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Experimental Investigation and Modelling of EWR, Ra and MRR in Electric Discharge Machining of AISI 316 Steel

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Abstract: The triangular shape graphite electrode materials have been utilized in the electric discharge machining by considering this objective, the parameters discharge current, pulse time, and voltage considered as input parameters and EWR, MRR, and Ra value as output parameters to perform machining on AISI 316 steel in EDM. The experimentation performed on the commercial EDM machine by considering the number of runs which was defined by the DOE Taguchi method. By using regression analysis, the different correlations were formed in between discharge current, pulse time, and voltage i.e. input parameters and EWR, MRR, and Ra value i.e. output parameters. The individual as well as combined correlations are formed in between input and output parameters. The result analysis shows the co-relation between runs and the estimated and experimental values for the different output parameters. The conclusion shows that the final equation for different output parameters would be able to predict EWR with accuracy of 97.09%, MRR with accuracy 99.39%, and Ra with accuracy of 99.51%.

Keywords: Electric Discharge Machining, Triangular Shape Graphite Electrode, AISI 316 Steel, Taguchi, Regression

1. Introduction

Electro Discharge Machining (EDM) is an electro-thermal non-traditional machining process, where electrical energy is used to generate electrical spark and material removal mainly occurs due to thermal energy of the spark. [1, 2]. EDM is mainly used to machine difficult-to-machine materials and high strength temperature resistant alloys. EDM can be used to machine difficult geometries in small batches or even on job-shop basis. Work material to be machined by EDM has to be electrically conductive. [3, 4, 5].

Electrical Discharge Machining (EDM) was not completely in use benefit of this method until 1943. When established up how the erosive properties of the method could be employed and make use of machining functions. Once that one was discovered by Joseph Priestly in 1770, In the middle of 1980s machining process on EDM were converted to a production instrument. Effective movement through EDM makes it more commonly offered and also engaging above out-dated machining procedures. At starting days EDM process was actually inaccurate plus damaged using let-downs. Commercially established in the mid-1970s, the wire EDM machining originated to be a feasible practice that facilitated to run-through the metallic operational industry we have seen nowadays.

1.1. Electric Discharge Machining (EDM)

Electro Discharge Machining (EDM) is an electro-thermal non-traditional machining process, where electrical energy is used to generate electrical spark and material removal mainly occurs due to thermal energy of the spark. EDM is mainly used to machine difficult-to-machine materials and high strength temperature resistant alloys. EDM can be used to machine difficult geometries in small batches or even on job-shop basis. Work material to be machined by EDM has to be electrically conductive.

1.2. Principle of EDM

The process has been explained by different theories, being the thermo-electric model the one that best fits the practical experiments. The charge loaded electrode approaches the surface of the component, which is loaded with the opposite charge. In between both electrodes there is an isolating fluid, referred as dielectric fluid. Despite being an electric insulator, a large voltage difference can produce the dielectric breakage, producing ionic fragments that make possible the electric current to jump between the electrode and the work piece. The presence of metallic particles suspended in the dielectric fluid can be good for the electricity transfer in two different ways: on one side, the particles are good to ionise the dielectric and, what is more, they can provide the electric charge; on the other side, the particles can catalyse the dielectric breakage. For that reason, the electric field is larger in that position in which the electrode and the work piece are closer. [3, 11, 12].

2. Experimental Setup and Procedure

The present study was aimed at investigation of effect of process parameters such as discharge current, pulse-on-time voltage on material removal rate (MRR), surface roughness (Ra) and tool wear rate (TWR). ELECTRONICA-ELECTRAPLUS PS 50 ZNC whose polarization on the electrode is located as negative whereas that of work piece be located as positive. The dielectric liquid recycled was EDM oil having specific gravity - 0.763.

