

# Investigation of Material Removal Rate for wire-cut EDM of EN-31 Alloy Steel using Taguchi Technique

Surinder Kumar<sup>1\*</sup> and Parveen Kumar<sup>2</sup>

<sup>1</sup>Associate Professor, Mechanical Engineering Department, Chandigarh Engineering College, Landran (Mohali), INDIA,  
Corresponding author E-mail: [surinder.asd@gmail.com](mailto:surinder.asd@gmail.com)

<sup>2</sup>Assistant Professor, Mechanical Engineering Department, Shivalik College of Engineering, Dehradun, INDIA, E-mail: [parviin@gmail.com](mailto:parviin@gmail.com)

**Abstract**— This paper presents the investigation on material removal rate of EN-31 alloy steel using wire-cut EDM process. Process parameters (pulse-on-time, pulse-off-time, spark gap voltage, wire feed) were investigated using Taguchi's robust design methodology. The EN-31 alloy steel is used as a work piece, brass wire of 0.25mm diameter used as a tool and distilled water is used as dielectric fluid for experimentation. Taguchi L<sub>16</sub>, orthogonal array has been used. The relative significance of various factors has also been evaluated and analyzed using ANOVA. The experimental results reveal that the most significant machining parameter for material removal rate is pulse-on-time, followed by pulse-off-time. The material removal rate increases with increase in Pulse on time, Wire feed and decreases with increase in Pulse off time and nominal with increase in Spark voltage. The predicted values and measured values are in good agreement as observed by further confirmation experiments.

**Keywords** - WEDM, EN-31 alloy steel, Material Removal Rate, Taguchi technique

## 1 INTRODUCTION

Recent developments in mechanical industry have fuelled the demand for materials having high toughness, hardness and impact resistance. These materials are difficult to machine with traditional methods. (Mahapatra, 2006). Due to advent of new materials and globalization, the need to reduce the cost of machining and meeting the stringent customer requirements has arisen. This requirement has become more important due to the use of nontraditional machining processes like EDM, USM and Laser beam machining to machine hard to cut materials and very complex shapes. The common application of wire electrical discharge machining include the fabrication of stamping and extrusion tools and dies, fixtures and gauges, prototypes, aircraft and medical parts and Grinding wheels form tools. Recent development in technology has led to the vast use of engineering materials with high strength and hardness. Traditional machining processes have been replaced by nontraditional manufacturing processes such as wire electrical discharge machining (Ho et al., 2004). Kunieda and Furudate, (2001) investigated with High precision finish cutting by dry WEDM. The largest single use of EDM is in die making. Tosun and Cogun, (2003) evaluated the effect of cutting parameters on the wire wear ratio of the AISI 4140 steel using brass wire. Three parameters such as cutting speed, feed rate and depth of cut were selected to minimize the surface roughness. It was found that, increasing the pulse duration and open circuit voltage increased the wire wear ratio (WWR), whereas increasing the speed decreased it. Puri and Bhattacharyya, (2003) presented machinability study in the wire lag phenomenon in WEDM and the trend of variation of the geometrical inaccuracy caused

due to wire lag with various machine control parameters has been established. It was found that, the main influencing factors are determined for given machining criteria, such as average cutting speed, surface finish characteristic and geometrical inaccuracy caused due to wire lag. Manna and Bhattacharyya, (2006) established mathematical models relating to the machining performance criteria like MRR, SR, spark gap and gap current using the Gauss elimination method for effective machining of Al/SiC-MMC. Mahapatra and Patnaik, (2006) outline the development of a model and its application to optimize WEDM machining parameters. Experiments are conducted to test the model and satisfactory results are obtained. Mahapatra and Patnaik, (2007) developed relationships between various process parameters and responses like MRR, SR and kerf by means of non-linear regression analysis and then employed genetic algorithm to optimize the WEDM process with multiple objectives. Menzies and Koshy, (2008) investigated the machinability of hybrid wire EDM process that utilizes a wire embedded with electrically non-conducting abrasives as machining speed and surface integrity continue to be issues of focus in current wire EDM research. It was found that, the removal rate and generate surfaces with minimal recast material, in comparison to an equivalent wire EDM process. Gadakh, (2012) used TOPSIS method for solving multicriteria optimization problem in wire electro discharge machining process. It was found that, the optimal process parameter selection a good amount of research has been done using this area (TOPSIS). Nayak and Mahapatra, (2013) used AHP and TOPSIS method for optimization of multi-responses such as MRR, surface finish, and kerf. It was

