (WEDM). WEDM involves a series of complex heating and cooling processes. In this case, the relative motion between the electrode and the work piece is non axial. Cutting can be done with wire, ribbon, blade or a rotating disc. Cutting using the wire is more popular and the wire is continuously fed from spools. WEDM is always carried out with wire electrode and work piece supplied with dielectric fluid. The electrode and the work piece are separated by a small gap varying from 20 micron to 1mm which is always maintained in order to initiate the spark. Because of the spark localized heating takes place increasing the temperature to the extent of 10000ºC. Thus each spark removes a small, discrete portion of material from the work piece leaving a small crater.

Gokler et al. [1], made an attempt to select the most suitable cutting and offset parameter combination for the WEDM process on 1040 steel to get the desired surface roughness value. Rozenek et al. [2], studied the effect of pulse-on time, pulse off-time, voltage on the surface roughness and machining feed rate during WEDM of metal matrix composite. Puri et al. [3], determined the influencing parameters on performances such as average cutting speed and surface finish characteristics. Tosun et al. [4], investigated the influence of voltage, wire speed and dielectric pressure on the metal removal rate. From the literature survey, it is found that the Material Removal Rate (MRR), Surface Roughness (R_a), of WEDM is an important performance characteristic and Spark Gap (SG) and Dimensional Deviation (DD) has not been addressed by many researchers.

Hence, in this paper an attempt has been made to identify the influencing (significant) parameters on the multiple machining performances and optimize these machining parameters for minimizing the variations in multiple machining

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performances and process model (empirical relationship/regression model) between the process parameters (V, T_{on}, T_{off}, Inj, WB, WS) and the performance characteristics (MRR, R_a, SG and DD) has been developed. The process model can predict the level of performance that the machine would render for a given set of process parameters, thereby providing prior knowledge of desired machining performance before actually producing the part. The process model is able to show the dependency of machining performance on process parameters, which will be useful for both machine designers and the machine users.

Experimental Setup

ROBOFIL 290P CNC WEDM was used for this study. The process considered was slicing of High Speed Steel (HSS) tool bar (AISI T-15). The tool material is taken as 0.25 mm diameter SOFT BRASS WIRE. The Dielectric fluid is deionised water and its specific resistance is maintained at 15µ Siemens/cm. Discharge Voltage is -80Volts. Spark Current is 8Amps. Cutting length is 7 mm. Work piece height set to be 10 mm. Short pulse time is set as 0.4µs. It has cutting speed ranging from 28 in^2/hr to 30 in^2/hr. The figure 1 shows the slicing of the HSS tool bar.

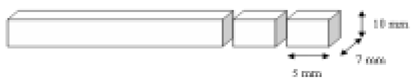


Fig. 1 - Slicing of HSS tool bar

This slicing process creates more variations in the following machining performances: Metal Removal Rate (MRR), Surface Roughness (R_a), Spark Gap (SG), and Dimensional Deviation (DD). Hence these performance characteristics have been taken for the study.

Methodology

To achieve the required performance characteristics in a specific situation, process parameters are often determined with the aid of building the test specimens. Full factorial method is one of the best methods of experimental design when there are only few factors to be considered. If there are more factors, full factorial method is time consuming and expensive. The number of experimental trials on full factorial method for six process parameters (p) with three levels (L) is 729 ($L^p = 3^6$), which is highly laborious. To overcome this, Taguchi suggested a simple, efficient and a systematic approach called Fractional factorial method in order to minimise the number of experimental runs. Also, Hefin et al. [5], says that Taguchi technique, which is based on statistical Design of Experiments (DOE), is a proven methodology to establish optimum process parameters for design of robust process and products. Montgomery [6], pointed out the Taguchi method is a more refined and advanced version of Fractional Factorial experiment in DOE. Onuch and Hon [7], suggests that Taguchi technique is the most efficient problem solving tool that can improve the product, process, design and system with a significant slash in experimental time and cost. Yang and Tarng [8], Tosun et al. [4], Kim et al. [9], Syrcos [10] and Ghani et al. [11], observed that the Taguchi technique increases the power of analysis of experimental data by complex analysis of variance (ANOVA) and an efficient way to determine the optimum facto level combination to achieve the variation at a minimum while keeping the mean on target. Concerning the power of DOE, Taguchi framework is chosen as the methodology to materialize the objectives.

Steps

Step 1: Identification of process parameters that influence on response variable / performance characteristics with expertise knowledge and brainstorming

Step 2: Setting of levels for identified parameters to conduct experiments through the following series of steps:

2.1 Selection of levels for screening experiment.

2.2 Conducting screening experiment to find the value of the response variable.

2.3 Determination of number levels (two or three) and their values to conduct main experiment.

Step 3: Selection of Orthogonal Array (OA) to design the experimental runs for main experiment by analyzing the interaction effect between the parameters.

Step 4: Experimentation for the OA setting to find the values of response variable.

Step 5: Prediction of optimal level for each parameter for the set objective with the response variable data using Signal to Noise (S/N) ratio.

Step 6: Identification of critical (most influencing) parameter for the response variable with the percentage contribution of each parameter on the response variable using ANOVA technique.

Step 7: Establishment of empirical relationship for the response variable in terms of parameters in order to estimate the values of the response variable under different parameter settings.

Selection Parameters

The WEDM machining parameters are classified into three categories such as user parameters, generator parameters and drawing parameters. The drawing parameters mainly concentrate on graphic display setting and changing. The user parameters have On/Off switch control unit to control the parameter and additionally it has the parameters list which does not fall under the category of generator parameters. The generator parameters are indirectly related to surface roughness and material removal rate. Thus Machining performance characteristics are mainly influenced by generator parameters and moderately influenced by user parameters. Figure 2 shows the various process parameters involved in CNC Wire EDM process.

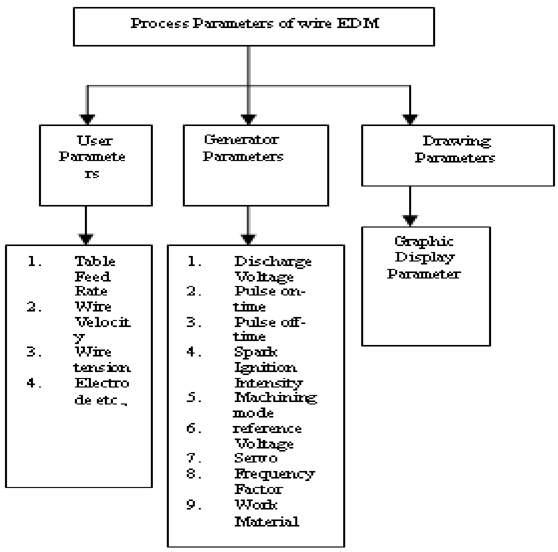


Fig.2 - Various WEDM process parameters

Apart from the literature survey, the parameters for this study are identified by consulting the experienced operators, supervisors and brainstorming. The selected controllable parameters are Reference Voltage (V), Pulse on-time (T_{on}), Pulse off-time (T_{off}), Wire Velocity (WS), Wire Tension (WB), Injection Pressure Mode (Inj) which influence the measurable machining performance characteristics Material Removal Rate (MRR), Surface Roughness (R_a), Spark Gap (SG) and Dimensional Deviation (DD)

Screening experiment

The number of experimental trials should be as minimum as possible to reduce the experimental cost and time. Screening experiment helps to reduce the number of main experiments by finding necessary levels for each parameter based on the two-way interaction effect between the parameters. Montgomery [**6**] and Ross [**12**] suggested that two extreme values of each parameter are considered for conducting screening experiment. The selected parameters (Reference Voltage (V), Pulse on-time (T_{on}), Pulse off-time (T_{off}), Wire Velocity (WS), Wire Tension (WB), Injection Pressure Mode (Inj)) are set at two levels (minimum and maximum values of parameters available in the ROBOFIL 290 CNC WEDM) for screening experiment to identify the behaviour pattern and interactions between the parameters. Table 2 shows the selected parameters and its levels.