Figure 1. *Set-up of Electrical Discharge Machine.*

Table 1. *Composition of different elements present in AISI 316 [3].*

Elements	C	Mn	Si	P	S	Cr	Mo	Ni	N
Weight %	0.08	2	0.75	0.045	0.03	18	3	14	0.10

Table 2. *Mechanical properties of AISI 316 grade stainless steels [3].*

Tensile strength (MPa)	Yield stress (MPa)	Rockwell hardness (HRB)	Brinell hardness (BHN)
515	205	95	217

2.1. Material

AISI 316 grade austenitic stainless steel, it contains 16% to 18% chromium and 11% to 14% nickel. AISI 316 stainless steel has molybdenum added to the nickel and chrome of the 304. AISI 316 stainless steel has molybdenum, which gives it more corrosion resistance. Type 316 stainless steel is often used in heavy gauge welding applications because the risk of pitting, cracking and corrosion is reduced. Grade 316 is the standard molybdenum bearing grade. Molybdenum gives 316 better overall corrosion resistant properties than grade 304. It has excellent forming and welding characteristics. It is readily brake or roll formed into a variety of parts. Material for use in sea-water, equipment for manufacturing dye, paper, acetic acid, fertilizer and chemicals, in the photo industry, food industry, the facilities constructed in the coastal area, bolts and nuts [3, 8, 9, 11].

2.2. Selection of Tool Material

The prime requirement of any electrode material is that it must be electrically conductive and maintain less electrode wear. In principle, the materials best suited should have a very high melting point and a very low resistance to electricity. Electrode tool materials perform with varying degree of success on different work piece materials. The selection of particular electrode material depends primarily upon the specific cutting application and upon the material being machined. The graphite electrodes of triangular shape 22x22x32 mm diameter were selected for the purpose of this research. The physical properties of all the electrode materials are given in.

2.3. Formula of MRR Calculation

MRR is calculated as the proportion of the change of weight of the work piece before and after machining to the product of machining period and density of the material.

MRR = Wbm-Wam/t x ρ

Whereas:

Wbm = Weight of work piece before machining. (In gm.)

Wam = Weight of work piece after machining. (In gm.)

t = Machining period = 15 (In minutes)

ρ = Density of AISI 316 stainless steel work piece (In gm/mm^3)

2.4. Formula of Tool Wears Rate Calculation

TWR is expressed as the ratio of the difference of weight of the tool before and after machining to the machining time. That can be explain this equations

TWR = Wtb-Wta/t

Whereas:

Wtb = Weight of the tool before machining. (In gm.)

Wta = Weight of the tool after machining. (In gm.)

t = Machining period = 15 (In minutes)

2.5. Measurement of Surface Roughness

Surface Roughness is the size of the surface texture. It is expressed in µm and denoted by Ra. If the value comes higher that means the surface is rough and if lower comes that means that the surface is smooth. The surface roughness values are measured by means of an apparatus portable type profilometer, Mitutoyo roughness tester. After measurement calculate by arithmetic mean of three data is in use as the absolute value.

2.6. Experimental Taguchi Design

The working ranges of the parameters for subsequent design of experiment, based on Taguchi's L_9 orthogonal array (OA) design have been selected. In the present experimental study, Pulse Time, Current and Voltage have been considered as process variables. The process variables with their units (and notations) are listed in table 3.

The working ranges of the parameters for subsequent design of experiment, based on Taguchi's L_9 (3^3) orthogonal array (OA) design have been selected. In the present experimental work, Current (A), Pulse on Time (s), and Gap Voltage (V) have been considered as machining parameters. The machining parameters and their associated ranges are given in the table 3. Taguchi design concept, for three levels and three parameters, nine experiments are to be performed and hence L_9 orthogonal array has selected.

Table 3. *Physical properties of Graphite.*

Material	Density (g/cm^3)	Melting point (°C)	Electrical resistivity (µΩ·cm)
Graphite	1.811	3675	14

Table 4. *Process variables and their limits.*

FACTORS	LEVEL 1	LEVEL 2	LEVEL 3
Current (A)	10	15	20
Pulse on Time (s)	200	250	300
Gap voltage (V)	40	50	60

The L_9 orthogonal array of taguchi experiment design sequence results is revealed in below table 5.