found that, the methodology is capable of optimizing any type of problem with any number of responses. Ikram et al., (2013) reported the optimization of wire electrical discharge machining for tool steel D2 using Taguchi's L<sup>18</sup>orthogonal array, with eight control factors on material removal rate (MRR), surface roughness and kerf in WEDM process. Results show that MRR increases and surface roughness decreases with increase in pulse-on time, open voltage. MRR decreases with increase in servo voltage. Kerf increases with increase in open voltage, pulse-off time and wire tension. Surinder Kumar et al., (2014) proposed an approach for WEDM of a EN-31 alloy steel using brass wire. Four parameters such as pulse-on-time, pulse-off-time, spark gap voltage, wire feed were selected to maximize the material removal rate. It was concluded that the Pulse-on time (Ton) major factor affecting the MRR. The MRR increases with increase in Pulse on time, Wire feed and decreases with increase in Pulse off time and nominal with increase in Spark voltage. A comprehensive literature review has been performed on various aspects of WEDM process and has been summarized in Table 1. It is evident from the literature review; almost no investigation has been performed on the machinability of EN-31 Alloy Steel WEDM process. Moreover the investigations reported on WEDM of the other conventional materials (listed in Table 1) have been focused on parametric optimization of WEDM process with MRR as the responses of interest. In this paper Taguchi's DOE approach is used to analyze the effect of WEDM process parameters – pulse-on-time, pulse-off-time, spark gap voltage and wire feed on the material removal rate by using brass wire on EN-31 alloy steel and optimal setting of these parameters is found that may result in maximizing material removal rate.

## 2. METHODOLOGY

### 2.1 Single response optimisation

The Taguchi approach for predicting the mean performance characteristics and determination of confidence intervals for the predicted mean has been applied. Three confirmation experiments for each performance characteristics have been performed at optimal settings of the process parameters and the average value has been reported for material removal rate. The Taguchi method is a commonly adopted approach for optimizing design parameters. The method was originally proposed as a means of improving the quality of products through the application of statistical and engineering concepts. It is a method based on Orthogonal Array (OA) experiments, which provides much-reduced variance for the experiment resulting is optimum setting of process control parameters. Orthogonal Array (OA) provides a set of well-balanced experiments (with less number of experimental runs) and Taguchi's signal-to-

noise ratios (S/N), which are logarithmic functions of desired output, serves as objective function in the optimization process. The standard S/N ratios generally used are as follows: - Nominal-is-Best (NB), lower-the-better (LB) and Higher-the-Better (HB). The optimal setting is the parameter combination, which has the highest S/N ratio. In this study, material removal rate is taken "higher the better" type. The corresponding loss function can be expressed as follows (Ross, 1988).

Larger the better:

$$S/N = -10 \text{Log} \frac{1}{n} \sum \frac{1}{y^2} \quad (1)$$

"Where n is the number of observations, y is the observed data". The material removal rate (MRR) will be calculated using equation (2) this equation has been used by Rao et al. (2010).

$$MRR = F \times Dw \times H \quad (2)$$

Where F is the machine feed rate [mm/min], Dw is wire diameter [mm] and H is piecework thickness [mm] and MRR is material removal rate [mm<sup>3</sup> /min].

## 3. EXPERIMENTATION

Experiments were performed on Electronica Ecocut CNC wire electrical discharge machine to study the material removal rate affected by machining process variable at different setting of pulse-on time, pulse-off time, spark gap set voltage and wire feed. L<sub>16</sub> orthogonal array with four input variables was selected for experimentation. Figure 1 shows the experimental setup of the WEDM. Table 2 and Table 3 show the various process parameters with their values at four levels and L<sub>16</sub> orthogonal array respectively. EN-31 alloy steel (1.00% C, 0.20% Si, 0.50% Mn, 1.40% Cr) block of thickness 40 mm was used as work material. Work piece material, EN-31 plate size with 40 thk x 205 width x 205 length was used for all experimental investigations. A pure brass wire with a diameter 0.25mm was used as an electrode to erode a work piece, alloy steel EN 31. Electrolytic water was used as the dielectric fluid. The EN-31 alloy steel before machining as shown in Figure 2. The En-31 alloy steel after machining as shown in Figure 3.

