International Journal of Hybrid Information Technology
Vol. 9, No. 5 (2016), pp. 343-358
http://dx.doi.org/10.14257/ijhit.2016.9.5.29

Effect and Optimization of EDM Process Parameters on Surface Roughness for En41 Steel

Ch. Maheswara Rao[1] and K.Venkatasubbaiah[2]

[1](Assistant Professor, Department of Mechanical Engineering, Raghu Institute of Technology, Visakhapatnam, India)
[2](Professor, Department of Mechanical Engineering, Andhra University, Visakhapatnam, India)
[1]mahe.mech129@gmail.com, [2]drkvsau@yahoo.co.in

Abstract

*Unconventional machining is gaining more and more importance in today's manufacturing methods because of its applications over conventional machining. Machining of Complex shapes, high dimensional accuracy and good surface finish can be achieved by unconventional machining processes. Surface Finish is an important quality characteristic for machined parts. In the present work, an investigation has been done to find the effect of EDM process parameters on Surface Roughness in machining of medium carbon steel EN41. For the experimentation, Pulse on time (P_{ON}) and Pulse off time (P_{OFF}), wire tension (WT) and wire speed or wire feed (WF) are selected as input parameters and Surface Roughness (R_a) is considered as a response. The experiments were performed on CNC- EDM machine as per Taguchi's standard L27 (3level*4factors) Orthogonal array. Taguchi's single objective optimization method is used to find the optimal combination of process parameters affecting the Surface Roughness. From the results, the optimal combination of process parameters is found at P_{ON} (level 2, value 123 μs), P_{OFF} (level 2, value 58 μs), WT (level 1, value 2 Kg-f) and WF (level 1, value 4 m/min). From Analysis of variance (ANOVA) results, Wire Feed rate has high influence (F = 61.94, P = 0.000) in effecting the Surface Roughness and Pulse ON time has the least influence (F = 1.99, P = 0.166) among all the process parameters. A Mathematical model was developed for Surface Roughness by using MINITAB-16 software. The model is a good fit and it can be used for the prediction of Surface Roughness as it has low variance (S = 0.608144) and high Coefficient of determination value (R-Sq = 82.4%). The model values are compared with experimental values and they found very close to each other.*

***Keywords**: Taguchi, ANOVA, Regression Analysis, Surface Roughness (R_a)*

1. Introduction

Electrical Discharge Machining (EDM) is a thermo-electrical process in which material is eroded by a series of sparks generated between the workpiece and electrode tool. Workpiece and the electrode are immersed in a dielectric fluid. In EDM, dielectric fluid acts as a coolant and to maintain a constant gap between the workpiece and electrode. During machining, there will be no contact between workpiece and the electrode, thus materials of any hardness can be cut as long as they can conduct electricity, physical pressure imparted on the workpiece is low and the amount of clamping pressure required to hold the workpiece is also minimized. EDM process has wide applications in aero space, nuclear and automotive industries to machine precise, complex and irregular shapes.[1-2] Wire EDM process parameters are Pulse on time (P_{ON}), Pulse off time (P_{OFF}), Peak current, gap voltage, servo voltage, servo feed rate, dielectric flow rate, wire speed or wire feed and wire tension, etc. Electric discharge machining must occur (ON time) and stop (OFF time) alternately during machining. During the ON time, the voltage is

ISSN: 1738-9968 IJHIT

applied to the gap between the workpiece and the electrode (wire), while no voltage is placed during the OFF time. Consequently, electric discharge occurs only for the duration of the ON time. Peak current is the amount of power used in WEDM and measures in amperes. During each pulse ON time, the current increases until it reaches a preset level and is governed by the surface area of the cut. High currents will be used for rough operations and for cavities with large surface areas. Gap voltage represents the voltage to be placed in the gap between workpiece and the electrode. Servo voltage (SV) is used for controlling advances and retracts of the wire. The servo feed rate represents the feed rate of the table during machining and it can be manually set in WEDM. In general, electric discharge can be occurring in the air, but it is not stable and cannot be used for rough machining. To obtain stable electric discharge dielectric fluid is required. Within the dielectric fluid, electric discharge machining can be stabilized with efficient cooling and chip removal. The deionised water is typically used as a dielectric in wire EDM. As the wire speed increases, the wire consumption and the cost of machining will increase while low wire speed can cause to wire breakage in high cutting speed. Wire tension is the factor that controls the tension of the wire in WEDM. If the wire tension is high enough the wire stays straight otherwise the wire will bend.[3-6] Different process responses in WEDM are Material Removal Rate, Electrode wear rate and Surface Roughness etc. In any conventional machining process it is difficult to produce a perfectly smooth surface, imperfection and irregularities may be found. These irregularities on the surfaces are present in the form of a succession of hills and valleys varying in height and spacing. These irregularities are usually termed as surface roughness (or) surface finish. Irregularities on the surfaces are responsible to a great extent for the appearance of a surface of machined components and its suitability for an intended application. The properties like fatigue resistance, dimensional tolerances, wear, frictional wear and corrosion of machined components will get affected by surface roughness. The surface quality of machined components depends on various parametric conditions of machine. [7-11] Unconventional machining became more popular than conventional because of its applications like good surface finish, high dimensional tolerances can be achieved, avoid manual errors, easy to machine complicated and difficult shapes, etc.