Table 5. *L_9 orthogonal array taguchi experiment design.*

Run No.	Cutting parameters level by Taguchi method		
	A	s	V
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

The L_9 orthogonal array of taguchi experiment design sequence and the actual reading results is revealed in below table 6:

Table 6. *L_9 orthogonal array taguchi experiment design with actual 9 runs.*

Run No.	parameters level by Taguchi method			Actual parameters level by Taguchi method		
	A	s	V	A	s	V
1	1	1	1	10	200	40
2	1	2	2	10	250	50
3	1	3	3	10	300	60
4	2	1	2	15	200	50
5	2	2	3	15	250	60
6	2	3	1	15	300	40
7	3	1	3	20	200	60
8	3	2	1	20	250	40
9	3	3	2	20	300	50

3. Modeling

Statistics plays an important role in business, because it provides the quantitative basis for arriving at decisions in all matters. Moreover, without education of statistics, business management is incomplete. According to Danish physicist and Nobel laureate, Niels Bohr, Nothing exists until it is experimental. This is very much relevant in the present times for creation of knowledge, just as steel is the raw material for manufacturing automobiles.

The use of computers in teaching statistics can make an impact in two ways. First, it can affect the amount and rate of learning of statistics. Second, it can affect one's attitude towards computers such as SPSS, SYSTAT, SAS, MINITAB, etc.

MINITAB is an easy to use, general purpose software package for statistical analysis, covering a basic range of statistical analysis and high resolution graphics. MINITAB statistical software gives you the tools needed to analyze the data and make informed decisions about how to improve the business.

Here in the dissertation work we have used the regression analysis, in brief the regression analysis is the statistical technique that identifies the relationship between two or more quantitative variables: a dependent variable, whose value is to be predicted, and an independent or explanatory variable (or variables), which is known.

The goal of regression analysis is to determine the values of parameters for a function that cause the function to best fit a set of data observations that you provide. A simple regression analysis can show that the relation an independent variable X and a dependent variable Y is linear, using the simple linear regression equation:

$$Y = a + b X \text{ (Where a and b are constants)}$$

Multiple regressions will provide an equation that predicts one variable from two or more independent variables:

$$Y = a + bX_1 + cX_2 + dX_3 \text{ (Where a, b and c are constants).}$$

As the modelling done through the modelling software, the various statistical correlations formed from the analysis by Minitab software version 16. The various correlations formed and which are having individual property relation with Electrode wear rate, Material removal rate, and Roughness value.

The correlations developed from the statistical analyses, which are given below:

Equation developed from the modelling for Electrode Wear Rate

$$\text{Exp. EWR} = -0.0105161 + 0.00103967 A + 1.76667e\text{-}006 s + 6.05e\text{-}005 V \quad (1)$$

Equation developed from the modelling for Material Removal Rate

$$\text{Exp. MRR} = 75.5882 - 1.03679 A - 0.105049 s + 0.0183517 V \quad (2)$$

Equation developed from the modelling for Roughness Value

$$\text{Exp. Ra} = 1.74485 - 0.0644933 A + 0.00869633 s + 0.08727 V \quad (3)$$

3.1. Electrode Wear Rate (EWR)

The regression analysis done through the software, the new value of electrode wear rate had estimated from the regression analysis derived formula. At last the absolute error and the percentage error calculated. The modelling of electrode wear rate from current, pulse on time and voltage