The orthogonal array for the screening experiments is selected based on the number of parameters and the number of levels at each parameter. According to the orthogonal array concept, L_{12} standard orthogonal array was chosen for the screening experiments (Total degrees of freedom (DOF) of the screening experiment is 6 and L_{12} Orthogonal Array has the DOF of 11). Six machining parameters were chosen as control factors and each parameter was designed at two levels. Six machining parameters were assigned at first six columns. Others are considered as error columns. Table 3 indicates the details about the screening experiments.

Measurement of performances

- Surface Roughness (R_a) is measured using a surfcom 120A-TSK, a roughness measuring instrument.
- Spark Gap (SG in µm) is calculated from the equation,

$$(2*SG) + D + ET = GW, \quad (1)$$

where GW – Gap Width (mm), measured using Mitutoyo Digimatic caliper and Mitutoyo Profile Projector PH-600.

D – Diameter of the electrode wire (250 µm)

ET- Extra thickness (mm) = 0

Hence the equation becomes,

$$(2*SG) + D = GW \quad (2)$$

- Metal Removal Rate (MRR) is calculated from the equation

$$MRR = V_c * GW * h \quad (3)$$

Where V_c – mean cutting speed (mm/min), taken directly from the ROBOFIL 290 CNC WEDM machine

h – Height of the work piece (mm)

The four machining performances characteristics (Two trails in each setup), were obtained during the screening experimentation and the average value of each performances characteristics were given in the Table 4.

From the screening experiment the two way interaction between Reference Voltage & Pulse on-time and Pulse on-time & pulse off-time were analysed through the plot shown in figure 3 and figure 4.

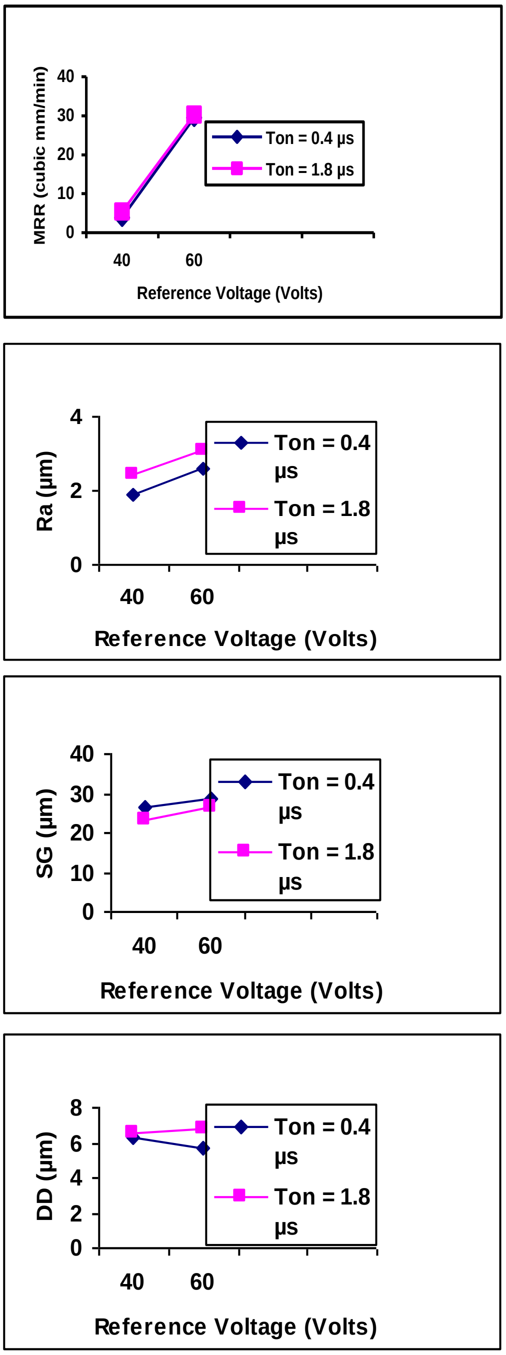
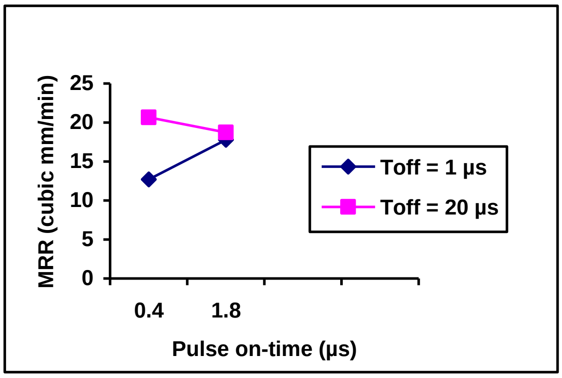


Fig. 3 - Interaction Plot between Reference Voltage and Pulse on-time (V x T_{on})



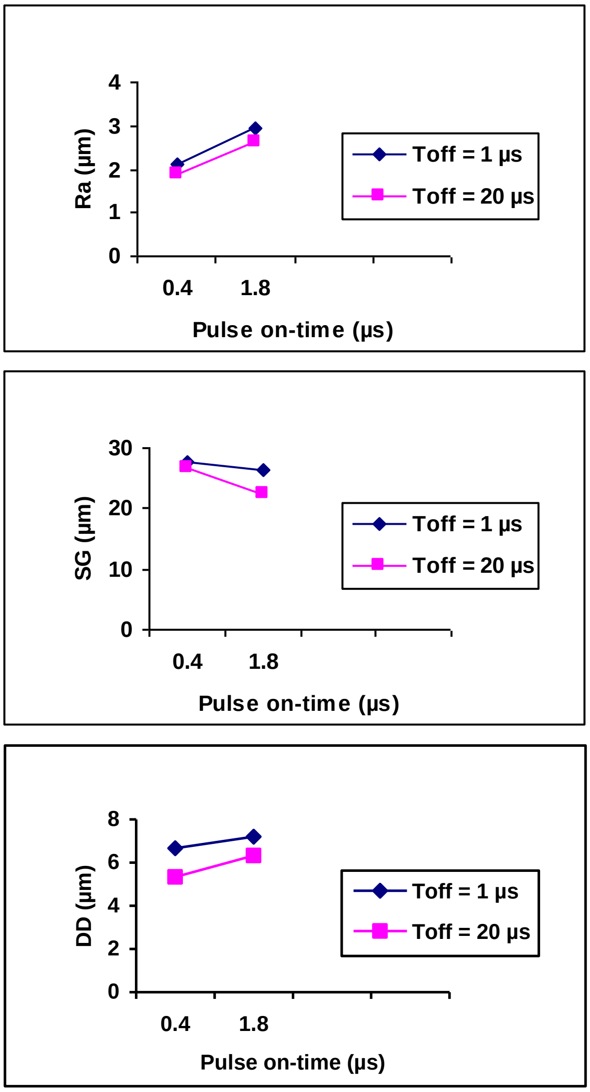


Fig. 4 - Interaction Plot between Pulse on-time and pulse off-time (T_{on} x T_{off})

From the interaction plot (figure 3 and figure 4), it is inferred that there are no two way interactions (lines do not intersect) available for selected parameters, for all multiple machining performances. Hence for the main experiment, there is no need to design any interaction column in the L_{18} orthogonal array.