Table 1: Summary of Recent Machining Optimizatio Technique

Summarizes the Review of Literature						
Sr. No.	Year /Author	Cutting Tool Materials	Input Parameters	Output Responses	Techniques	Researcher's Findings
1	Mahapatra (2007)	D2 tool steel	Discharge current, Pulse duration, Pulse frequency, wire tension, Dielectric flow rate, wire feed	MRR, Surface Roughness and kerf width	Taguchi's L27 orthogonal array and regression analysis	It was found that, the Discharge current, pulse duration; dielectric flow rate and the interaction between discharge current and pulse duration are most significant Parameters for cutting operation.
2	Ramakrishnan and Karunamoorthy (2006)	Heat treated tool steel	Pulse-on time, wire tension, feed speed, ignition current intensity, delay time, wire	MRR, wire wear ratio and surface roughness	Taguchi's L16 orthogonal array	It was found that, the Pulse-on time and ignition current had influenced more than the other parameters on MRR, SR and WW Ratio.
3	Jangra, Grover and Aggarwal (2011)	WC-Co composite	Pulse-on time, pulse-off time, peak current, wire tension, dielectric flow rate, taper angle	MRR, surface and roughness	GRA along with Taguchi method	It was found that, the Taper angle, pulse-on time and pulse-off time are the most significant parameters affecting the MRR and surface roughness.
4	Azhiri, Teimouri, Ghameshi and Leseman (2013)	Al/SiC metal matrix composite	Pulse-on time, pulse-off time, Discharge current, Gap voltage, Wire feed rate, Wire tension	Cutting velocity and Surface roughness	Taguchi's L27 orthogonal array and GRA	It was found that, the Pulse-on time and current are the most significant factors for cutting velocity and surface roughness.
5	Fard, Afza and Teimouri (2013)	Al-SiC metal matrix composite	Pulse-on time, pulse-off time, Wire feed rate, Wire tension, Discharge current, Gap voltage,	Surface roughness and Cutting velocity	Taguchi's L27 orthogonal array and AN-FIS	It was found that, the Pulse-on time and discharge current are the most significant factors for cutting velocity and surface roughness. Oxygen gas and brass wire gives superior cutting velocity.



Figure 1: Experimental setup Wire Cut Electrical Discharge Machining



Figure 2: Work piece & Brass wire before Wire Cut Electrical Discharge Machining



Figure 3: Work piece after Wire Cut Electrical Discharge Machining & profile in the form of bars

Table 2: L<sub>16</sub> orthogonal array with parameters

Parameter → No of Expt. ↓	Time-on (μs)	Time-off (μs)	W.F (kgf)	S.V (volts)
Sr. no.	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	1	4	4	4
5	2	1	2	3
6	2	2	1	4
7	2	3	4	1
8	2	4	3	2
9	3	1	3	4
10	3	2	4	3
11	3	3	1	2
12	3	4	2	1
13	4	1	4	2
14	4	2	3	1
15	4	3	2	4
16	4	4	1	3

Table 3: Process Parameters, Symbols and Ranges

Input Parameters	Symbols	Level 1	Level 2	Level 3	Level 4
Pulse on time μs	A	105	110	115	120
Pulse off time μs	B	25	35	40	45
Wire feed kgf	C	5	7	9	11
Spark vol-	D	35	40	45	50

tage volts					
------------	--	--	--	--	--

Table 4: Test data summary for MRR

Parameters→ No of Expt. ↓	Time-on (μs)	Time-off (μs)	W.F. (kgf)	S.V. (volts)	MRR (mm <sup>3</sup> /min)
1	105	25	5	35	8.42
2	105	35	7	40	6.67
3	105	40	9	45	5.9
4	105	45	11	50	4.3
5	110	25	7	45	12.3
6	110	35	5	50	11.4
7	110	40	11	35	10.67
8	110	45	9	40	9.37
9	115	25	9	50	15.23
10	115	35	11	45	14.67
11	115	40	5	40	12.1
12	115	45	7	35	10.4
13	120	25	11	40	25.89
14	120	35	9	35	22.86
15	120	40	7	50	17.78
16	120	45	5	45	13.97
					T <sub>MRR</sub> = 12.617 mm <sup>3</sup> /min