***Table** 7. Electrode Wear Rate calculations.*

Sr. No.	By Taguchi Method			Actual Values			Exp. EWR in g/min	Est. EWR in g/min	Absolute Error
	A	s	V	A	s	V			
1	1	1	1	10	200	40	0.00192	0.002654	0.000730
2	1	2	2	10	250	50	0.00333	0.003347	0.000017
3	1	3	3	10	300	60	0.00491	0.004041	0.000869
4	2	1	2	15	200	50	0.00888	0.008457	0.000423
5	2	2	3	15	250	60	0.00798	0.009151	0.001170
6	2	3	1	15	300	40	0.00854	0.008029	0.000511
7	3	1	3	20	200	60	0.01489	0.014261	0.000629
8	3	2	1	20	250	40	0.01369	0.013139	0.000551
9	3	3	2	20	300	50	0.01277	0.013832	0.001060

$$\text{Exp. EWR} = -0.0105161 + 0.00103967 A + 1.76667e\text{-}006 s + 6.05e\text{-}005$$

Coefficients						
Term	**Coef**	**SE Coef**	**T**	**P**		
Constant	-0.0105161	0.0031324	-3.3573	0.020		
A	0.0000018	0.0000811	12.8191	0.000		
s	0.0000018	0.0000081	0.2178	0.836		
V	0.0000605	0.0000406	1.4919	0.196		
Summery Model						
S = 0.000993301		R – Sq = 97.09%		R – Sq (Adj) = 95.34%		
Press = 0.0000196358		R – Sq (Pred) = 88.40%				
Analysis of Variance						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	3	0.0001644	0.0001644	0.0000548	55.535	0.000292
A	1	0.0001621	0.0001621	0.0001621	164.330	0.000061
s	1	0.0000000	0.0000000	0.0000022	0.047	0.836172
V	1	0.0000022	0.0000022	0.0000010	2.226	0.195922
Error	5	0.0000049	0.0000049			
Total	8	0.0001693				
Fits and Diagnostics for Unusual Observations						
Obs	Ra	Fit	SE Fit	Residual	St Resid	
No unusual observations.						

3.2. Material Removal Rate (MRR)

The regression analysis done through the software, the new value of material removal rate had estimated from the regression analysis derived formula. At last the absolute error and the percentage error calculated. The modelling of material removal rate from current, time and voltage have laid down in table.

Table 8. *Material Removal Rate calculations.*

Sr. No.	By Taguchi Method			Actual Values			Exp. MRR (mm^3/min)	Est. MRR (mm^3/min)	Absolute Error
	A	s	V	A	s	V			
1	1	1	1	10	200	40	34.3557	34.6890	0.3333
2	1	2	2	10	250	50	40.4998	39.8331	0.6666
3	1	3	3	10	300	60	44.6439	44.9772	0.3333
4	2	1	2	15	200	50	28.9550	29.2883	0.3333
5	2	2	3	15	250	60	35.4242	34.7575	0.6666
6	2	3	1	15	300	40	39.5683	39.9016	0.3333
7	3	1	3	20	200	60	23.8794	24.2127	0.3333
8	3	2	1	20	250	40	30.0235	29.3568	0.6666
9	3	3	2	20	300	50	34.4927	34.8260	0.3333

$$\text{Exp. MRR} = 75.5882 - 1.03679\ A - 0.105049\ s + 0.0183517\ V$$

Coefficients						
Term	**Coef**	**SE Coef**	**T**	**P**		
Constant	75.5882	18.2923	4.13223	0.009		
A	-1.0368	0.4736	-2.18905	0.080		
s	-0.1050	0.0474	-2.21799	0.077		
V	0.0184	0.2368	0.07749	0.941		
Summery Model						
S = 0.632456	R – Sq = 99.39%		R – Sq (Adj) = 99.03%			
Press = 6.28124	R – Sq (Pred) = 98.09%					
Analysis of Variance						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	3	326.971	326.971	108.990	3.23914	0.119134
A	1	161.239	161.239	161.239	4.79194	0.080193
s	1	165.530	165.530	165.530	4.91948	0.077323
V	1	0.202	0.202	0.202	0.00601	0.941236
Error	5	168.240	168.240	33.648		
Total	8	495.211				
Fits and Diagnostics for Unusual Observations						
Obs	Ra	Fit	SE Fit	Residual	St Resid	
No unusual observations.						

