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Experimental Investigations and development of empirical model for gap current and cutting rate in Wire Electric Discharge Machining of AISI D2 steel

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Abstract: The performance of the WEDM machining process mainly depends upon the suitable selection of the appropriate machining variables. Optimization is one of the techniques used in manufacturing sectors to arrive for the best manufacturing conditions, for improving productivity of the system. The objective of the present work is to investigate the effect of various WEDM parameters like pulse on time, pulse off time peak current, servo voltage and wire feed rate on gap current and cutting rate in Machining of AISI D2 Steel. Second order mathematical model for the response characteristics using central composite rotatable design has been developed using MINITAB design statistical software. The design of experiments has been done using Taguchi's orthogonal array L27 (35). Each experiment was conducted under different conditions of input parameters as per the L27 array. The interrelation ship of various input parameters on response characteristics has been evaluated.

Key words: WEDM, MRR, SR, Pulse on Time, Pulse off Time, Analysis Of Variance (ANOVA) Signal-To-Noise Ratio (S/N Ratio), Taguchi's Technique

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INTRODUCTION:

WEDM is considered as a special variant of conventional EDM process, which uses an electrode to initialize the spark process. WEDM however utilize a continuously travelling electrode in the form a wire made of thin copper (0.05-0.30 mm) diameter of copper, brass and tungsten that is capable of achieving very small corner radius. The wire is kept in tension using tensioning devise. During the machining process of WEDM, the material is eroded ahead of the wire and no direct is established between the work piece and the wire, thus eliminating the mechanical stress between the wire.

1. Experimental Set Up

1.1. Electrode and Workpiece material

Experiment was performed with AISI D2 steel as workpiece and brass wire of 0.25 mm diameters as electrode. The experiment work was conducted on the wire EDM of ELECTRONICA ULTRACUT S2 machine. De-ionized water was used as the dielectric fluid. Cutting rate and Gap Voltage were recorded through digital and analog display respectively on the machine interface panel.

1.2. Design of experiment

In the present study according to the Taguchi method, a robust design and an L27 (3^4) orthogonal array are employed for the experimentation. Based on the machine tool, cutting tool (electrode) and workpiece capability, five machining parameters are considered as controlling factors – namely, Pulse on time, Pulse off time, Servo voltage, Wire Feed and Peak Current with each parameter at three levels – namely low, medium and high, denoted by L1, L2 and L3, respectively. The factors and their respective levels have been selected on the basis of performed pilot experimentations.

Table 1: Important process parameters and their levels

Factor	Parameters	unit	Levels		
			L1	L2	L3
A	Pulse on time	µ sec	110	115	120
B	Pulse off time	µ sec	45	50	55
C	Servo voltage	volts	20	35	50
D	Wire feed	mm/min	2	4	6
E	Peak current	Amp	50	100	150

Apart from the parameters considered, there are other factors that can have an effect on the performance parameters. In order to minimize their effects, these parameters are held constant. These are- workpiece material (AISI D2 steel), electrode material (brass wire), wire tension (110 units), water pressure (115 units) workpiece thickness (14mm) and vertical angle of cut.

The tabulated results below (table 2) depict the process parameter, performance parameter and the SN ratio for the L_{27} orthogonal array. S/N ratio signifies the higher value representing better machining performance such as Gap Voltage and Cutting Rate, 'higher-the-better'.

Table2. L_{27} Experimental result and Signal-to-noise ratio

Ru n	MACHINING PARAMETERS					PERFORMANCE PARAMETERS			
	T_{ON}	T_{OFF}	SV	WF	I_P	CR	S/N ratio	VG	S/N ratio
	µ sec	µ sec	volt	mm/min	amp	mm/min		volt	
1	120	55	50	6	50	0.76	-2.38373	49	33.8039
2	110	45	35	6	50	0.98	-0.17548	35	30.8814
3	115	45	50	4	100	1.10	0.82785	51	34.1514
4	110	50	50	2	150	0.55	-5.19275	48	33.6248
5	115	55	35	2	50	0.80	-1.93820	35	30.8814
6	115	55	35	2	100	0.82	-1.72372	34	30.6296
7	115	50	20	6	50	1.25	1.93820	20	26.0206
8	120	55	50	6	150	0.72	-2.85335	50	33.9794
9	120	45	20	2	150	1.86	5.39026	23	27.2346
10	115	50	20	6	150	1.30	2.27887	21	26.4444
11	115	55	35	2	150	0.83	-1.61844	34	30.6296
12	120	45	50	6	100	0.75	-2.49877	50	33.9794
13	120	45	20	2	50	1.88	5.48316	22	26.8485
14	115	45	50	4	50	1.18	1.43764	50	33.9794
15	110	45	35	6	100	0.98	-0.17548	34	30.6296
16	115	45	50	4	150	1.18	1.43764	51	34.1514
17	110	50	50	2	50	0.57	-4.88250	48	33.6248
18	115	50	20	6	100	1.24	1.86843	21	26.4444
19	120	50	35	4	50	1.22	1.72720	36	31.1261
20	110	55	20	4	150	0.62	-4.15217	19	25.5751
21	120	45	20	2	100	1.86	5.39026	24	27.6042
22	110	55	20	4	100	0.59	-4.58296	21	26.4444
23	120	50	35	4	150	1.25	1.93820	36	31.1261
24	110	50	50	2	100	0.58	-4.73144	49	33.8039
25	110	55	20	4	50	0.64	-3.87640	19	25.5751
26	110	45	35	6	150	1.00	0.00000	34	30.6296
27	120	50	35	4	100	1.20	1.58362	34	30.6296