In the present work, an attempt has been made to investigate the effect of EDM process parameters on Surface Roughness (R_a) in Machining of medium carbon steel EN41. EN graded materials are medium carbon steels having high applications in tool, oil and gas industries. They commonly used for axial shafts, propeller shafts, crank shafts, high tensile bolts and studs, connecting rods, riffle barrels and gears manufacturing, etc.[12] The experiments were performed on ULTRACUT with pulse generator ELPULS 50-f CNC- EDM machine as per Taguchi's standard L27 (3level*4factors) Orthogonal array. For the experimentation, Pulse on time (P_{ON}), Pulse off time (P_{OFF}), wire tension (WT) and wire speed or wire feed (WF) are selected as input parameters and Surface Roughness considered as an output. Taguchi's single objective optimization method has been used to find the optimal combination of process parameters affecting the Surface Roughness. Analysis of variance (ANOVA) is used to find the significance of process parameters on the response. A Mathematical model was developed for Surface Roughness by using MINITAB-16 software. The model values are compared with experimental values and the accuracy and adequacy of the models are checked using Regression Analysis. [13-18]

2. Experimental Details

Medium carbon steel EN41 has been considered in the present work. All the experiments were performed on ULTRACUT with pulse generator ELPULS 50f EDM machine as per Taguchi's standard L27 Orthogonal Array. Brass wire of 0.25mm diameter and water is used as wire electrode and dielectric fluid respectively. Brass wire is a combination of copper and zinc (63-65 % cu & 35-37% Zn). The addition of zinc provides high tensile strength, low melting point and high vapour pressure rating properties of the electrode wire. The work piece material and machined components of EN41 are shown in figures 1 and 2. Chemical composition of EN41 is given in the table 1. The parameters and their ranges available on CNC WEDM are given in the table 2. After machining, the machined surfaces are cleaned with acetone solution and Surface Roughness is measured at three different points by using a surface profile meter shown in figure 3 and the average value is considered as a response.

Table 1. Chemical Composition of En41 Steel

Element	%Weight
C	0.35-0.45
Mn	0.65
Si	0.10-0.45
S	0.05
P	0.05
Cr	1.40-1.80
Ni	0.40
Mo	0.10-0.25
Al	0.9-1.30

Table 2. Parameters Range Available on CNC WEDM Machine

S.no	Parameters	Units	Range
1	Pulse on time (T_{ON})	µs	115-131
2	Pulse off time (T_{OFF})	µs	40-63
3	Peak current	Ampere	180-230
4	Spark gap voltage	Volts	10-20
5	Wire feed (WF)	m/min	0-10
6	Wire tension (WT)	Kg-f	0-5
7	Flushing pressure	Kg/cm^2	3-15

Figure 1. EN41 Work Piece

Figure 2. EN41 Machined Components

Figure 3. Surface Roughness Gauge

3. Methodology

In the present work, Taguchi's single objective optimization method is used to know the effect of EDM process parameters on Surface Roughness. Taguchi parametric design is a robust design which can be applied for all the engineering optimization problems. Taguchi has proposed a special design called orthogonal array (OA) which covers the entire design space with a limited number of experimentations. Taguchi method is most commonly used because of its Robust design and it minimizes the experimentation time and cost. For the experimentation, four input parameters Pulse on time (P_{ON}), Pulse off time (P_{OFF}), wire tension (WT), wire speed or wire feed (WF) are selected at three different levels. Standard L27 OA (3levels * 4factors) has been selected for conducting experiments. L27 OA consisting of four columns and 27 rows. 4 columns, each for four selected input parameters of EDM and 27 rows represent the number of experiments to be done. The selected machining parameters with their levels and L27 Orthogonal Array are given in the tables 3 and 4. For the analysis of Surface Roughness Lower-the-better Signal-to-noise characteristic has been used. In addition to Taguchi method, Analysis of variance (ANOVA) is used to find the influence of machining parameters on Surface Roughness. A Mathematical model was developed for Surface Roughness by using MINITAB-16 software. The accuracy and adequacy of the models were checked and experimental values are compared with model values.

Smaller-the-better:

It is used where the smaller value of response is desired.

S/N ratio = $-10 \log_{10} [Y_i^2]$

Where, Y_i is observed response.

The steps involved in Taguchi method are:

a) Determination of the quality characteristics to be optimized.
b) Identification of the noise factors and test conditions.
c) Identification of the control factors and their levels.
d) Designing the matrix experiment and defining the data analysis procedure.
e) Conducting the matrix experiment.
f) Analyzing the data and determining the optimum levels of control factors.
g) Predicting the performance at these levels.