Main Experiment

The orthogonal array for the main experiment is selected based on the number of factors and interactions between them and the number of levels at each factor. The nature of curve at intermediate levels will not be possible to predict if two levels are chosen, as evident from the graphs. In DOE, it is crucial to select the proper levels for the chosen controllable factors. Normally the number of levels of each factor will be based on linear or non-linear pattern of response variable. The linearity could not be assumed for all the parameters. Hence non-linearity effect is assumed and three levels are set with lower limit, higher limit and the middle of the above limits for accounting the quadratic effect of the particular process parameter on response variable. For the main experiment, L_{18} orthogonal array was used. (Each parameter has 2 DOF, totally (6 x 2) 12 DOF) the six machining parameters were arranged for the first six columns of the array. The last two columns were set as dummy columns. All the controllable parameters are set at 3 levels except 'parameter 1', because L_{18} standard array has the rule that the 'parameter 1' must have only two levels. The parameter 6 is qualitative as the injection pressure cannot be controlled in quantifiable term. It has three modes selected for experiment mode: mode1: 3.5 bar, mode2: 5.5 bar, mode3: 8.0 bar.

The levels of controllable parameters for the main experiments are divided into upper, lower and middle values of each parameter as listed in the Table 5 and the details of L_{18} orthogonal array was given in Table 6.

The values of four machining performances characteristics obtained during the main experimentation were given in Table 7.

Statistical Analysis

Signal to Noise Ratio

The control factors that may contribute to reduce variation can be quickly identified by looking at the amount of variation present as a response. Signal to noise ratio yields the effect on variation as well. The S/N ratio consolidates several repetitions (at least two data points are required) into one value that reflects the amount of variation present. The types of S/N ratios depending on the type of characteristics are: Lower is Better (LB). Nominal is Better (NB), higher is Better (HB). The equations for calculating S/N ratios for LB, NB, HB characteristics are:

Lower is Better

$$S/N\ LB\ \eta = -10*\log\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \qquad (4)$$

Nominal is Better

$$S/N_{LB}\ \eta = -10*\log\ [V_e] \qquad (5)$$

Higher is Better

$$S/N_{HB}\ \eta = -10*\log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \qquad (6)$$

Here Metal Removal Rate is taken as 'Higher is better' characteristics and Surface Roughness, Spark Gap & Dimensional Deviation are taken as 'Lower is better' characteristics and corresponding values were given in table 8.

The average values of S/N ratio (db) are shown in the Table 9.

Fig. 5, Fig. 6, Fig. 7, and Fig. 8 show the average S/N ratio with respect to the levels of all parameter for surface roughness, Spark Gap, Dimensional Deviation and Material Removal Rate respectively. The objective is maximise Metal Removal Rate during the machining and minimise Surface Roughness, Spark Gap and Dimensional Deviation. To achieve this, S/N ratio should be maximum for material removal rate and minimum for surface roughness, Spark Gap, Dimensional Deviation.

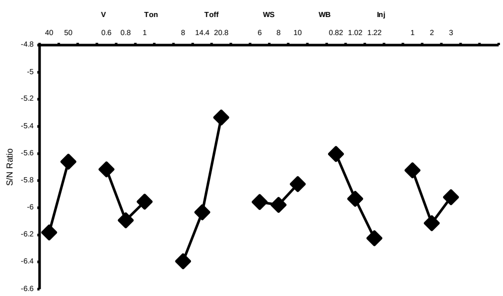


Fig. 5 - Average S/N ratio Graph for surface roughness

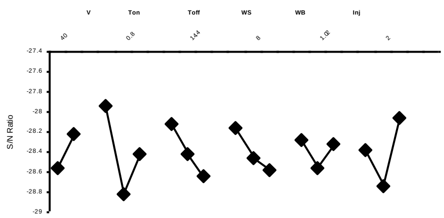


Fig. 6 - Average S/N ratio Graph for spark gap

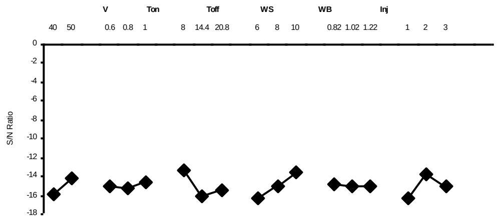


Fig. 7 - Average S/N ratio Graph for dimensional deviation

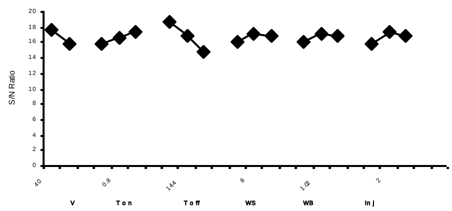


Fig. 8 - Average S/N ratio Graph for material removal rate

From the above graphs, it is noted that the robust parameters to achieve the objectives are as follows:

- For maximum Material removal rate are: V_1, T_{on3}, T_{off1}, WS_2, WB_3, Inj_2
- For minimum surface roughness are :V_2, T_{on1}, T_{off3}, WS_3, WB_1, Inj_1
- For minimum spark gap are : V_2, T_{on1}, T_{off1}, WS_1, WB_1, Inj_3
- For minimum dimensional deviations are :V_2, T_{on3}, T_{off1}, WS_3, WB_1, Inj_2

Identification of Significant Process Parameters and their Percentage of Contribution by ANOVA

The process parameter that has much influence on response variable is identified through the percentage of contribution of each parameter on it. The process parameter one which has more percentage of contribution is the significant parameter to the response variable. Yang and Tarng [8], Tosun et al. [4], Kim et al. [9], Syrcos [10], and Ghani et al. [11] have addressed that ANOVA is the methodology that is proposed and used widely for the determination of percentage of contribution. The procedural steps of ANOVA are outlined below.

Step 1: Calculation of sum of squares of the response variable (SS_{RV}).

$$SS_{RV} = \sum_{j=1}^{N} RV_j^{\,2} \quad (7)$$

Step 2: Calculation of correction factor (CF).

$$CF = \left(\sum_{j=1}^{N} RV_j \right)^2 / N \,. \quad (8)$$

Step 3: Calculation of total sum of squares (SST)

$SST = SS_{RV} - CF$ (9)

Step 4: Calculation of individual sum of squares of parameters (SS_i) (i= process parameter identifier).

Step 5: Calculation of individual sum of squares of errors (SS_E)

$SS_E = SST - SS_i$ (10)

Step 6: Set degrees of freedom (DOF) for each parameter DOF = Number of levels of parameter ‘i’ –1 (11)

Step 7: Calculation of Mean Sum of Squares of the parameters ‘i’ (MSS_i) $MSS_i = SS_i / DOF_i$- (12)

Step 8: Calculation of Mean Sum of squares of the error (MSE)$MSE = SS_E / DOF_E$ (13)

Step 9: Estimation of Variance Ratio $F_{statistic}$ for each parameter ‘i’ $F_{statistic} = MSS_i / MSE$

Step 10: Selection of $F_{tabulated}$ valve for $F_{\propto, v1, v2}$

Step 11: Comparison of $F_{statistic}$ and $F_{tabulated (\alpha, v1, v2)}$.

Step 12: Identification of Significant parameters ($F_{statistic} \geq F_{tabulated}$). (If $F_{statistic} \geq F_{tabulated}$ then that particular parameter is most significant).

Step 13: Determination of Percentage of Contribution of each parameter Percentage of contribution = P_{RV} = $(MSS_i / \sum_{i=1}^{g} MSS_i) \times 100$ (14)

Table 10, Table 11, Table 12, Table 13 show the percentage of contribution of the parameters on the performance characteristics surface roughness, Spark Gap, Dimensional Deviation and Material Removal Rate respectively.

From the ANOVA analysis, the significance of each parameter on the performance characteristics and their percentage contribution is identified. The percentage contribution of each parameter on the performance characteristics shown in Table 14, it is evident that T_{off} is the parameter having the highest percentage of contribution for all the four machining performances (MRR - 49.80 %, R_a – 42.27 %, SG – 49.80 %, DD – 49.80 %). Thus it may be concluded that the parameter T_{off} is the most significant parameter for the multiple machining performances.