3. Effect on Gap Voltage:

Figure 3.1 and 3.2 illustrates that the gap voltage increases slightly with increase in pulse on time and decreases with the increase in pulse off time and servo voltage. The peak current and wire feed don't have any significant effect on the gap voltage. It is also evident that gap voltage is minimum at first level of servo voltage and maximum at third level of servo voltage. Figure 3.3 illustrates the interactions between the process parameters in affecting the gap voltage.

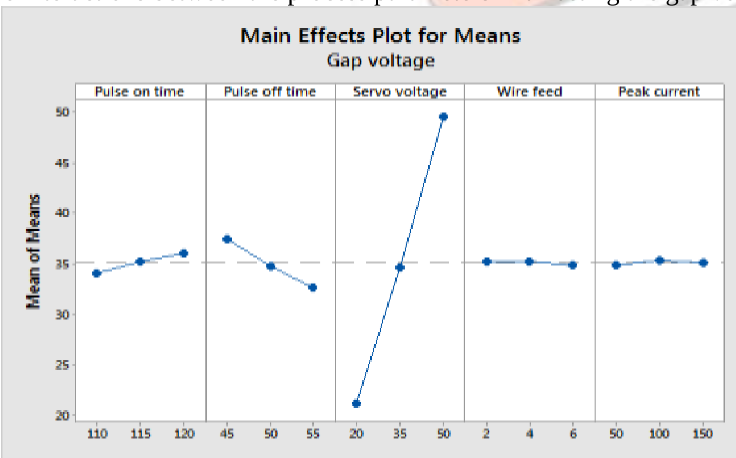

Figure 3.1: Effects of process parameters on gap voltage (raw data)

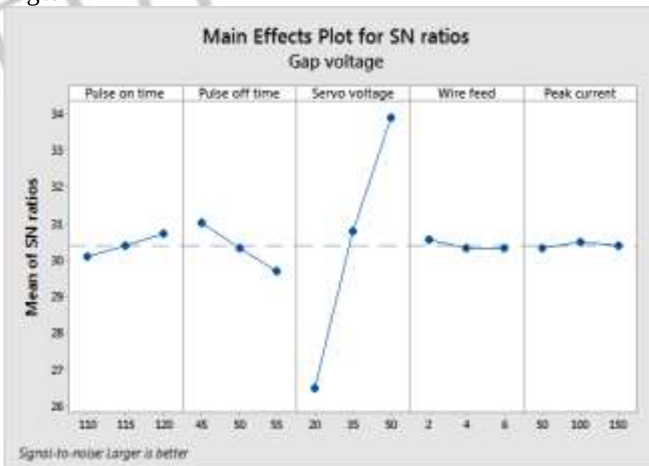

Figure 3.2: Effects of process parameters on gap voltage (S/N data)

The signal-to-noise (S/N) ratio is used to represent the quality characteristic and larger S/N ratio is better for gap voltage and illustrated in the figure below.

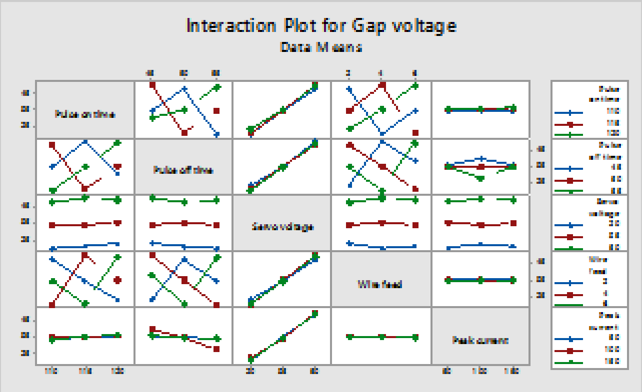

Figure 3.3: Effects of process parameters interactions on gap voltage

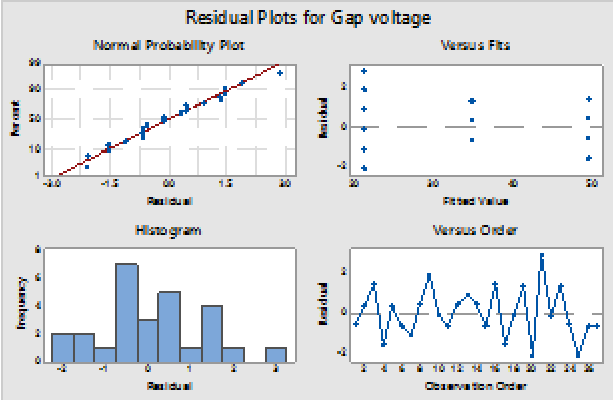

Figure 3.4: Residual plots for gap voltage

Residual plots (figure 3.4) are used to evaluate the data for the problems like non-normality, non-random variation, non-constant variance, higher order relationships, and outliers. This layout is essential to check whether the model meets the expectation of the analysis.