Table 3. Experiment Input Parameters and Their Levels

S.no	Parameters	Units	Level 1	Level 2	Level 3
1	Pulse on time (TON)	µs	115	123	131
2	Pulse off time, (TOFF)	µs	53	58	63
3	Wire tension (WT)	Kg-f	02	03	04
4	Wire feed rate (WF)	m/min	04	05	06

Table 4. L27 Orthogonal Array

S.no	Actual design				Experimental values			
	P_{ON}	P_{OFF}	WT	WF	P_{ON}	P_{OFF}	WT	WF
1	1	1	1	1	115	53	2	4
2	1	1	2	2	115	53	3	5
3	1	1	3	3	115	53	4	6
4	1	2	1	2	115	58	2	5

5	1	2	2	3	115	58	3	6
6	1	2	3	1	115	58	4	4
7	1	3	1	3	115	63	2	6
8	1	3	2	1	115	63	3	4
9	1	3	3	2	115	63	4	5
10	2	1	1	2	123	53	2	5
11	2	1	2	3	123	53	3	6
12	2	1	3	1	123	53	4	4
13	2	2	1	3	123	58	2	6
14	2	2	2	1	123	58	3	4
15	2	2	3	2	123	58	4	5
16	2	3	1	1	123	63	2	4
17	2	3	2	2	123	63	3	5
18	2	3	3	3	123	63	4	6
19	3	1	1	3	131	53	2	6
20	3	1	2	1	131	53	3	4
21	3	1	3	2	131	53	4	5
22	3	2	1	1	131	58	2	4
23	3	2	2	2	131	58	3	5
24	3	2	3	3	131	58	4	6
25	3	3	1	2	131	63	2	5
26	3	3	2	3	131	63	3	6
27	3	3	3	1	131	63	4	4

4. Results and Discussions

The experimental values of Surface Roughness and their S/N ratios are given in the table 5. Twenty seven experiments have been conducted to prepare twenty seven components as per specified L27 OA design.

Table 5. Experimental and S/N Ratios of Surface Roughness

S. No.	Ra (EN41)	S/N (EN41)
1	2.56	-8.165
2	4.68	-13.405
3	6.41	-16.137
4	3.21	-10.130
5	5.29	-14.469
6	2.54	-8.097
7	6.03	-15.606
8	3.26	-10.264
9	4.94	-13.875
10	3.01	-9.571
11	6.23	-15.890
12	2.31	-7.272
13	3.54	-10.980
14	2.24	-7.005
15	4.53	-13.122
16	2.10	-6.444
17	4.78	-13.589
18	5.79	-15.254
19	4.48	-13.026
20	3.13	-9.911
21	4.51	-13.084
22	2.45	-7.783
23	3.61	-11.150
24	5.74	-15.178
25	4.19	-12.444
26	4.96	-13.910
27	3.34	-10.475

From the experimental results, mean values of process parameters at their levels were calculated and given in the table 6. From the table 6, main effect plots for surface roughness of EN41 steel were drawn and shown in figures 4 and 5. The plots show the variation of R_a with process parameters. In the plots, the X-axis indicates the value of each process parameters at their levels and Y-axis the response value. Horizontal line indicates the mean value of the response. From the figure 5, it is observed that initially R_a is decreased and then increased with an increase in levels of T_{ON} and T_{OFF}. R_a value is increased gradually with an increase in levels of WT and it is more significant in case of WF.

Table 6. Response Table for Means of R_a

Level	T_{ON}	T_{OFF}	WT	WF
1	4.324	4.147	3.508	2.659
2	3.837	3.683	4.242	4.162
3	4.046	4.377	4.457	5.386
Delta	0.488	0.693	0.949	2.727
Rank	4	3	2	1

