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# Experimental investigation of cutting speed during wire electric discharge machining of Inconel 718 alloy

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## Abstract

In this present study response surface methodology is proposed for wire electrical discharge machining (WEDM) operations. Experimentation was planned as central composite design. Each experiment has been performed under different cutting conditions of current (Ip), Pulse on time (Ton), Pulse off time (Toff) and Servo voltage (SV) to investigate the machining capability i.e. cutting speed. The Analysis of variance (ANOVA) was done to determine the optimum machining parameter combination for cutting speed CS. The regression analysis method was used to formulate the mathematical model. The experimental result shows that the predicted model suggested by the RSM method is suitable for improving the CS.

**Keywords:** ANOVA; WEDM; Electric discharge; Cutting

## 1. Introduction

The machining of super alloys is an active research area because of the widespread increase in demand of this category of materials and characteristic problems related to their machining. Inconel 718 is a high-strength temperature- resistant (HSTR) nickel-based super alloy which exhibits good resistance to corrosion and oxidation along with high creep-rupture strength and fatigue endurance limit. It is extensively used in the aerospace industry for manufacturing of gas turbine engine components such as turbine disks, blades, combustors and casings, nuclear power plant components such as reactor and pump, spacecraft structural components, medical devices, food processing equipment, extrusion dies and containers, casting dies, hot work tools and dies, etc.. Machining of Inconel 718 with conventional techniques is extremely difficult because of its high toughness, hardness, work hardening tendency, low thermal conductivity, and presence of hard abrasive particles. Therefore, nonconventional machining methods based on chemical, electro-chemical, thermal, thermoelectric, and mechanical energy are preferred over traditional methods for the machining of Inconel 718. Wire electrical discharge machining (WEDM) is a non-conventional, thermoelectric process that can be used to cut complex and intricate shapes in all electrically conductive materials used in tool and die, automobile, aerospace, dental, nuclear, computer, and electronic industries with better precision and accuracy. WEDM is a well-established process and its working is duly described in the literature. The most important performance measures in WEDM are material removal rate (or cutting speed), surface finish, kerf (cutting width), and wire wear rate. These measures, in turn, are influenced by numerous machining parameters such as peak current, pulse-on time, pulse-off time, wire tension, wire feed rate, spark gap voltage, and servo feed setting, average working voltage, and dielectric flushing condition. Owing to a large number of process parameters and a complex nature of the process, even a highly skilled operator with a state-of-the-art WEDM is rarely able to achieve the optimal performance. The improperly selected parameters may also result in serious consequences like short-circuiting of wire and wire breakage that in turn reduces productivity. An effective way to solve this problem is to determine the relationship between the performance measures and the controllable input parameters using a suitable modelling and optimization technique.

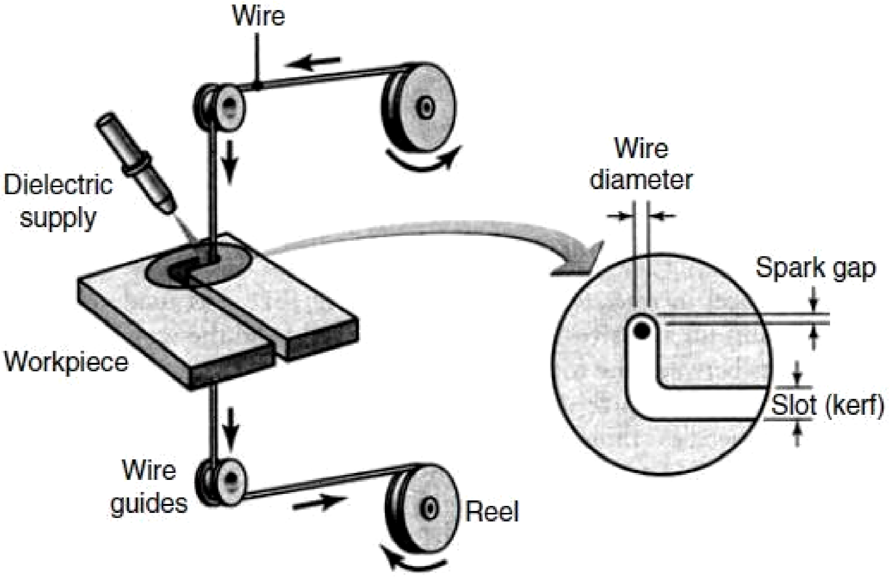

**Figure 1: Schematic Diagram of WEDM**

## 2. Literature Review

Since WEDM is an essential operation in several manufacturing processes in some industries, which need variety, precision and accuracy are of great important. In order to improve the performance namely the surface roughness, cutting speed, dimensional accuracy, and material removal rate of the WEDM process several researchers have attempted previously. However, the full potential utilization of this process is not completely solved because of its complex and stochastic nature and the increased number of variables involved in this operation [1], [2].