#### 4. RESULTS AND DISCUSSION

The results were analyzed using S/N ratio, response table & response graphs with help Minitab-16 software. Input parameters were set & OA L<sub>16</sub> was selected for experiment to get results for material removal rate values as follow. From Table 4 it has been found that the maximum MRR of 25.892mm<sup>3</sup>/min is achieved in trial 13 at pulse on time (120 μs), pulse off time (25 μs), wire feed (11 kgf) and spark voltage (40 volts). The highest level of Pulse on time, lowest Pulse off time, highest level Wire feed and moderate spark voltage resulted in maximum MRR. The MRR of 5.3mm<sup>3</sup>/min is obtained with trial 4, at the lowest pulse on time (105 μs), highest level Pulse off time (45 μs), highest Wire feed (11 kgf) and largest Spark voltage (50 volts). Response tables for MRR as shown in Table 5. Table 5 shows that pulse on time contributes the highest effect (Δ = 13.787) followed by pulse off time (Δ = 5.965) and wire feed (Δ = 2.425). The response curves for the individual effects of four process parameters for the value of material removal rate plotted as shown in Figure 4. The response graphs for material removal rate as shown in Figure 4. It is evident from the Figure 4 that the material removal rate is maximum at 4<sup>th</sup> level of pulse on time (A4), 1<sup>st</sup> level of pulse off time (B1), 4<sup>th</sup> level of wire feed (C4), 2<sup>nd</sup> level of spark voltage (D2). The results indicate that the material removal rate increases with increase in pulse on time, wire feed and decreases with increase in pulse off time and nominal with increase in spark voltage. Analysis of



Variance for material removal rate was performed to study effect of wire cut EDM parameters shown in table 6. Confidence level is chosen to be 95% in this study. So the P value which are less than 0.05 indicate that insignificant should be rejected. The variance ratio denoted by F in ANOVA table, is the ratio of the mean square and the error mean square due to a factor. The large value of F means that effect of that factor is large as compared to error variance. In table 6 shows that Pulse on time & pulse on time are significant factor due to values of P less than 0.05, Wire feed & Spark voltage are insignificant factors due to higher values. In table 6 shows that from the ANOVA result, it is concluded that pulse on time and pulse off time have significant effect on material removal rate while wire feed and spark voltage has no effect at 95% confidence level.

Table 5: Response Table for Means

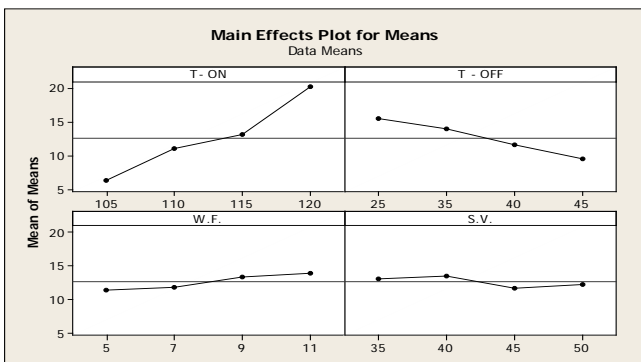
Levels	Time-on (μs)	Time-off(μs)	W.F. (kgf)	S.V. (volts)
1	6.323	15.460	11.458	13.088
2	10.935	13.900	11.788	13.508
3	13.100	11.613	13.340	11.695
4	20.110	9.495	13.883	12.178
Delta	13.787	5.965	2.425	1.813
Rank	1	2	3	4

Table 6: Analysis of variance for material removal rate

Source	DF	SS	V	F	P
Time-on(μs)	3	395.313	131.771	58.79	0.004
Time-off (μs)	3	81.939	27.313	12.19	0.035
W.F.(kgf)	3	16.627	5.542	2.47	0.238
S.V.(volts)	3	8.230	2.743	1.22	0.436
Error	3	6.724	2.241		
Total	15	508.833			

SS = sum of squares, DOF = degrees of freedom, variance (V) = (SS/DOF), T = total, SS' = pure sum of squares, P = percent contribution, e = error, F<sub>ratio</sub> = (V/error), Tabulated F-ratio at 95% confidence level F<sub>0.05; 1; 3</sub> = 10.1, \* Significant at 95% confidence level. S = 1.49709, R-Sq = 98.68%, R-Sq (adj.) = 93.39%

Figure 4: Main effects Plot for Means



The optimal material removal rate ( $\mu_{MRR}$ ) is predicted at the selected optimal setting of process parameters. The parameters and their selected levels are shown in Table 7. Three confirmation experiments are done at the optimal settings of the WEDM process parameters recommended by the investigation. Therefore, the optimum material removal rate (MRR= 25.89 mm<sup>3</sup>/min.) was obtained under the earlier-mentioned cutting condition on the WEDM machine. The significant parameters with optimal levels are already selected as: A4 and B1 (Ross, 1996).

$$\mu_{MRR} = T_{MRR} + (A4 - T_{MRR}) + (B1 - T_{MRR}) \quad (3)$$

Where,  $T_{MRR}$  = overall mean of material removal rate = 12.617 mm<sup>3</sup>/min. (from table 4)