Establishment of process model

ANOVA reveals that the Reference voltage, Pulse on time, Pulse off time, Wire velocity, Wire tension and Injection pressure mode are contributing significantly to the performance characteristics / Response variable like Material Removal Rate, Surface roughness, Spark gap, Dimensional deviation. But it will not say what would be the achievable performance characterises for a certain set of process variable. Hence an attempt is made to establish a process model (empirical relationship/regression model) for the performance characteristics / response variables (Material Removal Rate, Surface roughness, Spark gap, Dimensional deviation) as a function of process parameters (Reference voltage, Pulse on time, Pulse off time, Wire velocity, Wire tension and Injection pressure mode). This process model will be useful to predict how much performance can be achieved for a given set of the process parameters, thus providing prior knowledge before producing a part. Montgomery [**6**]suggests that orthogonal polynomial a useful method for developing process model (regression equation) with orthogonal array data. A quadratic polynomial model is proposed to establish process model between responsible variable of machine performance and process parameters as indicated in equation (15)

$$RV = \beta_0 + \sum_{i=1}^{g} [\beta_{1i} P_1(i) + \beta_{2i} P_2(i)] + \varepsilon \quad (15)$$

RV: Response variable (Material Removal Rate, Surface roughness, Spark gap, Dimensional deviation);

i: process parameter identifier;

β_0 Constant Coefficient = $\frac{\sum_{j=1}^{N} y_j}{n \times N}$; (16)

β_{1i}: linear coefficient for i[th] parameter = $\frac{\sum_{j=1}^{N}\left(\beta_1^j\right)_i}{\sum_{j=1}^{N}\left(c_{ij}^1\right)^2}$; (17)

β_{2i}: non linear coefficient for ith parameter = $\frac{\sum_{j=1}^{N}\left(\beta_2^j\right)_i}{\sum_{j=1}^{N}\left(c_{ij}^2\right)^2}$; (18)

C_{ij}^1: Orthogonal contrast coefficient of linear form for i[th] parameter in jth experiment;

C_{ij}^2: Orthogonal contrast coefficient of non linear term for i[th] parameter in j[th] experiment;

ε: error component;

P_1 (i): 1[st] order orthogonal polynomials of parameter i $= \left[\frac{\lambda_1(i - m_i)}{d_i^2}\right]$; (19)

P_2 (i): 2[nd] order orthogonal polynomials of parameter i = $\lambda_2 \left[\frac{(i-m_i)^2}{d_i^2}\right] - \lambda_2\left[\frac{L_i^2-12}{12}\right]$ (20)

λ_1: Constant polynomial for 1[st] order orthogonal polynomial for parameter i;

λ_2: Constant polynomial for 2[nd] order orthogonal polynomial for parameter i;

m_i: mean value of the parameters i;

d_i: Spacing between the values of the parameter i;

L_i: total number of levels for parameter i.

Empirical relation for Surface roughness R_a VS Process parameters

Reference voltage, Pulse on time, Pulse off time, Wire velocity, Wire tension and Injection pressure mode influencing the surface Roughness, which is the response variable. The regression equation for Surface roughness is given in Equation 13.

$$R_a = \beta_{2V}*\lambda_2\left[\left[\frac{(V-m_v)^2}{d_v^2}\right]-\left[\frac{V^2-1}{12}\right]\right]+\beta_{1V}*\lambda_1\left[\frac{V-m_v}{d_v}\right]+$$
$$\beta_{2Ton}*\lambda_2\left[\left[\frac{(T_{on}-m_{Ton})^2}{d_{Ton}^2}\right]-\left[\frac{T_{on}^2-1}{12}\right]\right]+\beta_{1Toff}*\lambda_1\left[\frac{T_{on}-m_{Ton}}{d_{Ton}}\right]+$$
$$\beta_{2Toff}*\lambda_2\left[\left[\frac{(T_{off}-m_{Toff})^2}{d_{Toff}^2}\right]-\left[\frac{T_{off}^2-1}{12}\right]\right]+\beta_{1Toff}*\lambda_1\left[\frac{T_{off}-m_{Toff}}{d_{Toff}}\right]+$$
$$\beta_{2WS}*\lambda_2\left[\left[\frac{(T_{WS}-m_{WS})^2}{d_{WS}^2}\right]-\left[\frac{T_{WS}^2-1}{12}\right]\right]+\beta_{1WS}*\lambda_1\left[\frac{T_{WS}-m_{WS}}{d_{WS}}\right]+$$
$$\beta_{2WB}*\lambda_2\left[\left[\frac{(T_{WB}-m_{WB})^2}{d_{WB}^2}\right]-\left[\frac{T_{WB}^2-1}{12}\right]\right]+\beta_{1WB}*\lambda_1\left[\frac{T_{WB}-m_{WB}}{d_{WB}}\right]+$$
$$\beta_{2Inj}*\lambda_2\left[\left[\frac{(T_{Inj}-m_{Inj})^2}{d_{Inj}^2}\right]-\left[\frac{T_{Inj}^2-1}{12}\right]\right]+\beta_{1Inj}*\lambda_1\left[\frac{T_{Inj}-m_{Inj}}{d_{Inj}}\right] \quad (21)$$

Among the process parameters, Reference voltage, Pulse on time, Pulse off time, Wire velocity, Wire tension are quantitative measures with equal spacing but Injection pressure mode is a qualitative measure. Hence, coded value of orthogonal array is used. The lower, middle and higher levels of process parameters are coded as -1, 0 and 1. For a six parameter study,

$\lambda_1 = 1$; $\lambda_3 = 3$;

'm' is the average value of the higher and the lower levels of the process parameters. Thus, m values are obtained to be: $m_{v} = 45$; $m_{Ton} = 0.8$; $m_{Toff} = 14.4$; $m_{WS} = 8$; $m_{WB} = 1.02$; $m_{Inj} = 2$;

'd' is the spacing between the values of process parameters at various levels.

$d_{V} = 5$; $d_{Ton}= 0.2$; $d_{Toff} = 6.4$; $d_{WS} = 2$; $d_{WB} = 0.2$; $d_{Inj} = 1$;

Calculation of Constants and Coefficients

The Table 15 shows the values of orthogonal contrast coefficients for linear (C_{ij}^1) and non linear (C_{ij}^2) term and Table 16 shows the Orthogonal Contrast Coefficients (Linear and Non Linear) considered for various process parameters

Substituting the constant values in the equation (21),

$$R_a = 1.984*3\left[\left[\frac{(V-45)^2}{5^2}\right]-\left[\frac{V^2-1}{12}\right]\right]+\left[\frac{V-45}{5}\right]+$$
$$(-0.021)*3\left[\left[\frac{(T_{on}-0.8)^2}{0.2^2}\right]-\left[\frac{T_{on}^2-1}{12}\right]\right]+0.025*1\left[\frac{T_{on}-0.8}{0.2}\right]+$$
$$(-0.0119)*3\left[\left[\frac{(T_{off}-14.4)^2}{6.4^2}\right]-\left[\frac{T_{off}^2-1}{12}\right]\right]+(-0.1192)*1\left[\frac{T_{off}-14.4}{6.4}\right]+$$
$$(-0.015)*3\left[\left[\frac{(T_{WS}-8)^2}{2^2}\right]-\left[\frac{T_{WS}^2-1}{12}\right]\right]+(-0.0094)*1\left[\frac{T_{WS}-8}{2}\right]+$$
$$0.0675*3\left[\left[\frac{(T_{WB}-1.02)^2}{0.2^2}\right]-\left[\frac{T_{WB}^2-1}{12}\right]\right]+(-0.0036)*1\left[\frac{T_{WB}-1.02}{0.2}\right]+$$
$$0.0192*3\left[\left[\frac{(T_{Inj}-2)^2}{1^2}\right]-\left[\frac{T_{Inj}^2-1}{12}\right]\right]+(-0.0219)*1\left[\frac{T_{Inj}-2}{1}\right] \quad (22)$$

Simplification of the above equation will provide a polynomial process model for the performance characteristics / response variable Surface roughness as a function of process parameters (Reference voltage, Pulse on time, Pulse off time, Wire velocity,

Wire tension and Injection pressure mode) and the same was given in equation 23.

$$Ra = 2.03 + 0.01176(V-45) + 0.125(T_{on}-0.8) + 1.5825(T_{on}-0.8)^2 - 0.01862(T_{off}-14.4) - 0.00087(T_{off}-14.4)^2 - 0.0075(WS-8) - 0.00705(WS-8)^2 + 0.3375(WB-1.02) - 0.27(WB-1.02)^2 + 0.0192(Inj-2) - 0.0657(Inj-2)^2 \quad (23)$$

Performance evaluation

The Final step is to validate the process model / regression equation with set of process parameters. The following Table 18 shows the comparison between the process model / regression value and the experimental value at various levels of process parameters. The negative sign in the % error column of the performance evaluation table represents the direction of error.