The various technological and NC aspects of the WEDM process were analyzed by [3]. Kinoshita et al. [4] pointed out that the ratio between the equilibrium clearance and the amplitude of wire vibration is the most appropriate value to judge the short circuit gap. A number of authors have performed research related to wire rupture problems. To avoid short sparks which causes the wire to rupture, Tanimura et al. [5] developed a short circuit detecting system, which is performed by adjusting the chock inductance of the pulse generator. They reported that the unusual high rate of short circuit pulses during a period of 30 ms or more proceeds wire rupture. Kinoshita et al. [6] analyzed the various types of wire breaking. To prevent the wire breaking they developed a control system by means of monitoring the pulse frequency. Once a sudden rise of pulse frequency was detected, the pulse generator and servo system was turned off instantaneously to

prevent the wire rupture from breaking. However, the machining efficiency was much reduced by such control strategy and the system was good if the work-piece thickness is restricted to 20 mm.
Scott et al. [2]constructed a mathematical model to predict the material removal rate and surface finish when machining D2 tool steel material at different machining conditions. They found that there is no single combination of levels of the different factors that can be optimal under all circumstances. To find the optimal machining parameters the non-dominated point approach was applied, using explicit enumeration of all possible combinations and the dynamic programming method. Dauw et al. [7] developed a mathematical model to analyze the wire deflection during machining. The deviation of the wire position relative to the programmed wire path position was continuously measured and corrections were made during machining of complex shapes, arc, and contours. In this study, substantial gain of machining time and improvement in corners' accuracy was obtained. Tarng et al. [8] formulated a neural network model and simulated annealing algorithm in order to predict and optimize the surface roughness and cutting velocity of the WEDM process when machining SUS–304 stainless steel materials.

Spedding et al. [1] attempted to model the WEDM process through the response surface methodology and artificial neural networks and found that the model accuracy of both was better. The same authors [1] attempted further to optimize the surface roughness, surface waviness, and speed of the artificial neural networks predicted values using a constrained optimization model. Huse et al. [9] developed a model to estimate the MRR in corner cutting of the WEDM by considering wire deflection in terms of discharge angle. Lin [10] et al. proposed a control strategy based on Fuzzy logic to improve the machining accuracy at corner parts of the WEDM process. Jun Qu et al. [11] derived a mathematical model for the material removal rate of a cylindrical wire EDM process. The same authors investigated through a mathematical model the surface integrity and roundness of cylindrical WEDM parts using brass and carbide work material. They found through the model a good estimate of the surface finish and roundness of cylindrical WEDM parts.

Gokler et al. [12] investigated under various experimental conditions the surface roughness achievable for 1040, 2379, and 2738 steel materials and the relative machining parameters for the WEDM process. Puri et al. [13] investigated the variation of geometrical inaccuracy caused due to wire lag with various machine control parameters. In order to predict the performance characteristics of the WEDM process Ramakrishnan et al. [14] developed a mathematical model using the response surface methodology. A good amount of research has already been done in the area of WEDM technology. To the best of the knowledge of the authors of this work, there is not found any published paper for optimizing multiple performance characteristics of the WEDM process using the Taguchi method. Keeping this consideration in view, this paper describes optimization of multiple performance characteristics using the robust parametric design approach, for achieving a better material removal rate, surface finish, and wire wear ratio.

## 3. Experimental procedure

In present work, a 5 axis sprint cut WEDM is used for conducting the experiments, made by Electronica M/C Tool LTD., installed at National Institute of Technology, kurukshetra. The performance of WEDM depends on setting of process parameters. Following section discusses the work material, machining parameters and experimental design used for present study.