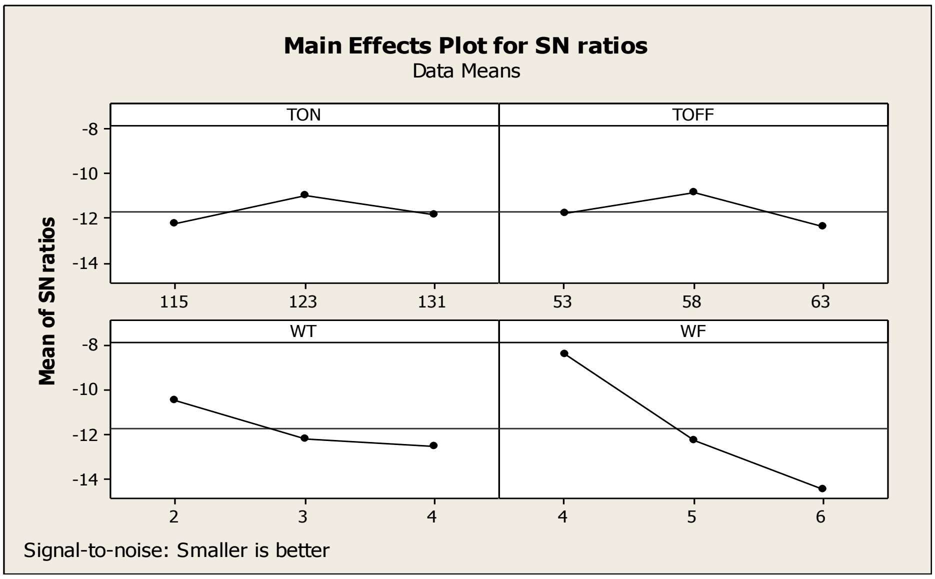

Figure 4. Main Effect Plot for S/N ratios of Surface Roughness

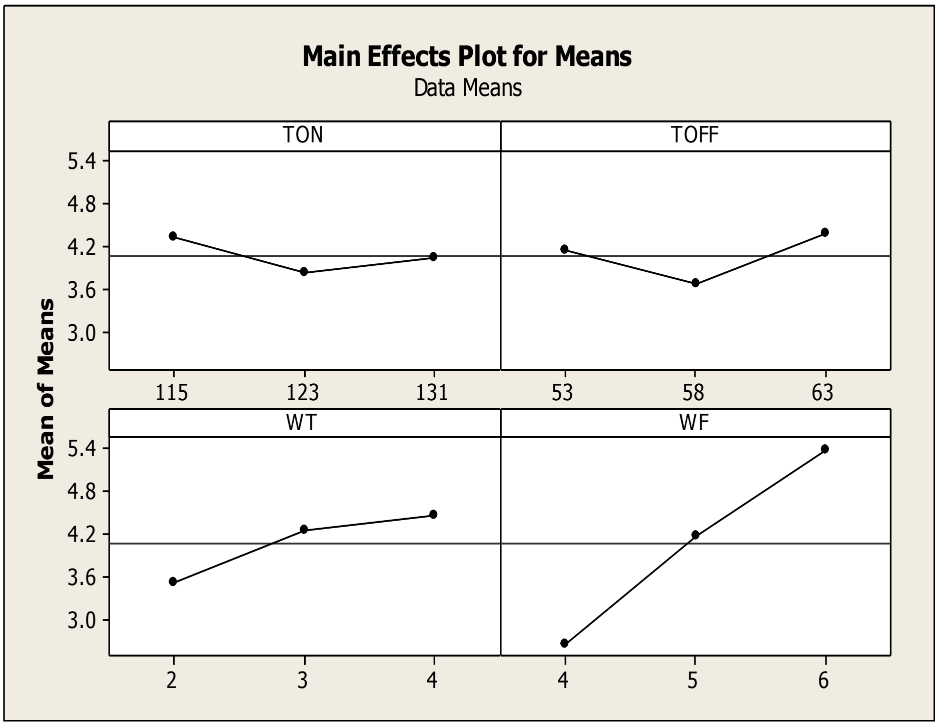

Figure 5. Main Effect Plot for means of Surface Roughness

From the mean response table and main effect plot for Surface Roughness the optimal combination of process parameters for the response is found and given in the table 7. Optimal Combination is P_{ON} (level 2, value 123 µs), P_{OFF} (level 2, value 58 µs), WT (level 1, value 2 Kg-f) and WF (level 1, value 4 m/min).

Table 7. Optimal Combination of Process Parameters for R_a

S. No.	Parameter	Units	Level	Value
1	Pulse on time (T_{ON})	µs	2	123
2	Pulse off time (TOFF)	µs	2	58
3	Wire Tension (WT)	Kg-f	1	2
4	Wire Feed (WF)	m/min	1	4

Analysis of variance was performed to find the significance of process parameters on Surface Roughness. From the results given in the table 8, it is found that the wire feed rate is the most significant parameter followed by wire tension and pulse time off. Pulse on time has very least significance among all the process parameters in effecting the surface roughness. F-test decides whether the parameters are significant or not. A large F value shows the greater impact on response value. Larger F-value is observed for wire feed as 61.94.

Table 8. Anova of R_a

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Significance
T_{ON}	2	1.0780	1.0780	0.5390	1.99	0.166	-
T_{OFF}	2	2.2449	2.2449	1.1224	4.14	0.033	Significant
WT	2	4.4574	4.4574	2.2287	8.22	0.003	Significant
WF	2	33.5738	33.5738	16.7869	61.94	0.000	Significant
Error	18	4.8784	4.8784	0.2710			
Total	26	46.2325					

S =0.520599 R-Sq = 89.45% R-Sq(adj) = 84.76%

Interactions between the parameters were studied by using interaction plot drawn and shown in figure 6. In the interaction plot crossed lines represent that interactions are present among the parameters at specific levels. Straight, parallel lines represent no evidence of an interaction among the parameters.