Similarly the process models for spark gap, dimensional deviation and material removal rate were established and indicated in equation 24, equation 25 and equation 26 respectively. These developed process models were evaluated with actual experimental values. This performance evaluation for spark gap, dimensional deviation and material removal rate were indicated in Table19, Table20 and Table21respectively.

Spark Gap

$$SG = 29.5278 - 0.0889(V-45) + 3.3333(T_{on}-0.8) - 47.9167(T_{on}-0.8)^2 + 0.1237(T_{off}-14.4) + 0.0071(T_{off}-14.4)^2 + 0.2917(WS-8) - 0.0417(WS-8)^2 - 0.2083(WB-1.02) - 19.7917(WB-1.02)^2 - 0.375(Inj-2) - 1.5417(Inj-2)^2 \quad (24)$$

Dimensional Deviation

$$DD = 5.7427 - 0.0944(V-45) + 0.4165(T_{on}-0.8) - 6.2475(T_{on}-0.8)^2 + 0.09114(T_{off}-14.4) - 0.0238(T_{off}-14.4)^2 - 0.375(WS-8) - 0.0000(WS-8)^2 + 0.8333(WB-1.02) - 6.2475(WB-1.02)^2 - 0.0833(Inj-2) + 1.5(Inj-2)^2 \quad (25)$$

Material Removal Rate

$$MRR = 7.9798 - 0.14988(V-45) + 3.15(T_{on}-0.8) - 1.4583(T_{on}-0.8)^2 - 0.2414(T_{off}-14.4) + 0.00254(T_{off}-14.4)^2 + 0.14955(WS-8) - 0.12645(WS-8)^2 + 1.1375(WB-1.02) - 18.765(WB-1.02)^2 - 0.155832(Inj-2) - 0.0375(Inj-2)^2 \quad (26)$$

Conclusion And Scope For Future

In this paper, an attempt has been made to analyze the process parameters that influence the Wire EDM performance. Conclusions of the analysis are as follows:

- Of the six parameters chosen for study, it was found that three parameters T_{off}, T_{on}, WS have profound influence on the MRR, Ra, SG and DD.
- Among the six parameters, T_{off} has most significant with respect to multiple performance characteristics.
- Optimal machining parameter settings are V – 40V, T_{on} – 1μs, T_{off} – 8μs, WS – 10m/min, WB – 1.02 kg, Inj – Mode 3.
- Process model between Wire Electrical discharge machine performance characteristics (MRR, Ra, SG and DD) and the most influencing parameters (V, Toff, Ton, WS, WB, Inj) have been established.
- The average percentage of deviation of the regression values is nearly six percent in all performance characteristics.
- Although factorial design is a well known technique for analysing the effect of variables over an objective, the uncertainty in measurements of the variables influence the result and subsequently the analysis. In order to guarantee precision in any result, it is necessary to consider the uncertainty in measurements.

Hence the future work should include uncertainty of the observed response so as to get accurate prediction on the results. In addition to this, work can be extended for other materials and checked for generalization. The regression equation may further be refined using non classical optimization approaches such as genetic algorithm, simulated annealing and neural network.

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Appendix

Notation

ANOVA : Analysis of variance
C^1_{ij} : Orthogonal contrast coefficient of linear term for i^{th} parameter in j^{th} experiment
C^2_{ij} : Orthogonal contrast coefficient of non linear term for i^{th} parameter in j^{th} experiment
CF : Correction Factor
CNC : Computer Numerically Controlled
DD : Dimensional Deviation
DOE : Design of Experiments
DOF : Degree of freedom
DOF_e : Degree of freedom of errors
DOF_i : Degrees of freedom of i^{th} parameter (i may be V, T_{on}, T_{off}, Inj, WB, WS)
d_i : Spacing between the value of levels for parameter i
D : diameter of the electrode wire
EDM : Electrical Di scharge machining
ET : Extra thickness (in mm)
F : Variance ratio

g : Number of parameters (=6 i.e., V, T_{on}, T_{off}, Inj, WB, WS)
GW : Gap width (mm)
h : Height of the work piece (mm)
HB : Higher is better
HSS : High Speed Steel
HSTR : High Strength Temperature Resistant
i : Parameter identifier
Inj : fluid injection pressure mode
j : Identifier for experimental run (j varies from 1 to N)
L : Total number of Level for a parameter
L_i : Total number of levels for parameter i
LB : Lower is better

m_i : Mean value of the levels of parameter i
MRR : Material / Metal Removal Rate
MSE : Mean Sum of Squares of the error
MSS_i : Mean Sum of Square for i^{th} parameter (i may be V, T_{on}, T_{off}, Inj, WB, WS)
MSS_T : Total Mean Sum of Square
n : Number of repetitions of the experiment
N : Total number of experiments
NB : Nominal is better
OA : Orthogonal Array
$P_1(i)$: 1^{st} order orthogonal polynomial of parameter i .
$P_2(i)$: 2^{nd} order orthogonal polynomial of parameter i .
RV : Response variable (RV may be MRR, R_a, SG and DD)
R_a : Surface Roughness
S/N : Signal to Noise ratio
SG : Spark Gap
SS_{RV} : Sum of squares of response variable
SS_i : Sum of squares of parameter i
SST : Total sum of squares
T_{on} : Pulse on-time
T_{off} : Pulse off-time
V : Reference Voltage
V_c : Mean cutting speed (mm/min)
WB : Wire tension
WEDM : Wire Electrical Discharge Machining
WS : Wire velocity
η_j : S/N ratio corresponding to j th experiment
η_{Avg} : Average S/N ratio at each level
α : Confidence Interval
β_0 : Constant coefficient in regression equation
β_{1i} : Linear coefficient for the i^{th} parameter
β_{2i} : Nonlinear coefficient for the i^{th} parameter
(β_1^j) : Linear coefficient for the i^{th} parameter in the j^{th}experiment
$(\beta_2^j)_i$: Non linear coefficient for the i^{th} parameter in the j^{th} experiment
λ_1 : Constant polynomial for 1^{st} order orthogonal polynomial for parameter i
λ_2 : Constant polynomial for 2^{nd} order orthogonal polynomial for parameter i
$\in$: Error component

Table 1- Parameters considered

Year	Author	T_{on}	T_{off}	Wire velocity	Wire tension	Peak current	Reference Voltage	Dielectric pressure	Table feed
1999	Liao et al[13]	✓	✓	x	X	x	X	✓	✓
2001	Rozenek et al	✓	✓	x	X	✓	✓	X	x
2003	Huang et al[14]	✓	✓	✓	✓	x	X	✓	✓
2004	Tosun et al	✓	✓	✓	X	x	X	✓	x
2009	Singh et al[15]	✓	✓	x	✓	✓	✓	X	x