### 3.1 Work material

Inconel is a family of austenitic nickel-chromium-based super alloys. The name is a trademark of Special Metals Corporation. Inconel 718 is a nickel-based super alloy that is well suited for applications requiring high strength in temperature ranges from cryogenic up to 1400°F. Inconel

718 also exhibits excellent tensile and impact strength.. The composition of Inconel 718 is as follows:

**Table 1. Composition of *Inconel 718***

| Component | Wt. % | Component | Wt. % | Component | Wt. % |
|---|---|---|---|---|---|
| **Carbon** | 0.08 max | **Chromium** | 17-21 | **Cobalt** | 1.00 max |
| **Manganese** | 0.35 max | **Nickel** | 50-55 | **Boron** | 0.006 max |
| **Phosphorus** | 0.015 max | **Molybdenum** | 2.8-3.3 | **Copper** | 0.30 max |
| **Sulfur** | 0.015 max | **Columbium** | 4.75-5.5 | **Tantalum** | 0.05 max |
| **Silicon** | 0.35 max | **Titanium** | 0.65-1.1 | **Iron** | Balance |
| **Aluminum** | 0.20-0.80 | | | | |

### 3.2 Machining parameters

Four discharge parameters, viz. Ip, Ton, Toff and SV are selected as input variable parameters other remaining least significant parameters are kept constant. A brass wire (zinc coated) of diameter 0.25 mm is selected as wire electrode. Wire feed rate 5 m/min is used with wire tension 10N. All experiments are performed at zero wire offset value. The distilled water having conductivity, 20mho is used as a dielectric fluid with high flow rate (i.e. 12 L/min). Selected levels and range of four variable input parameters are shown in Table 1 series of experimental trials have been conducted as per response surface methodology (RSM). The details about the work material, experimental set-up and measuring apparatus, selection of process parameters and their range, design of experiments, and reproducibility have been explained in the following sections.

### 3.3 Selection of process parameters and their range

In the present work, the effect of various process parameters (factors) such as viz., Ip, Ton, Toff and SV on cutting speed (response parameters) has been investigated. These process parameters and their range have been selected on the basis of the existing literature, pilot experimentation, manufacturer’s manual, and machine capability. The independent process parameters and their levels in coded and actual values are shown in Table 2.

### 3.4 Response Surface Methodology

Response surface methodology (RSM)[15] is a collection of mathematical and statistical techniques useful for analyzing problems in which several independent variables influence a dependent variable or response, and the goal is to optimize this response (Cochran and Cox, 1962). In many experimental conditions, it is possible to represent independent factors in quantitative form as given in Equation 3.1. Then these factors can be thought of as having a functional relationship with response as follows:

$$Y=\phi(X_1, X_2 \ldots\ldots\ldots\ldots\ldots, X_k)\pm e_r \qquad (3.1)$$

This represents the relation between response $Y$ and $x1, x2, \ldots, xk$ $of$ $k$ quantitative factors. The function $\phi$ is called response surface or response function. The residual er measures the experimental errors (Cochran and Cox, 1962). For a given set of independent variables, a characteristic surface is responded. When the mathematical form of $\phi$ is not known, it can be approximated satisfactorily within the experimental region by a polynomial. Higher the degree of polynomial, better is the correlation but at the same time costs of experimentation become higher.

For the present work, RSM has been applied for developing the mathematical models in the form of multiple regression equations for the quality characteristic of machined parts produced by turning process. In applying the response surface methodology, the dependent variable is viewed as a surface to which a mathematical model is fitted. For the development of regression equations related to various quality characteristics of turning process, the second order response surface has been assumed as:

$$\mathrm{y} \quad = b_o + \sum_{i=1}^{k} \mathrm{b_i x_{i+}} \sum_{i=1}^{k} \mathrm{b_i x_i^2} \ {}_{+} \sum_{i<j=2}^{2} \mathrm{b_i x_i \, x_{j\pm} e_r} \qquad (3.2)$$

This assumed surface Y contains linear, squared and cross product terms of variables$xi$‟$s$. In order to estimate the regression coefficients, a number of experimental design techniques are available. Box and Hunter (1957) have proposed that the scheme based on central composite rotatable design fits the second order response surfaces quite accurately.

### 3.4.1 Central composite design

Box and Hunter [38] proposed that the scheme based on central composite design (CCD) fits the second-order re- sponse surfaces quite accurately. Also, CCD[15] is the most popular among the various classes of RSM designs due to its flexibility, ability to run sequentially, and efficiency in providing the overall experimental error in a minimum number of runs. Therefore, it has been selected in the present work. In CCD, each factor is varied at five levels (−α, −1, 0, 1, α) for developing a second-order model as given in Eq. (2). When the number of factors (k)isfive or greater, it is not necessary to run all combinations of factors. The factorial part of the design can be run using a fraction of the total number of available combinations. The possible designs options can either be regular fractional factorials.