3.3. Surface Roughness (Ra)

The regression analysis done through the software, the new value of roughness had estimated from the regression analysis derived formula. At last the absolute error and the percentage error calculated. The modelling of roughness value from current, time and voltage have laid down in table.

Table 9. *Roughness value calculations.*

Sr. No.	By Taguchi Method			Actual Values			Exp. Ra in µm	Est. Ra in µm	Absolute Error
	A	s	V	A	s	V			
1	1	1	1	10	200	40	6.6673	6.671713	0.004410
2	1	2	2	10	250	50	7.8941	7.918530	0.024430
3	1	3	3	10	300	60	9.1209	9.165346	0.044450
4	2	1	2	15	200	50	7.0687	7.046497	0.022203
5	2	2	3	15	250	60	8.2955	8.293313	0.002187
6	2	3	1	15	300	40	7.0900	6.967780	0.122221
7	3	1	3	20	200	60	7.4702	7.421280	0.048920
8	3	2	1	20	250	40	5.9846	6.095747	0.111150
9	3	3	2	20	300	50	7.3315	7.342563	0.011060

$$Exp.\ Ra = 2.64978 - 0.0965333\ A + 0.00778733\ s + 0.085745\ V$$

Coefficients						
Term	**Coef**	**SE Coef**	**T**	**P**		
Constant	2.64978	0.255788	10.3593	0.000		
A	-0.09653	0.006623	-14.5758	0.000		
s	0.00779	0.000662	11.7583	0.000		
V	0.08575	0.003311	25.8937	0.000		
Summery Model						
S = 0.0811128	R – Sq = 99.51%	R – Sq (Adj) = 99.22%				
Press = 0.119934	R – Sq (Pred) = 98.22%					
Analysis of Variance						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	3	6.71876	6.71876	2.23959	340.400	0.0000034
A	1	1.39780	1.39780	1.39780	212.455	0.0000274
s	1	0.90964	0.90964	0.90964	138.258	0.0000783
V	1	4.41132	4.41132	4.41132	670.486	0.0000016
Error	5	0.03290	0.03290	0.00958		
Total	8	6.75166				
Fits and Diagnostics for Unusual Observations						
Obs	Ra	Fit	SE Fit	Residual	St Resid	
6	7.09	6.96778	0.0540752	0.1222217	R	

R denotes an observation with a large standardized residual

4. Results and Discussion

As the modelling done through the modelling software, the various statistical correlations formed from the analysis by Minitab software version 16. The various correlations formed and which are having machining parameters relation with roughness value, electrode wear rate and material removal rate.

4.1. Correlation Between Experimental and Estimated Electrode Wear Rate for Triangular Electrode from Current, Time and Voltage

The below given graphical representation show the correlation between the experimental and the estimated electrode wear rate. The experimental electrode wear rate is the actual electrode wear rate and the estimated electrode wear rates are the values, which are estimated from the regression equation and the main factor current, time and voltage have considered from the considered parameters.

The equation shows the excellent correlation between combined considered parameters i.e. the current, time and voltage and the electrode wear rate, the correlation gives R^2 value 97.09%. The below given figure show the correlation between experimental and estimated electrode wear rate from current, voltage.