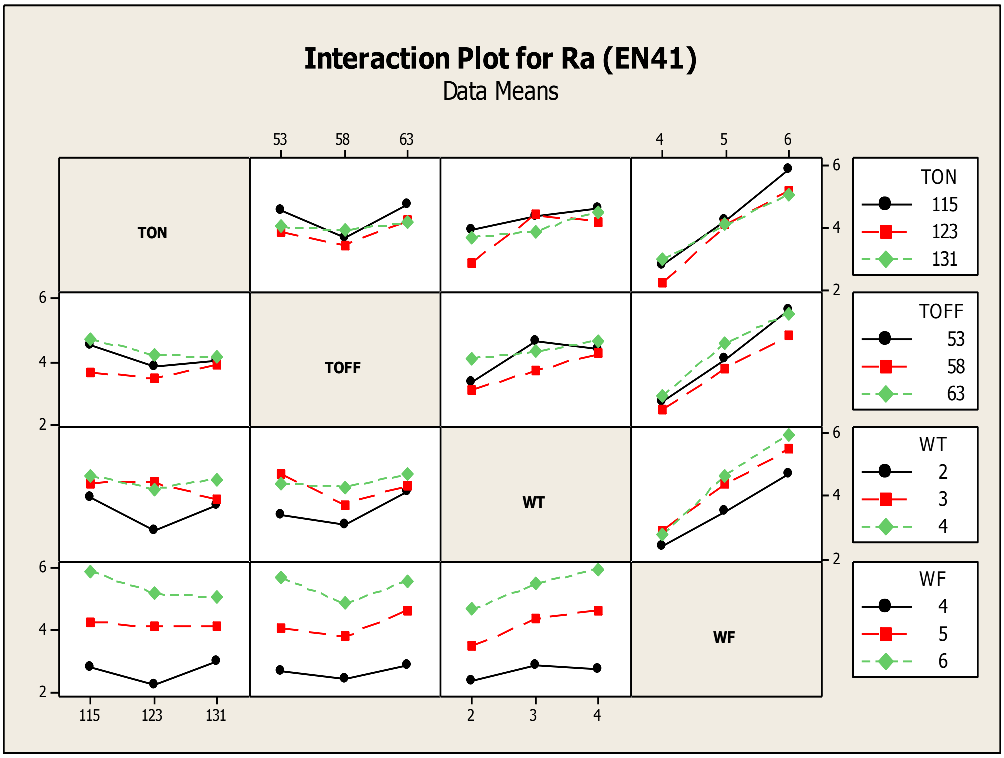

Figure 6. Interaction Plot for R_a

Prediction of optimal design

Performance of R_a when two most significant factors are at their better level (based on estimated average)

In the present work, two most significant factors are wire feed and wire tension at level 1.

$\mu_{A1B1} = A_1 + B_1 - T$

Where, $A_1 = 2.659$; $B_1 = 3.508$ (From table 6)

and T (Average of surface roughness values) = 4.449 (From Table 5)

$\mu_{A1B1} = A_1 + B_1 - T$

$\mu_{A1B1} = 2.659 + 3.508 – 4.449 = 1.718$

$CI = \sqrt{((F_{95\%,1,doferror}\ V_{error})/(\eta_{efficiency}))}$

Where, $\eta_{efficiency} = N/(1+dof)$

N = Total number of experiments

Dof = Degree of freedom for two significant factors

= 27/ (1+2+2) = 27/5 = 5.4

$V_{error} = 0.2710$ (From table 8)

$F_{95\%,1,18} = 4.4139$ (From standard F-table)

$CI = \sqrt{(4.4139 \times 0.2710)/5.4} = 0.4706$

The predicted optimal range of Ra at 95% confidence level is obtained as

$\mu_{A1B1} – CI \le \mu_{A1B1} \le \mu_{A1B1} + CI$

$1.718 – 0.4706 \le \mu_{A1B1} \le 1.718+0.4706$

$1.2474 \le \mu_{A1B1} \le 2.1886$

5. Regression Analysis

Regression model for the surface roughness was prepared to know the empirical relationship between responses and process parameters. A Mathematical model for surface roughness was developed by using MINITAB-16 software. The model prepared is checked for its accuracy and adequacy. Regression Analysis given in the table 9, model has low variance (S = 0.608144) and high coefficient of determination (R-Sq = 82.4%) value hence, the model can be used for the prediction of Surface Roughness.

The relation between Surface roughness and input parameters is given in equation 1.

$R_a = - 3.36 - 0.0174\ T_{ON} + 0.0230\ T_{OFF} + 0.474\ WT + 1.36\ WF$ (1)

Table 9. Regression Analysis

Predictor	Coef	SE Coef	T	P
Constant	-3.361	2.887	-1.16	0.257
T_{ON}	-0.01743	0.01792	-0.97	0.341
T_{OFF}	0.02300	0.02867	0.80	0.431
WT	0.4744	0.1433	3.31	0.003
WF	1.3633	0.1433	9.51	0.000

S = 0.608144 R-Sq = 82.4% R-Sq(adj) = 79.2%

Table 10. Analysis of Variance

Source	DF	SS	MS	F	P	Significance
Regression	4	38.0960	9.5240	25.75	0.000	Significant
Residual Error	22	8.1365	0.3698			
Total	26	46.2325				

The assumptions of ANOVA like normality, constant variance and independence are checked with Residual plots drawn by using MINITAB-16 software and shown in figure 7. The diagnostic checking has been performed through residual analysis for the model. The residuals are falling on a straight line implying that errors are distributed normally. From the residual plots is can be concluded that all the values are within the confidence level of 95%. Hence, these values yield better results in the prediction of Surface Roughness. Residual plots indicated that there is no obvious pattern and unusual structure. Hence, it can be concluded that the residual analysis does not indicate any model inadequacy.