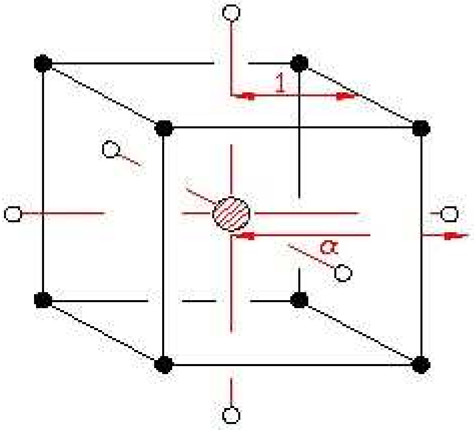

**Figure 2. Central Composite Design**

**Table 2: Process parameters and their levels**

| **Coded** | **Real** | **Parameters** | **Levels** | | |
|---|---|---|---|---|---|
| **Factors** | **Factors** | | **(-1)** | **(0)** | **(+1)** |
| A | Ton | Pulse on Time | 105 | 112 | 130 |
| B | Toff | Pulse off Time | 35 | 40 | 45 |
| C | SV | Spark Gap Set Voltage | 30 | 38 | 45 |
| D | IP | Peak Current | 105 | 190 | 120 |

## 4. Results and discussion

The present chapter gives the application of the response surface methodology. The scheme of carrying out experiments was selected and the experiments were conducted to investigate the effect of process parameters on the output parameter e.g. cutting speed. The experimental results are discussed subsequently in the following sections.

**Table 3: Observed Values for Performance Characteristics**

| | | **Factor 1** | **Factor 2** | **Factor 3** | **Factor 4** | **Response 1** |
|---|---|---|---|---|---|---|
| **Std** | Run | A:Peak current | B:Pulse on time | C:Pulse off time | D:Servo voltage | Cutting speed |
| **12** | 1 | 112 | 130 | 40 | 37 | 2.6909 |
| **10** | 2 | 120 | 117 | 40 | 37 | 2.3659 |
| **11** | 3 | 112 | 105 | 40 | 37 | 1.4309 |
| **15** | 4 | 112 | 117 | 40 | 30 | 2.5109 |
| **3** | 5 | 120 | 105 | 45 | 45 | 0.8969 |
| **17** | 6 | 112 | 117 | 40 | 37 | 2.3609 |
| **7** | 7 | 105 | 130 | 45 | 45 | 2.1489 |
| **2** | 8 | 120 | 130 | 35 | 30 | 2.8729 |
| **14** | 9 | 112 | 117 | 45 | 37 | 2.1259 |
| **19** | 10 | 112 | 117 | 40 | 37 | 2.3609 |
| **21** | 11 | 112 | 117 | 40 | 37 | 2.5809 |
| **8** | 12 | 105 | 105 | 35 | 30 | 1.4449 |
| **16** | 13 | 112 | 117 | 40 | 45 | 2.2109 |
| **4** | 14 | 105 | 130 | 35 | 45 | 2.3369 |
| **18** | 15 | 112 | 117 | 40 | 37 | 2.3609 |
| **6** | 16 | 105 | 105 | 45 | 30 | 1.0329 |
| **13** | 17 | 112 | 117 | 35 | 37 | 2.4259 |
| **5** | 18 | 120 | 105 | 35 | 45 | 1.3809 |
| **1** | 19 | 120 | 130 | 45 | 30 | 2.6849 |
| **9** | 20 | 105 | 117 | 40 | 37 | 2.1659 |
| **20** | 21 | 112 | 117 | 40 | 37 | 2.3609 |