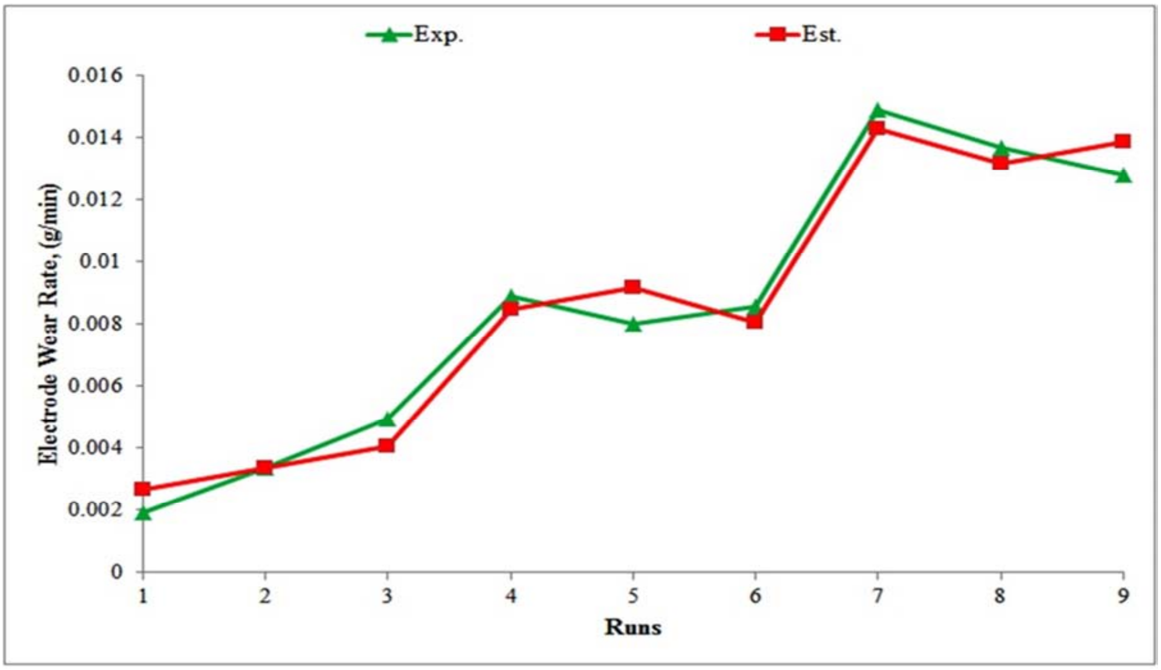

Figure 2. *Estimated and Experimental EWR versus Runs.*

4.2. Correlation Between Experimental and Estimated Material Removal Rate for Triangular Electrode from Current, Time and Voltage

The below given graphical representation show the correlation between the experimental and the estimated material removal rate. The experimental material removal rate is the actual material removal rate and the estimated material removal rates are the values, which are estimated from the regression equation and the main factor current, time and voltage have considered from the considered parameters.

The equation shows the moderate correlation between combined considered parameters i.e. the current, time and voltage and the material removal rate, the correlation gives R^2 value 99.39%. The below given figure show the correlation between experimental and estimated material removal rate from current, time and voltage.

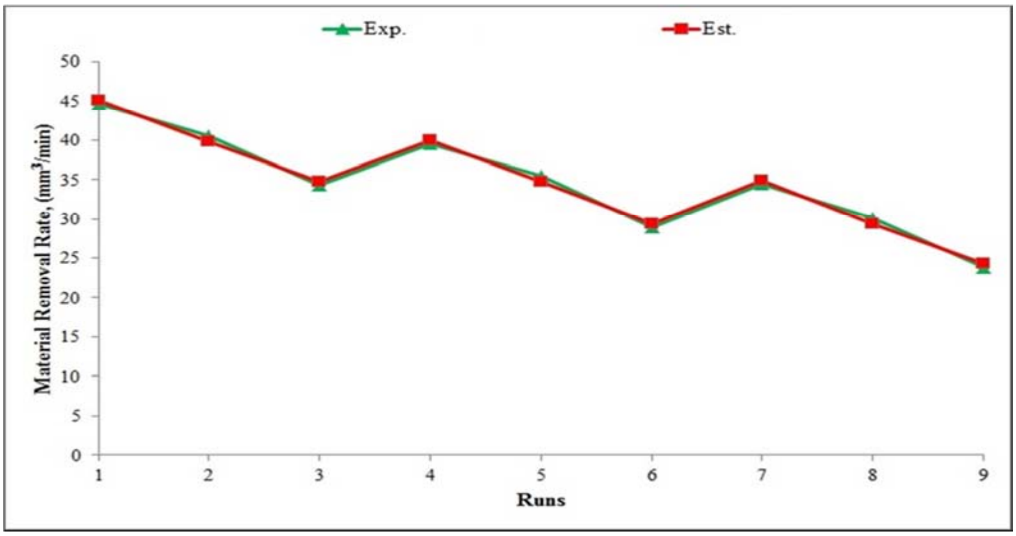

Figure 3. *Estimated and Experimental MRR versus Runs.*

4.3. Correlation Between Experimental and Estimated Roughness Value for Triangular Electrode from Current, Time and Voltage