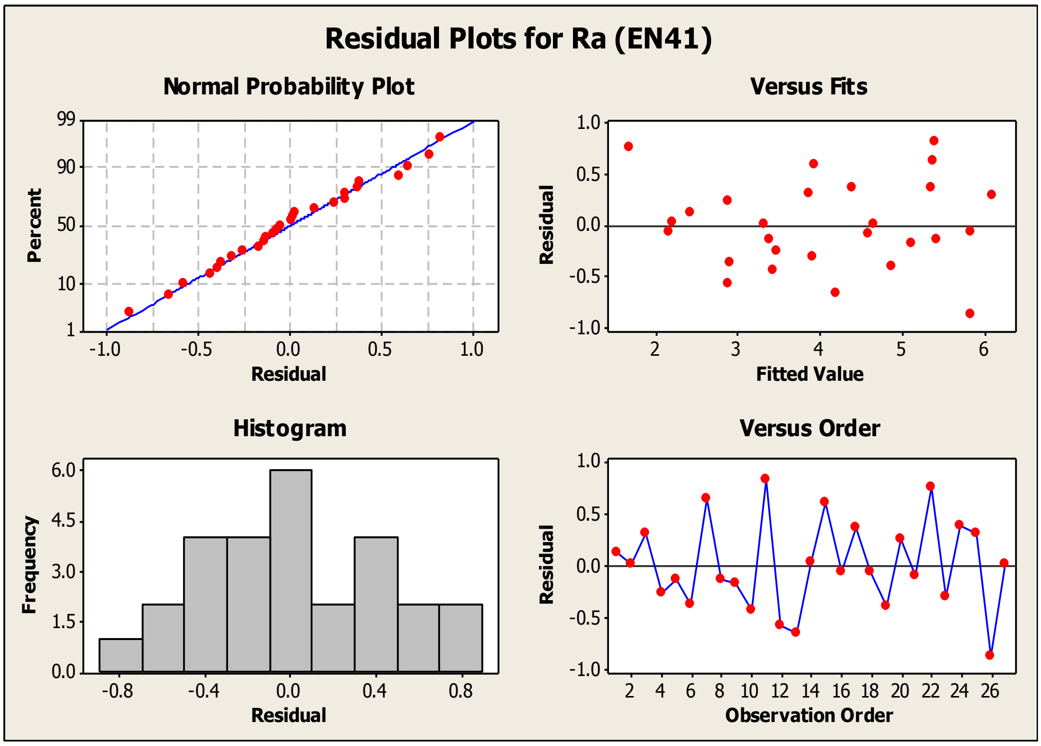

Figure 7. Residual Plots for R_a

The Surface and Contour plots were drawn by using MINITAB-16 software to find the relation between Response variable and input parameters. Surface plots show how a response variable relates to two factors based on model equation. Figure 8 shows how the Pulse on time (T_{ON}) and Pulse off time (T_{OFF}) related to Surface Roughness (R_a). Surface roughness value is initially decreased and then increased with the change in levels of T_{ON} and T_{OFF} and to minimize R_a, we have to choose medium level values of T_{ON} and T_{OFF}. Figure 9 shows how the Wire Tension (WT) and Wire Feed (WF) related to Surface

Roughness (R_a). From the plot, we can observe that R_a value is increasing with an increase in levels of wire tension and wire feed. Hence, to get the minimum value of R_a we have to choose low level values for Wire tension and Wire feed.

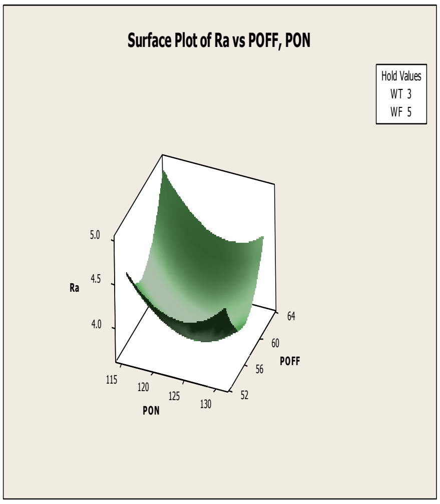

Figure 8. Surface Plots of Ra vs POFF, PON

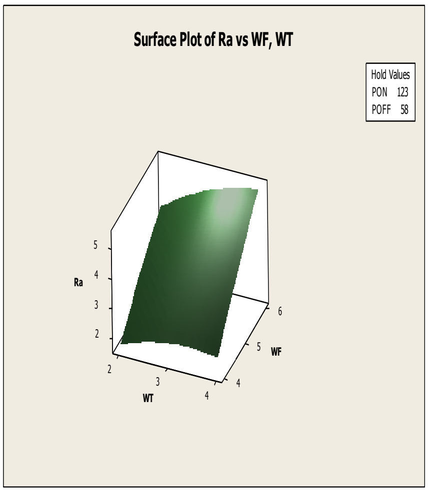

Figure 9. Surface Plots of Ra vs WF, WT

Contour plots are useful for establishing desirable response values and operating conditions. Figure 10 shows a contour plot of R_a versus P_{OFF} and P_{ON}. The darkest area indicates the contour where the Surface Roughness are the lowest (< 3.8). Figure 11 indicates a contour plot of R_a versus WF and WT. From the contour plots, we can conclude that to get the minimum value of R_a we have to choose medium level values of P_{OFF}, P_{ON} and lower level values of WF, WT.