**Table 4: Pooled ANOVA- Cutting speed**

| Source | Sum of Squares | df | Mean Square | F-Value | p-value Prob> F | |
|---|---|---|---|---|---|---|
| **Model** | 6.12852564 | 8 | 0.7660657 | 203.51458 | < 0.0001 | significant |
| **A-Peak current** | 0.1149184 | 1 | 0.1149184 | 30.529456 | 0.0001 | |
| **B-Pulse on time** | 4.2876304 | 1 | 4.2876304 | 1139.0606 | < 0.0001 | |
| **C-Pulse off time** | 0.2471184 | 1 | 0.2471184 | 65.649978 | < 0.0001 | |
| **D-Servo voltage** | 0.2471184 | 1 | 0.2471184 | 65.649978 | < 0.0001 | |
| **BC** | 0.0338 | 1 | 0.0338 | 8.9793769 | 0.0111 | |
| **A^2** | 0.03657517 | 1 | 0.0365752 | 9.7166346 | 0.0089 | |
| **B^2** | 0.28309573 | 1 | 0.2830957 | 75.207789 | < 0.0001 | |
| **C^2** | 0.03049247 | 1 | 0.0304925 | 8.100693 | 0.0147 | |
| **Residual** | 0.04517017 | 12 | 0.0037642 | | | |
| **Lack of Fit** | 0.00645017 | 8 | 0.0008063 | 0.0832925 | 0.9982 | not significant |
| **Pure Error** | 0.03872 | 4 | 0.00968 | | | |
| **Cor Total** | 6.17369581 | 20 | | | | |
| **Std. Dev.** | 0.06135292 | | R-Squared | 0.9926834 | | |
| **Mean** | 2.15009524 | | Adj R-Squared | 0.9878057 | | |
| **C.V. %** | 2.853497875 | | Pred R-Squared | 0.988222108 | | |
| **PRESS** | 0.07271312 | | Adeq Precision | 48.26102516 | | |

The selected process variables were varied up to four levels and central composite rotatable design was adopted to design the experiments. Response Surface Methodology was used to develop second order regression equation relating response characteristics and process variables. The process variables and their ranges are given in Table 2.

### 4.1 Results and Discussion

The WEDM experiments were conducted, with the process parameter levels set as given in Table 2, to study the effect of process parameters over the output parameters. Experiments were conducted according to the test conditions specified by the second order central composite design (Table 2). Experimental results are given in Table 3 for cutting speed. Altogether 20 experiments were conducted using response surface methodology.

#### 4.1.1 Analysis and Discussion of Results

The experiments were designed and conducted by employing response surface methodology (RSM). The selection of appropriate model and the development of response surface models have been carried out by using statistical software, “Design Expert (DX-9)”.

The regression equations for the selected model were obtained for the response characteristics viz. cutting speed. These regression equations were developed using the experimental data (Table 3) and were plotted to investigate the effect of process variables on various response characteristics. The analysis of variance (ANOVA) was performed to statistically analyze the results.

#### 4.1.2 Selection of Adequate Model

To decide about the adequacy of the model, three different tests viz. sequential model sum of squares, lack of fit tests and model summary statistics were performed for cutting speed characteristic of WEDM process. The sequential model sum of squares test in each table shows how the terms of increasing complexity contribute to the model. It can be observed that for all the responses, the quadratic model is appropriate. The „lack of fit‟ test compares the residual error to the pure error from the replicated design points. The results indicate that the quadratic model in all the characteristics does not show significant lack of fit, hence the adequacy of quadratic model is confirmed. Another test „model summary statistics‟ given in the following sections further confirms that the quadratic model is the best to fit as it exhibits low standard deviation, high “R-Squared” values, and a low “PRESS”

#### 4.1.3 Effect of Process Variables on Cutting Speed

The regression coefficient of the second order equation is obtained by using the experimental data (Table 2). The regression equation for the cutting speed as a function of five input process variables was developed using experimental data and is given below. The coefficients (insignificant identified from ANOVA) of some terms of the quadratic equation have been omitted.

$$\begin{aligned} Cutting\ Speed &= 59.30671 + 0.47442 \times Peakcurrent + 0.49211 \times Pulseontime \\ &+ 0.18246 \times Pulseofftime - 0.020960 \times Servovoltage + 1.04000E - 003 \\ &\times Pulseontime * Pulseofftime - 2.04502E - 003 * Peakcurrent^2 \\ &- 2.04821E - 003 \times Pulseontime^2 - 4.20130E - 003 \times Pulseofftime^2 \end{aligned} \qquad (4.1)$$

The response surface is plotted to study the effect of process variables on the cutting speed and is shown in Figures 3 and 4. From Figure 3 the cutting speed is found to have an increasing trend with the increase of pulse on time and decrease the peak current peak current. This establishes the fact that cutting speed is proportional to the energy consumed during machining and is dependent not only on the energy contained in a pulse determining the crater size, but also on the applied energy rate or power. It is observed from Figure 4 that cutting speed decreases with increase servo voltage. With increase in spark voltage the average discharge gap gets widened resulting into a lower cutting speed. It is seen from Figure 4 that cutting speed increases with increase in the peak current values. The higher is the peak current setting, the larger is the discharge energy. This leads to increase in cutting speed.