The below given graphical representation show the correlation between the experimental and the estimated roughness value. The experimental roughness value is the actual roughness value and the estimated roughness values are the values, which are estimated from the regression equation and the main factor current, time and voltage have considered from the considered parameters.

The equation shows the excellent correlation between combined considered parameters i.e. the current, time and voltage and the roughness value, the correlation gives R^2 value 99.51%. The below given figure show the correlation between experimental and estimated roughness value from current, time and voltage.

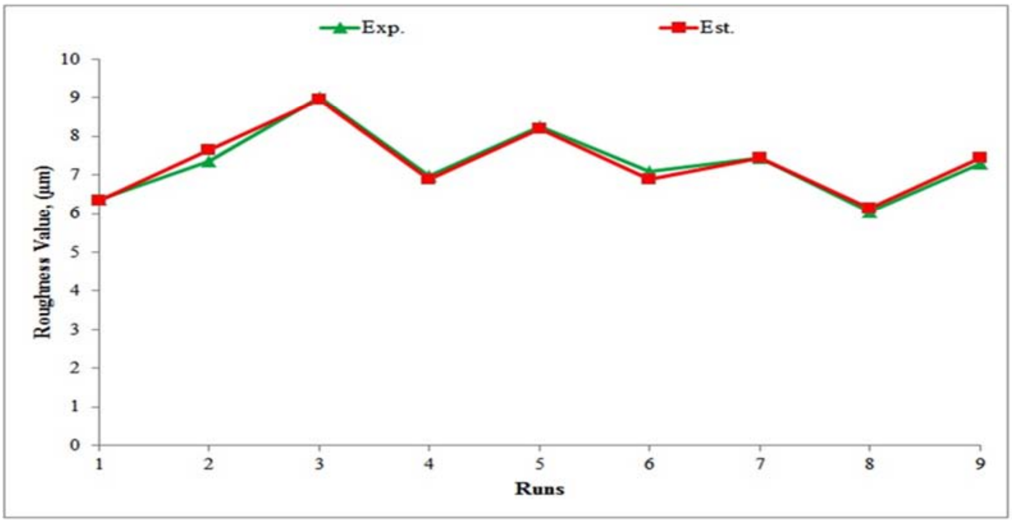

Figure 4. *Runs versus Estimated and Experimental Ra.*

5. Conclusions

Based on the experimental results presented in the modelling and discussed in the results and discussion section, the following conclusions are drawn on the effect of discharge current, pulse on time, and gap voltage on the performance of graphite electrode on roughness value, electrode wear rate, and material removal rate of AISI 316 stainless steel.

The conclusions drawn from the analysis are given below:

- In EDM machining, the taguchi method has proved to be efficient tools for controlling the effect machining parameters on roughness value, electrode wear rate, and material removal rate. The current, pulse on time, and gap voltage plays equally important role in the machining process but in analysis these parameters have showed an excellent bonding effect on roughness value prediction and electrode wear rate and material removal rate form the regression analysis.
- As the number of machining parameters increases in the correlation analysis the correlation value increases simultaneously. For roughness value the correlation equation would be able to predict the roughness value with an accuracy of 99.51%, for electrode wear rate the correlation would be able to predict the electrode wear rate with an accuracy of 97.09%, and for material removal rate the correlation would be able to predict the material removal rate with an accuracy of 99.39%.
- At last, the machining parameters current, pulse on time, and gap voltage have strong correlation with roughness value, electrode wear rate and with the material removal rate.

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