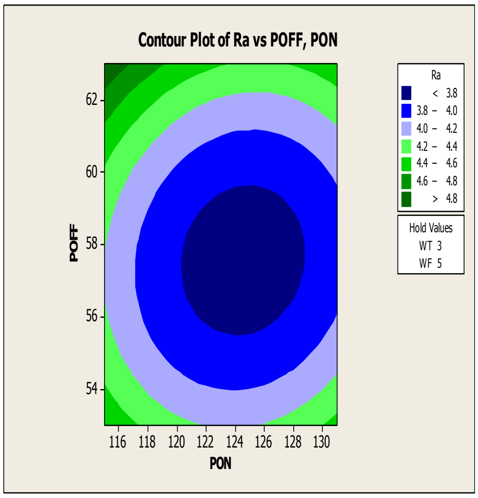

Figure10. Contour Plots of R_a vs P_{OFF}, P_{ON}

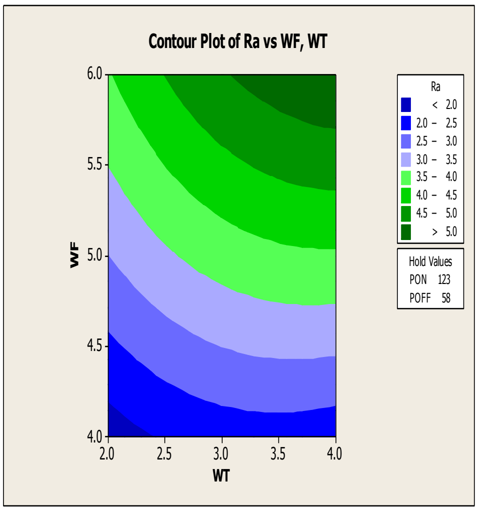

Figure11. Contour Plots of R_a vs WF,WT

5.1. Comparison Between Experimental & Regression Values

From the regression model prepared, the surface roughness values were calculated by substituting all the process parameters in the model. The regression values and experimental values were compared and the values are given in the table 11. A comparison graph was drawn by taking experiment number on X-axis and Surface roughness on Y-axis by using EXCEL and shown in figure 12. From the comparison graph we can observe both experimental and regression values of surface roughness values are nearer to each other hence, the model prepared can be used for the prediction of surface roughness.

Table 11. Experimental and Regression Values of R_a

S.No	Experimental	Regression
1	2.56	2.25
2	4.68	4.08
3	6.41	5.91
4	3.21	3.72
5	5.29	5.56
6	2.54	3.31
7	6.03	5.20
8	3.26	2.95
9	4.94	4.78
10	3.01	3.47
11	6.23	5.30
12	2.31	3.05
13	3.54	4.94
14	2.24	2.70
15	4.53	4.53
16	2.10	2.34
17	4.78	4.17
18	5.79	6.00
19	4.48	4.69
20	3.13	2.44
21	4.51	4.28
22	2.45	2.08
23	3.61	3.92
24	5.74	5.75
25	4.19	3.56
26	4.96	5.39
27	3.34	3.15

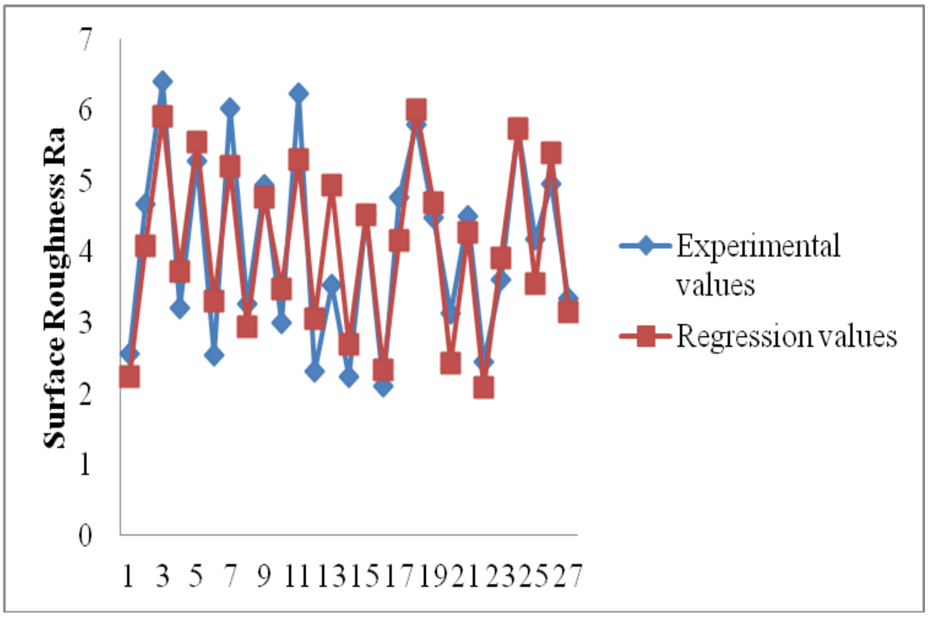

Figure 12. Comparison Graph Between Experimental and Regression Values of R_a

6. Conclusions

From the experimental and theoretical results the following conclusions can be drawn

- The optimal combination of process parameters for Surface Roughness is found at
  P_{ON} : level 2, value 123 µs
  P_{OFF} : level 2, value 58 µs
  WT: level 1, value 2 Kg-f
  WF: level 1, value 4 m/min
- From ANOVA results, the wire feed rate is the most significant parameter followed by wire tension and pulse time off. Pulse on time has the least significance among all the process parameters in effecting the surface roughness.
- Mathematical model for the surface roughness is accurate and adequate; it can be used for the prediction of surface roughness.

7. Future Scope of Work

- The work may be continued for machining different materials at different levels of process parameters.
- The work may be extended by varying the wire materials or with coated wire materials.
- The present work is carried out by Taguchi Analysis for Surface Roughness only, further this work can be extended for output characteristics like Material Removal Rate and Tool Wear Rate etc.
- The work may be extended for multiple optimizations by considering multiple output characteristics.