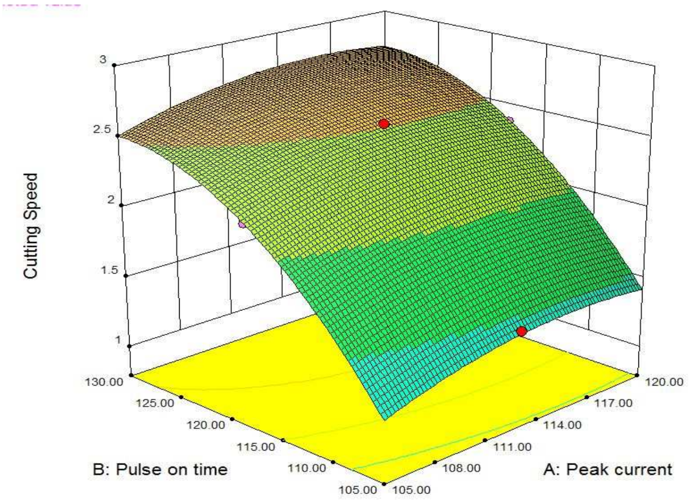

Figure 3: Combined Effect of Pulse on Time and Peak Current on Cutting Speed

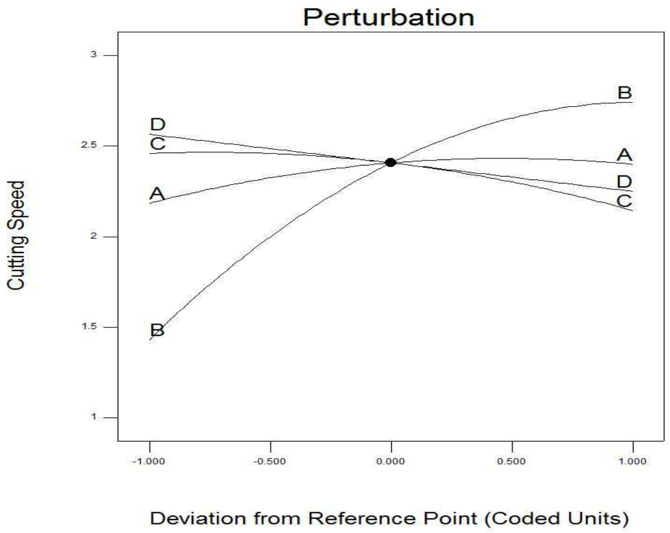

Figure 4: Overall Performance of Cutting Speed

But, the sensitivity of the peak current setting on the cutting performance is stronger than that of the pulse on time. While the peak current setting is too high, wire breakage may occur frequently. It can be also seen from Figure 4 that cutting speed almost remains constant with increase in the peak current. Though with increase in peak current, the machining stability increases as vibrations get restricted. But its increment does not influence the cutting speed much.