Table 2 - Parameters levels of Screening Experiment

S. No	Machining Parameters	Levels			Units
		Lower	Medium	Higher	
1	Reference Voltage (V)	40	N/A	60	Volts
2	Pulse on-time (T_{on})	0.4	N/A	1.8	μs
3	Pulse off-time (T_{off})	1	N/A	20	μs
4	Wire Velocity (WS)	2	N/A	12	m/min
5	Wire Tension (WB)	0.25	N/A	1.5	Kg
6	Injection Pressure Mode (Inj)	1	N/A	4	Bar

Table 3 - L_{12} Orthogonal Array

Experimental Run	Machining Parameters Column					
	V (Volts)	T_{on} (μs)	T_{off} (μs)	WS (m/min)	WB (kg)	Inj
1	40	0.4	1	2	0.25	1
2	40	0.4	1	2	0.25	2
3	40	0.4	20	12	1.5	1
4	40	1.8	1	12	1.5	1
5	40	1.8	20	2	1.5	2
6	40	1.8	20	12	0.25	2
7	60	0.4	20	12	0.25	1
8	60	0.4	20	2	1.5	2
9	60	0.4	1	12	1.5	2
10	60	1.8	20	2	0.25	1
11	60	1.8	1	12	0.25	2
12	60	1.8	1	1	0.25	1

Table 4 - Measured Data of Machining Performances

Response	MRR (mm^3/min)			R_a (µm)			SG (µm)			DD (µm)		
Trial No.	1	2	Avg	1	2	Avg	1	2	Avg	1	2	Avg
1	3.95	3.96	3.96	1.92	1.89	1.91	26	25	26	6	5	5.50
2	3.83	3.90	3.87	1.96	1.95	1.96	28	30	29	7	8	7.50
3	3.61	3.71	3.66	1.87	1.89	1.88	25	26	25	6	6	6.00
4	1.03	1.10	1.07	2.48	2.48	2.48	26	24	25	6	5	5.50
5	8.66	8.64	8.65	2.48	2.51	2.50	20	20	20	7	8	7.50
6	9.05	9.24	9.15	2.36	2.37	2.37	24	24	24	6	7	6.50
7	29.77	29.84	29.81	2.61	2.60	2.61	25	27	26	4	3	3.50
8	28.03	28.99	28.51	2.59	2.63	2.61	30	30	30	7	6	6.50
9	30.39	30.24	30.32	2.61	2.62	2.62	31	29	30	6	8	7.00
10	38.36	38.59	38.48	3.06	3.06	3.06	23	24	23	5	5	5.00
11	21.98	21.94	21.96	3.07	3.03	3.05	26	26	26	4	5	4.50
12	30.01	30.66	30.34	3.11	3.17	3.14	30	28	30	8	6	7.00

Table 5 - Levels of Main Experiment

S. No	Machining Parameters	Levels			Units
		Lower	Medium	Higher	
1	Reference Voltage (V)	40	N/A	50	Volts
2	Pulse on-time (T_{on})	0.6	0.8	1.0	µs
3	Pulse off-time (T_{off})	8.0	14.4	20.8	µs
4	Wire Velocity (WS)	6	8	10	m/min
5	Wire Tension (WB)	0.82	1.02	1.22	Kg
6	Injection Pressure Mode (Inj)	3.5	5.5	8.0	Bar

N/A-Not Applicable

Table 6 - L_{18} Orthogonal Array

Experimental Run	Machining Parameters Column					
	V (Volts)	T_{on} (µs)	T_{off} (µs)	WS (m/min)	WB (kg)	Inj
1	40	0.6	8.0	6	0.82	1
2	40	0.6	14.4	8	1.02	2
3	40	0.6	20.8	10	1.22	3
4	40	0.8	8.0	6	1.02	2
5	40	0.8	14.4	8	1.22	3
6	40	0.8	20.8	10	0.82	1
7	40	1.0	8.0	6	0.82	3
8	40	1.0	14.4	8	1.02	1
9	40	1.0	20.8	10	1.22	2
10	50	0.6	8.0	6	1.22	2
11	50	0.6	14.4	8	0.82	3
12	50	0.6	20.8	10	1.02	1
13	50	0.8	8.0	6	1.22	1
14	50	0.8	14.4	8	0.82	2
15	50	0.8	20.8	10	1.02	3
16	50	1.0	8.0	6	1.02	3
17	50	1.0	14.4	8	1.22	1
18	50	1.0	20.8	10	0.82	2

Table 7 - Measured Data of Machining Performances

Response	MRR (mm^3/min)			R_a (µm)			SG (µm)			DD (µm)		
Trial No.	1	2	Avg	1	2	Avg	1	2	Avg	1	2	Avg
1	8.72	8.46	8.59	2.02	2.04	2.03	27	25	26	6	7	6.5
2	8.45	8.51	8.48	2.11	2.12	2.12	28	28	28	5	6	5.5
3	6.41	6.40	6.40	1.99	1.97	1.98	29	26	27	5	6	5.5
4	9.18	9.18	9.18	2.21	2.22	2.22	27	27	27	6	5	5.5
5	8.45	8.21	8.33	2.12	2.11	2.12	27	26	26.5	7	8	7.5
6	4.68	4.62	4.65	1.73	1.75	1.74	26	27	26.5	6	6	6
7	8.91	8.85	8.88	2.08	2.08	2.08	26	25	25.5	6	5	5.5
8	8.75	8.90	8.82	2.12	2.06	2.09	28	30	29	7	8	7.5
9	6.96	7.13	7.04	2.01	2.01	2.01	25	26	25.5	6	7	6.5
10	6.80	6.59	6.69	2.12	1.94	2.03	26	24	25	4	3	3.5
11	4.99	4.99	4.99	1.82	1.84	1.83	20	20	20	7	6	6.5
12	3.87	3.87	3.87	1.62	1.66	1.64	24	24	24	6	8	7
13	8.64	8.63	8.64	2.22	2.22	2.22	25	27	26	5	5	5
14	6.60	6.79	6.70	1.94	1.95	1.95	30	30	30	4	5	4.5
15	5.18	5.11	5.15	1.91	1.91	1.91	31	29	30	8	6	7
16	9.62	10.22	9.92	1.99	1.94	1.97	23	24	23.5	3	3	3
17	5.16	5.19	5.18	1.95	1.93	1.94	26	26	26	6	8	7
18	6.26	6.21	6.24	1.83	1.84	1.84	30	28	29	3	5	4

Avg – Average value of trials

Table 8 - S/N Ratio values of machining performances

Run	S/N Ratio (db)			
	MRR (mm^3/min)	R_a (µm)	SG (µm)	DD (µm)
1	18.6792	-6.1500	-28.3059	-16.2839
2	18.5639	-6.5062	-28.9432	-14.8430
3	16.1296	-5.9334	-28.7996	-14.8430
4	19.2576	-6.9075	-28.6273	-14.8430
5	18.4132	-6.5062	-28.4665	-17.5205
6	13.3502	-4.811	-28.4665	-15.5630
7	18.9676	-6.3613	-28.1325	-14.8430
8	18.9127	-6.4038	-29.2531	-17.5205
9	16.9541	-6.0639	-28.1325	-16.2839
10	16.5059	-6.1584	-27.9657	-10.9691
11	13.9585	-5.2492	-26.0206	-16.2839
12	11.7632	-4.2975	-27.6042	-16.9897
13	18.7271	-6.9271	-28.3059	-13.9794
14	16.5138	-5.7784	-29.5424	-13.1175
15	14.2289	-5.6207	-29.5472	-16.9897
16	19.9189	-5.8680	-27.4233	-9.5424
17	14.2853	-5.7561	-28.2995	-16.9897
18	15.8992	-5.2728	-29.2531	-12.3045
Mean	16.7238	-5.9206	-28.3938	-14.9839

The average values of S/N ratio (db) are shown in the Table 9.