A4 and B1 are the mean values of material removal rate with parameters at optimum levels,

A4=20.110 mm<sup>3</sup>/min, B1=15.460 mm<sup>3</sup>/min. (from table 5)

Hence  $\mu_{MRR} = 22.953$  mm<sup>3</sup>/min.

$$CI_{CE} = \sqrt{F_{\alpha}(1, f_e) V_e \left[ \frac{1}{n_{eff}} + \frac{1}{R} \right]} \quad (4)$$

Where  $F_{\alpha}(1, f_e) = F_{0.05}(1; 3) = 10.1$  (tabulated)

$\alpha$  = risk = 0.05,  $f_e$  = error DOF = 3 (table 6)

N = total number of experiments = 16

$V_e$  = error variance = 2.241 (from table 6)

Total DOF associated with the mean ( $\mu_{MRR}$ ) = 12, Total trial = 16, N=16×3 = 48,

$n_{eff}$  = effective number of replications

=  $N / \{1 + [\text{Total DOF associated in the estimate of mean}]\} = 48 / (1 + 12) = 3.69$

R = number of repetitions for confirmation experiment = 3

A confidence interval for the predicted mean on a confirmation run is ±3.698 using Equation (3)

The 95% confidence interval of the predicted optimal material removal rate is:

$$[\mu_{MRR} - CI] < \mu_{MRR} < [\mu_{MRR} + CI] \text{ i.e. } 19.255 < \mu_{MRR} < 26.651$$

Equation (4)

Three confirmation experiments are done at the optimal setting of the WEDM process parameters recommended by the investigation. Table 8 shows the single response optimization results. Table 9 shows the confirmatory experimental results. The mean values of the responses from these experiments are found to be within the confidence Interval. Table 10 shows the comparison of results between predicted optimal value and actual value for material removal rate.

Table 7: Parameters and their selected levels

Parameter designation	Process parameters	Optimal levels MRR
A	Pulse on time	120
B	Pulse off time	25
C	Wire feed	11 (the insignificant factor are set at economic levels)
D	Spark Voltage	40 (the insignificant factor are set at economic levels)

Table 8: Single Response Optimization Results

Method	Characteristics	Optimal condition	Optimal Predicted Value
Single Response Optimization	material removal rate	A4 B1 C4 D2	22.953mm <sup>3</sup> /min

Table 9: Confirmatory Experimental Result

Response	Predicted value	Optimal Experimental Value	CI <sub>CE</sub>
MRR (mm <sup>3</sup> /min)	22.953mm <sup>3</sup> /min	25.89 mm <sup>3</sup> /min	19.255 < μ <sub>MRR</sub> < 26.651

Table 10: Actual value for Material Removal Rate

Re-sponse	Optimal set of Parameters	Predicted Optimal Value	Predicted Confidence Interval at 95% Confidence level	Actual Value
MRR	A4 B1 C4 D2	22.953mm <sup>3</sup> /min	19.255 < μ <sub>MRR</sub> < 26.651	25.89 mm <sup>3</sup> /min

## 5. CONCLUSIONS

In this research part, the effect of machining parameters on the machining outputs of EN-31 alloy steel was investigated experimentally in wire cut electric discharge machining.

Pulse-on time (Ton) was found to be the major factor affecting the MRR. The MRR increases with increase in Pulse on time, Wire feed and decreases with increase in Pulse off time and nominal with increase in Spark voltage.

It is concluded that, the maximum MRR of 25.89mm<sup>3</sup>/min is achieved in trial 13 at Pulse on time (120 μs), Pulse off time (25 μs), Wire feed (11 kgf) and Spark voltage (40 volts). The highest level of Pulse on time, lowest Pulse off time, highest level Wire feed and moderate Spark voltage resulted in maximum material removal rate.

ANOVA result, it is found that A and B have significant effect on MRR. C and D have no effect at 95% confidence level. It is found that pulse on time is more significant factor than other parameters, whilst pulse off time is the least significant parameter.