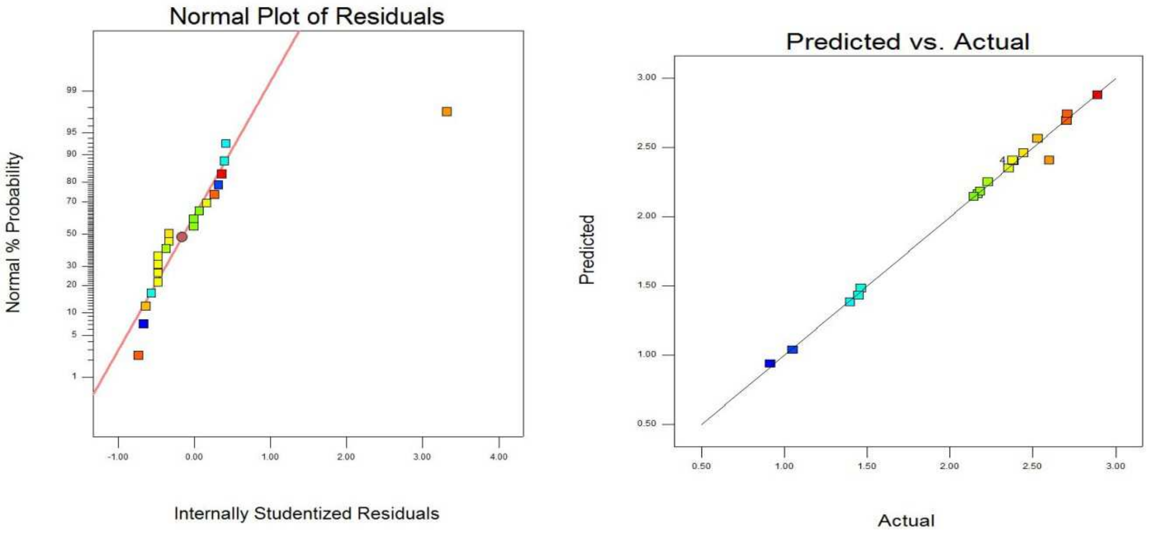

**Figure 5 For Cutting Speed A) Residual Plot B) Predicted and Actual Value**

The residual analysis as a primary diagnostic tool is also done. Normal probability plot of residuals has been drawn (Figure 5 a). All the data points are following the straight line. Thus the data is normally distributed. It can be seen from Figure 5 b that all the actual values are following the predicted values and thus declaring model assumptions are correct.

## 5. Conclusions

The important conclusions drawn from the present study are summarized below:

1. For cutting speed, Pulse on time (A), pulse off time (B), peak current (C), spark gap set voltage (D), are the significant factors. The higher is the current setting, higher the cutting speed.
2. For cutting speed, Pulse off time (B), Peak current, Spark gap set voltage (D) and few interactions BC and quadratic terms ($A^2$, $B^2$, $C^2$) are significant.
3. The technique presented in this study might also be tried for the other non-traditional machining processes such as electro chemical machining, electron beam machining, laser beam machining, and water jet machining operations for effective utilization of such machine tools. This technique can also be applied for the various conventional
4. The experimental values are in good agreement with the predicted values, thus the results are validated.

## References

[1] T. Spedding and Z. Wang, “Parametric optimization and surface characterization of wire electrical discharge machining process,” *Precis. Eng.*, 1997.

[2] D. Scott, S. Boyina, and K. Rajurkar, “Analysis and optimization of parameter combinations in wire electrical discharge machining,” *Int. J.*, 1991.

[3] “NC wire spark erosion - a survey.,” 1976. [Online].

[4] G. G. Kinoshhita N, Fukui M, “Study on EDM with wire electrode; Gap phenomena.,” 1976.

[5] T. Tanimura, “The properties of the servo gap sensor with wire spark-erosion machining,” *Ann. CIRP*, 1977.

[6] N. Kinoshita, M. Fukui, and G. Gamo, “Control of wire-EDM preventing electrode from breaking,” *CIRP Ann. Technol.*, 1982.

[7] D. Dauw and L. Albert, “About the evolution of wire tool performance in wire EDM,” *CIRP Ann. Technol.*, 1992.

[8] Y. Tarng, S. Ma, and L. Chung, “Determination of optimal cutting parameters in wire electrical discharge machining,” *Int. J. Mach. Tools*, 1995.

[9] W. Hsue, Y. Liao, and S. Lu, “Fundamental geometry analysis of wire electrical discharge machining in corner cutting,” *Int. J. Mach. tools*, 1999.

[10] C. Lin, I. Chung, and S. Huang, “Improvement of machining accuracy by fuzzy logic at corner parts for wire-EDM,” *Fuzzy sets Syst.*, 2001.

[11] R. Scattergood, “Development of the cylindrical wire electrical discharge machining process, part 2: surface integrity and roundness,” 2002.

[12] M. Gökler and A. Ozanözgü, “Experimental investigation of effects of cutting parameters on surface roughness in the WEDM process,” *Int. J. Mach. tools*, 2000.

[13] A. Puri and B. Bhattacharyya, “An analysis and optimisation of the geometrical inaccuracy due to wire lag phenomenon in WEDM,” *Int. J. Mach. tools*, 2003.

[14] K. L. Ramakrishnan R, “Surface roughness model for CNC wire electro discharge machining,” 2004.

[15] C. Tzeng, Y. Lin, Y. Yang, and M. Jeng, “Optimization of turning operations with multiple performance characteristics using the Taguchi method and Grey relational analysis,” vol. 9, pp. 2753–2759, 2008.