Table 9 - S/N ratio (db) values for all levels of MRR, R_a, SG and DD

Machining Performances	Levels	V	T_{on}	T_{off}	WS	WB	Inj
MRR	1	17.6920*	15.9334	18.6760*	16.2273	16.2281	15.9529
	2		16.7484	16.7746	17.0557*	17.1075*	17.2824*
	3	15.7556	17.4896*	14.7208	16.8885	16.9358	16.9361
R_a	1	-6.1826	-5.7158	-6.3954	-5.9579	-5.6038*	-5.7243*
	2		-6.0918	-6.0333	-5.9785	-5.9339	-6.1145
	3	-5.6587*	-5.9543	-5.3332*	-5.8255*	-6.2242	-5.9231
SG	1	-28.5697	-27.939*	-28.126*	-28.155*	-28.286*	-28.3725
	2		-28.8260	-28.4209	-28.4509	-28.5664	-28.7440
	3	-28.218*	-28.4157	-28.6338	-28.5751	-28.3283	-28.064
DD	1	-15.8382	-15.0354	-13.410	-16.2790	-14.732*	-16.2210
	2		-15.3355	-16.0458	-15.0800	-15.1214	-13.726*
	3	-14.129*	-14.580*	-15.4956	-13.592*	-15.0976	-15.0037

* Significant

Table 10 - ANOVA for surface roughness

Sources of Variation	Sum of Squares (SS)	Degrees of freedom (DOF)	**Mean Sum of squares (MSS)**	$F_{Statistic}$	$F_{0.05,v1,v2}$	% Contribution
V	0.12	1	0.12	21.70**	4.26	30.33
V_L	0.12	[1]	0.12			
T_{on}	0.05	2	0.025	3.94	3.40	5.51
T_{onL}	0.01	[1]	0.01			
T_{onQ}	0.03	[1]	0.03			
T_{off}	0.35	2	0.175	30.25*		42.27
T_{offL}	0.34	[1]	0.34			
T_{offQ}	0.01	[1]	0.01			
WS	0.01	2	0.01	1.01		1.41
WS_L	0.01	[1]	0.005			
WS_Q	0.01	[1]	0.01			
WB	0.12	2	0.06	10.16		14.21
WB_L	0.12	[1]	0.12			
WB_Q	0.00	[1]	0.00			
Inj	0.04	2	0.02	3.49		4.88
Inj_L	0.01	[1]	0.01			
Inj_Q	0.03	[1]	0.03			
ERROR	0.14	24	0.01			1.40
TOTAL	0.82	35	0.41			

* Most Significant ** Significant

Table 11 - ANOVA for spark gap

Sources of Variation	Sum of Squares SS	Degrees of freedom DOF	Mean Sum of squares MSS	$F_{Statistic}$	$F_{0.05,v1,v2}$	% Contribution
V	7.11	1	7.11	1.36	4.26	12.23
V_L	7.11	[1]	7.11			
T_{on}	40.06	2	20.03	3.82*	3.40	34.44
T_{onL}	10.67	[1]	10.67			
T_{onQ}	29.39	[1]	29.39			
T_{off}	15.72	2	7.86	1.50		13.52
T_{offL}	15.04	[1]	15.04			
T_{offQ}	0.68	[1]	0.68			
WS	8.39	2	4.19	0.80		7.21
WS_L	8.17	[1]	8.17			
WS_Q	0.22	[1]	0.22			
WB	5.06	2	2.53	0.48		4.35
WB_L	0.04	[1]	0.04			
WB_Q	5.01	[1]	5.01			
Inj	22.39	2	11.19	2.14		19.25
Inj_L	3.38	[1]	3.38			
Inj_Q	19.01	[1]	19.01			
ERROR	125.83	24	5.24			9.01
TOTAL	224.56	35	58.16			

Table 12 - ANOVA for dimensional deviation

Sources of Variation	Sum of Squares SS	Degrees of freedom DOF	Mean Sum of squares MSS	$F_{Statistic}$	$F_{0.05,v1,v2}$	% Contribution
V	8.03	1	8.03	9.61**	4.26	24.93
V_L	8.03	[1]	8.03			
T_{on}	0.67	2	0.33	0.40	3.40	1.04
T_{onL}	0.17	[1]	0.17			
T_{onQ}	0.50	[1]	0.50			
T_{off}	16.17	2	8.08	9.67*		25.11
T_{offL}	8.17	[1]	8.17			
T_{offQ}	8.00	[1]	8.00			
WS	13.50	2	6.75	8.08		20.96
WS_L	13.50	[1]	13.50			
WS_Q	0.00	[1]	0.00			
WB	1.17	2	0.58	0.70		1.81
WB_L	0.67	[1]	0.67			
WB_Q	0.50	[1]	0.50			
Inj	15.17	2	7.58	9.07		23.55
Inj_L	2.67	[1]	2.67			
Inj_Q	12.50	[1]	12.50			
ERROR	20.06	24	0.84			2.60
TOTAL	74.75	35	32.20			

Table 13 - ANOVA for material removal rate

Sources of Variation	Sum of Squares (SS)	Degrees of freedom (DOF)	Mean Sum of squares (MSS)	$F_{Statistic}$	$F_{0.05,v1,v2}$	% Contribution
V	18.83	1	18.83	27.57**	4.26	32.22
V_L	18.83	[1]	18.83			
T_{on}	8.31	2	4.15	6.08	3.40	7.11
T_{onL}	8.30	[1]	8.30			
T_{onQ}	0.00	[1]	0.00			
T_{off}	57.32	2	28.66	41.97*		49.06
T_{offL}	57.32	[1]	57.32			
T_{offQ}	0.00	[1]	0.00			
WS	3.27	2	1.64	2.40		2.80
WS_L	1.56	[1]	1.56			
WS_Q	1.71	[1]	1.71			
WB	4.87	2	2.43	3.56		4.16
WB_L	0.84	[1]	0.84			
WB_Q	4.03	[1]	4.03			
Inj	4.07	2	2.03	2.98		3.48
Inj_L	2.55	[1]	2.55			
Inj_Q	1.51	[1]	1.51			
ERROR	16.39	24	0.68			1.17
TOTAL	113.05	35	58.42			

Table 14 – Percentage Contribution of each parameter on the performance characte

Performance Characteristic	% Contribution of the parameter						% Error
	V	T_{on}	T_{off}	WS	WB	Inj	
MRR	32.22	7.11	49.8	2.8	4.16	3.48	1.17
R_a	30.33	5.51	42.27	1.41	14.21	4.88	1.40
SG	12.23	34.44	49.8	7.21	4.35	19.25	9.01
DD	24.93	1.04	49.8	20.96	1.81	23.55	2.60

Table 15 - Orthogonal Contrast Coefficients (Linear and Non Linear) for different levels levels

Levels	C_{ij}^1	C_{ij}^2
Lower	-1	1
Medium	0	-2
Higher	1	1

Table 16 - Orthogonal Contrast Coefficients (Linear and Non Linear) considered for various process parameters