The predicted range of the optimal material removal rate is: 19.255 < μ<sub>MRR</sub> (mm<sup>3</sup>/min) < 26.651

## REFERENCES

- [1] A.R. Bagherian, R. Teimouri, B.M. Ghasemi, Z. Leseman, "Application of Taguchi, ANFIS and grey relational analysis for studying, modeling and optimization of wire EDM process while using gaseous media," *The International Journal of Advanced Manufacturing Technology*, Vol. 71, No. 1, pp. 279–295, 2014.
- [2] R.K. Fard, R.A. Afza, R. Teimouri, " Experimental investigation, intelligent modeling and multi-characteristics optimization of dry WEDM process of Al- SiC metal matrix composite," *Journal of Manufacturing Processes*, Vol. 15, No. 4, pp. 483–494, 2013.
- [3] V.S. Gadakh, "Parametric optimization of wire electric discharge machining using TOPSIS method," *Advances in Production Engineering and Management*, Vol. 7, No. 3, pp. 157–164, 2012.
- [4] K.H. Ho, S.T. Newman, S. Rahimifard, R.D. Allen, " State of art in wire electrical discharge machining (WEDM)," *International Journal of Machine Tools and Manufacture*, Vol. 44, No. 12–13, pp. 1247–1259, 2004.
- [5] A. Ikram, N.A. Mufti, M.Q. Saleem, A.R. Khan, "Parametric optimization for surface roughness, kerf and MRR in wire electrical discharge machining (WEDM) using Taguchi design of experiment," *Journal of Mechanical Science and Technology*, Vol. 27, No. 7, pp. 2133–2141, 2013.
- [6] K. Jangra, S. Grover, A. Aggarwal, "Simultaneous optimization of material removal rate and surface roughness for WEDM of WCCo composite using grey relational analysis along with Taguchi method," *Int. J. Ind. Eng. Comput.*, Vol. 2, pp. 479–490, 2011.
- [7] A., Manna, B. Bhattacharyya, "Taguchi and Gauss elimination method: A dual response approach for parametric optimization of CNC wire cut EDM of PRAISICMMC," *International Journal of Advanced Manufacturing Technology*, Vol. 28, pp. 67–75, 2006.
- [8] S.S. Mahapatra, A. Patnaik, "Parametric optimization of Wire Electrical Discharge Machining (WEDM) Process using Taguchi Method," *Journal of Brazilian Society of Mechanical Science & Engineering*, Vol. 8, 2006.

- [9] S.S. Mahapatra, A. Patnaik, "Optimization of wire electrical discharge machining (WEDM) process parameters using Taguchi method," *International Journal of Advanced Manufacturing Technology*, Vol. 34, pp. 911-925, 2007.
- [10] Menzies, P. Koshy, "Assessment of abrasion-assisted material removal in wire EDM," *CIRP Annals- Manufacturing Technology*, Vol. 57, No. 1, pp. 195-198, 2008.
- [11] B.B. Nayak, S. S. Mahapatra, "Multi-response optimization of WEDM process parameters using the AHP and TOPSIS method. *International Journal on Theoretical and Applied Research in Mechanical Engineering*, Vol. 2, No. 3, pp. 109-215, 2013.
- [12] Pujari Srinivasa Rao, Koonam Ramji, Beela Satyanarayan, "A Prediction of Material removal rate for Aluminum BIS-24345 Alloy in wire-cut EDM," *International Journal of Engineering Science and Technology*, Vol. 2, No. 12, pp. 7729-7739, 2010.
- [13] .B., Puri, B. Bhattacharyya, "An analysis and optimization of the geometrical inaccuracy due to wire lag phenomenon in WEDM," *International Journal of Machine Tools & Manufacture*, Vol. 43, pp. 151-159, 2003.
- [14] R. Ramakrishnan, L. Karunamoorthy, "Multi response optimization of wire EDM operations using robust design of experiments," *Int. J. Adv. Manuf. Technology*, Vol. 29, pp. 105-112, 2006.
- [15] P.J. Ross, "Effective Engineering design through simulation," *International transactions in operational research and Taguchi techniques for Quality Engineering*, Vol. 3, No. 2, pp. 169-185, 1996.
- [16] S.S. Mahapatra, A. Patnaik, "Parametric optimization of wire electrical discharge machining (WEDM) process using taguchi method," *J. Braz. Soc. Mech. Sci. Eng.*, Vol. 28, pp. 422-429, 2006.
- [17] Surinder Kumar, Sanjeev Kumar, Vipin Kumar, "Investigation of Cutting Rate in Wire Cut Electrical Discharge Machining with EN-31 Alloy Steel using Single Objective Taguchi Method," *International Conference on Newest Drifts in Mechanical Engineering*, pp. 528-535, 2014.
- [18] N., Tosun, C. Cogun, "An Investigation of Wire Wear in WEDM," *Journal of Materials Processing Technology*, Vol. 134, pp. 273-278, 2003.