References

[1] M. K. Sorabh, and N. Nirmal, "A Literature Review on Optimization of Machining Parameters in Wire EDM", International Journal of Latest Research in Science and Technology, vol. 2, no. 1, **(2013)**, pp.492.
[2] B. Kuriachen, J. Kunju Paul and J. Mathew, "Modelling of Wire Electrical Discharge Machining Parameters Using Titanium Alloy (Ti-6Al-4v)", International Journal of Emerging Technology and

Advanced Engineering, vol.2, no.4, **(2012)**, pp.377-381.

[3] S.S. Mahapatra and A. Patnaik, "Optimization of Wire Electrical Discharge Machining (WEDM) Process Parameters Using Taguchi Method", International Journal of Advanced Manufacturing Technology, vol. 34, **(2007)**, pp. 911-925.

[4] V. Muthu Kumar, A. Suresh Babu, R Venkataswamy and M. Raajenthiren, "Optimization of the WEDM Parameters on Machining Incoloy800 Super Alloy with Multiple Quality Characteristics", International Journal of Engineering Science and Technology, vol. 2, no.6 ,**(2010)**, 1538-1547.

[5] Y.S.Tarng and L.K.Chung, ''Determination of Optimal Cutting Parameters in Wire Electrical Discharge Machining'', International Journal of Machine Tools and Manufacture, vol. 35, no 12, **(1995)**, pp.1693–170.

[6] D. Scott, S. Boyina and K.P. Rajurkar, "Analysis and Optimization of Parameter Combination in Wire Electrical Discharge Machining", International Journal of Production Research, vol.29, no 11, **(1991)**, pp. 2189- 2207.

[7] K. P. Vamsi , B. B Surendra, V. P. Madar and M. Swapna, ''Optimizing Surface Finish in WEDM Using the Taguchi Parameter Design Method'', Journal of the Brazilian Society of Mechanical Sciences and Engineering, vol. XXXII, no.2, **(2010)**, pp.107-113.

[8] P.S. Rao, K. Ramji and B. Satyanarayana, ''Effect of WEDM Conditions on Surface Roughness: A Parametric Optimisation Using Taguchi Method'', International Journal of Advanced Engineering Sciences and Technologies, vol. 6, **(2011)**, pp. 041 – 048.

[9] Pujari Srinivasa rao, Koona Ramji and Beela Satyanarayana, "Effect of WEDM Conditions on Surface Roughness A Parametric Optimization Using Taguchi Method", International Journal of Advanced Engineering Sciences and Technologies, vol.6, issue 1, pp. 41-48.

[10] K. Kanlayasiri and S. Boonmung, ''Effects of Wire- EDM Machining Variables on Surface Roughness of Newly Developed DC 53 Die Steel: Design of Experiments and Regression Model'', Journal of Materials Processing Technology. vol. 192–193, **(2007)**, pp. 459–464.

[11] F. Han and J. Jiang, ''Influence of Machining Parameters on Surface Roughness in Finish Cut of WEDM'', The International Journal of Advanced Manufacturing Technology, vol. 34, Issue 5-6, **(2007)**, pp. 538-546.

[12] Vikas, A. Kumar Roy and K. Kumar "Effect and Optimization of Machine Process Parameters on Material Removal Rate in EDM for EN41 Material Using Taguchi", International Journal of Mechanical Engineering and Computer Applications, vol 1, Issue 5, **(2013)**, pp. 35-39.

[13] D.b. Ghodsiyeh, MA. Lahiji, M. Ghanbari, Shirdar and A. Golshan, ''Optimizing Material Removal Rate (MRR) in WEDM Titanium Alloy (Ti6Al4V) Using the Taguchi Method'', Research Journal of Applied Sciences, Engineering and Technology, vol. 4, no. 17, **(2012)**, pp.3154-3161.

[14] A. Kumar, V. Kumar and J.Kumar, ''Prediction of Surface Roughness in Wire Electric Discharge Machining (WEDM) Process Based on Response Surface Methodology'', International Journal of Engineering and Technology (IJET), vol. 2, no. 4, **(2012)**, pp.708-719.

[15] Mohd Amri Lajis and H.C.D. Mohd Radzi, "The Implementation of Taguchi Method on EDM Process of Tungsten Carbide", European Journal of Scientific Research, ISSN 1450-216X, vol.26, no.4, **(2009)**, pp.609-617.

[16] J. Kamal, G. Sandeep and A. Aman, "Simultaneous Optimization of Material Removal Rate and Surface Roughness for WEDM of WCCo Composite Using Grey Relational Analysis Along With Taguchi Method", International Journal of Industrial Engineering Computations, vol. 2, **(2011)**, pp.479-490.

[17] S. Sarkar, S. Mitra and B. Bhatta charyya, "Parametric Analysis and Optimization of Wire Electrical Discharge Machining of γ – Titanium Alluminide Alloy", Journal of Material Processing Technology, vol. 159, **(2005)**, pp.286-294.

[18] A.K Swain, S.Ray and N.K. Mandal, ''Study on Kerf Width in Wire-EDM Based on Taguchi Method'', Applied Mechanics and Materials, vol. 110-116, **(2012)**, pp. 1808-1816.

[19] A. Shah, A.N. Mufti, D. Rakwal and E. Bamberg, ''Material Removal Rate, Kerf and Surface Roughness of Tungsten Carbide Machined with Wire Electrical Discharge Machining'', Journal of Materials Engineering and Performance, vol. 20, **(2011)**, pp. 71-76.