Ra	Orthogonal Contrast Coefficient for linear term c_{ij}^1						Orthogonal Contrast Coefficient for non-linear term c_{ij}^2					
	V	T_{on}	T_{off}	WS	WB	Inj	V	T_{on}	T_{off}	WS	WB	Inj
2.03	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1
2.12	-1	-1	0	0	0	0	1	1	-2	-2	-2	-2
1.98	-1	-1	1	1	1	1	1	1	1	1	1	1
2.22	-1	0	-1	-1	0	0	1	-2	1	1	-2	-2
2.12	-1	0	0	0	1	1	1	-2	-2	-2	1	1
1.74	-1	0	1	1	-1	-1	1	-2	1	1	1	1
2.08	-1	1	-1	0	-1	1	1	1	1	-2	1	1
2.09	-1	1	0	1	0	-1	1	1	-2	1	-2	1
2.01	-1	1	1	-1	1	0	1	1	1	1	1	-2
2.03	1	-1	-1	1	1	0	1	1	1	1	1	-2
1.83	1	-1	0	-1	-1	1	1	1	-2	1	1	1
1.64	1	-1	1	0	0	-1	1	1	1	-2	-2	1
2.22	1	0	-1	0	1	-1	1	-2	1	-2	1	1
1.95	1	0	0	1	-1	0	1	-2	-2	1	1	-2
1.91	1	0	1	-1	0	1	1	-2	1	1	-2	1
1.97	1	1	-1	1	0	1	1	1	1	1	-2	1
1.94	1	1	0	-1	1	-1	1	1	-2	1	1	1
1.84	1	1	1	0	-1	0	1	1	1	-2	1	-2
$\sum_{j=1}^{18}\left(C_{ij}^1\right)^2$	18	12	12	12	12	12						
$\sum_{j=1}^{18}\left(C_{ij}^2\right)^2$							18	36	36	36	36	36

Table 17 – Calculation of constants and coefficients

	$(\beta_1)_V$	$(\beta_2)_V$	$(\beta_1)_{Ton}$	$(\beta_2)_{Ton}$	$(\beta_1)_{Toff}$	$(\beta_2)_{Toff}$	$(\beta_1)_{WS}$	$(\beta_2)_{WS}$	$(\beta_1)_{WB}$	$(\beta_2)_{WB}$	$(\beta_1)_{Inj}$	$(\beta_2)_{Inj}$
	-2.03	2.03	-2.03	2.03	-2.03	2.03	-2.03	2.03	-2.03	2.03	-2.03	2.03
	-2.12	2.12	-2.12	2.12	0	-4.24	0	-4.24	0	-4.24	0	-4.24
	-1.98	1.98	-1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98
	-2.22	2.22	0	-4.44	-2.22	2.22	-2.22	2.22	0	-4.44	0	-4.44
	-2.12	2.12	0	-4.24	0	-4.24	0	-4.24	2.12	1.12	2.12	2.12
	-1.74	1.74	0	-3.48	1.74	1.74	1.74	1.74	-1.74	1.74	-1.74	1.74
	-2.08	2.08	2.08	2.08	-2.08	2.08	0	-4.16	-2.08	2.08	2.08	2.08
	-2.09	2.09	2.09	2.09	0	-4.18	2.09	2.09	0	-4.18	-2.09	2.09
	-2.01	2.01	2.01	2.01	2.01	2.01	-2.01	2.01	2.01	2.01	0	-4.02
	2.03	2.03	-2.03	2.03	-2.03	2.03	2.03	2.03	2.03	2.03	0	-4.06
	1.83	1.83	-1.83	1.83	0	-3.66	-1.83	1.83	-1.83	1.83	1.83	1.83
	1.64	1.64	-1.64	1.64	1.64	1.64	0	-3.28	0	-3.28	-1.64	1.64
	2.22	2.22	0	-4.44	-2.22	2.22	0	-4.44	2.22	2.22	-2.22	2.22
	1.95	1.95	0	-3.90	0	-3.90	1.95	1.95	-1.95	1.95	0	-3.90
	1.91	1.91	0	-3.82	1.91	1.91	-1.91	1.91	0	-3.82	1.91	1.91
	1.97	1.97	1.97	1.97	-1.97	1.97	1.97	1.97	0	-3.94	1.97	1.97
	1.94	1.94	1.94	1.94	0	-3.88	-1.94	1.94	1.94	1.94	-1.94	1.94
	1.84	1.84	1.84	1.84	1.84	1.84	0	-3.68	-1.84	1.84	0	-3.68
$\sum_{j=1}^{18}\left(\beta_1^j\right)_i$	-1.08		0.3		-1.43		-0.18		0.81		0.23	
$\sum_{j=1}^{18}\left(\beta_2^j\right)_i$		35.72		-0.76		-0.43		-0.34		-0.13		-0.79
$(\beta_1)_i = \frac{\sum_{j=1}^{18}\left(\beta_1^j\right)_i}{\sum_{j=1}^{18}\left(c_{ij}^1\right)^2}$	-0.06		0.025		-0.1192		-0.015		0.0675		0.0192	
$(\beta_2)_i = \frac{\sum_{j=1}^{18}\left(\beta_2^j\right)_i}{\sum_{j=1}^{18}\left(c_{ij}^2\right)^2}$		1.984		-0.021		-0.0119		-0.0094		-0.0036		-0.0219

Table 18 – Performance evaluation for Surface roughness R_a

Exp. No.	Surface roughness R_a in µm		% error
	Regression value	Experiment value	
1	1.9166	2.03	5.58
2	2.0095	2.12	5.21
3	1.82	1.98	8.08
4	2.04	2.22	8.10
5	1.97	2.12	7.07
6	1.60	1.74	8.04
7	2.01	2.08	3.36
8	1.93	2.09	7.65
9	1.95	2.01	2.98
10	2.22	2.03	-9.35
11	1.98	1.83	-8.69
12	1.88	1.64	-14.63
13	2.14	2.22	3.6
14	1.96	1.95	0.51
15	1.87	1.91	2.09
16	2.17	1.97	-10.15
17	2.13	1.94	-9.79
18	1.94	1.84	-5.43
Average % error = 6.68%			

Table 19 - Performance evaluation for Spark gap (SG)

Exp. No.	Spark gap SG in µm		% error
	Regression value	Experiment value	
1	24.971	26	3.9
2	27.38	28	2.21
3	26.13	27	3.22
4	28.72	27	-6.3
5	27.22	26.5	-2.7
6	28.804	26.5	-8.69
7	24.804	25.5	2.72
8	27.155	29	6.36
9	32.00	25.5	-25.49
10	24.415	25	2.34
11	23.833	20	-19.165
12	26.83	24	-11.79
13	25.832	26	0.646
14	28.335	30	5.56
15	28.74	30	4.2
16	24.665	23.5	-4.9
17	25.83	26	0.653
18	28.58	29	1.44
Average error % = 6.23%			

Table 20 - Performance evaluation for Dimensional deviation (DD)

Exp. No.	Dimensional deviation DD in µm		% error
	Regression value	Experiment value	
1	6.22	6.5	4.3
2	5.88	5.5	-7.05
3	6.05	5.5	-10.11
4	5.38	5.5	2.00
5	7.55	7.5	-0.7
6	6.22	6	-3.66
7	5.47	5.5	0.5
8	6.88	7.5	8.15
9	6.3	6.5	2.98
10	2.53	3.5	27.71
11	6.69	6.5	-2.98
12	5.94	7	15.06
13	5.02	5	-0.57
14	4.11	4.5	8.65
15	7.02	7	-0.4
16	4.19	3	-39.79
17	7.36	7	-5.14
18	4.27	4	-6.75
Average error % = 8.13%			

Table 21 - Performance evaluation for Material removal rate (MRR)

Exp. No.	Material removal rate MRR in mm^3 / min		% error
	Regression value	Experiment value	
1	8.11	8.59	5.91
2	8.04	8.48	5.17
3	5.67	6.40	11.29
4	9.57	9.18	-4.28
5	8.01	8.33	3.8
6	5.985	4.65	-28.71
7	9.65	8.88	-8.76
8	8.97	8.82	-1.76
9	6.53	7.04	7.4
10	7.46	6.69	-11.52
11	4.56	4.99	8.50
12	4.98	3.87	-28.75
13	7.55	8.64	14.43
14	6.04	6.70	9.76
15	4.79	5.15	6.96
16	9.5	9.92	8.75
17	6.35	5.18	-22.58
18	5.38	6.24	13.7
Average error % = 11.22%			