- The residual plot in the graph for normal probability plot indicates the data are normally distributed and variables are influencing the response.
- The residuals versus fitted value indicate the variation is constant.
- The Histogram proved the data are not skewed and no outline exists.
- The residual versus order of the data indicates that there are systematic effects in the data due to time or data collection order.

Table 3: Response table for gap voltage

Level	**Pulse on time**	**Pulse off time**	**Servo voltage**	**Wire feed**	**Peak current**
1	30.09	31.01	26.47	30.54	30.30
2	30.37	30.32	30.80	30.31	30.48
3	30.70	29.69	33.90	30.31	30.38
Delta	0.62	1.32	7.43	0.24	0.18
Rank	3	2	1	4	5

The response table 3 illustrates the average of each response characteristic for each level of each factor. The table includes ranks based on delta statistics, which compare the relative magnitude of efforts. The delta statistic is the highest minus the lowest average for each factor. Minitab 17 assigns ranks based on delta values; rank 1 to highest delta value, rank 2 to the second highest and, so on. The ranks indicate the importance of each factor to the response. The ranks and the delta values show that servo voltage have the greatest effect on gap voltage and is followed by pulse off time, pulse on time, wire feed and peak current in that order.

Table 4: Analysis of variance for gap voltage

Source	**Sum of Squares**	**Df**	**Mean Square**	**F Value**	**p-value Prob> F**	**Percentage contributions**
Model	3671.19	10	367.12	511.97	< 0.0001	
A-pulse on time	13.70	2	6.85	9.55	0.0019	0.38
B-pulse off time	9.86	2	4.93	6.88	0.0070	0.27
C-servo voltage	3553.99	2	1777.00	2478.12	< 0.0001	99.10
D-wire feed	1.42	2	0.71	0.99	0.3928	0.04
E-peak current	0.40	2	0.20	0.28	0.7582	0.01
Residual Error	11.47	16	0.72			
Total	3682.67	26				100

The results of the ANOVA are represented in the table 4, and from the table, it is clear that servo voltage is the major influencing factor (contributing 99.10 % to performance measures), followed by pulse on time (contributing 0.38 %), pulse off time (contributing 0.27 %), wire feed (contributing 0.04 %) and peak current (contributing 0.01 %).

3.1 Regression equation for gap voltage

Regression coefficients of the second order equation are obtained by using experimental data. The regression equation for the gap voltage as a function of five input process parameters was developed and is given below.

$$\text{Gap Voltage} = 35.3785 + 0.574653 * A + -0.895833 * B + 14.1319 * C + -1.05729 * D + -0.0798611 * E + 0.159722 * AB + 0.979167 * AC + 0 * AD + 0.125 * AE + 0.232639 * BC + 1.10417 * BD + -0.0416667 * BE + 0 * CD + 8.77277e\text{-}017 * CE + 0.0625 * DE + -0.661458 * A^2 + 0 * B^2 + 0 * C^2 + 0 * D^2 + -0.078125 * E^2$$

4. Effect on Cutting Rate:

Figure 4.1 and 4.2 illustrates that the cutting rate increases with increase in pulse on time and decreases with the increase in pulse off time and servo voltage. The cutting rate first decreases and then remains constant with increases in wire feed. The peak current doesn't have any significant effect on the cutting rate. It is also evident that cutting rate is minimum at first level of pulse on time and maximum at first level of pulse off time. Figure 4.3 illustrates the interactions between the process parameters in affecting the cutting rate.

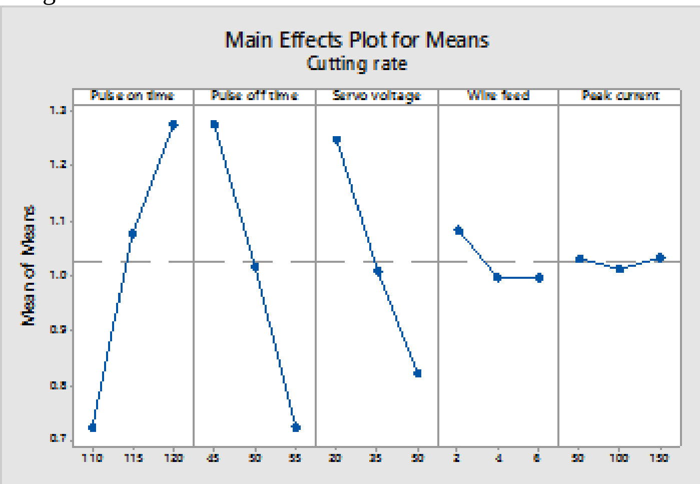

Figure 4.1: Effects of process parameters on cutting rate (raw data)

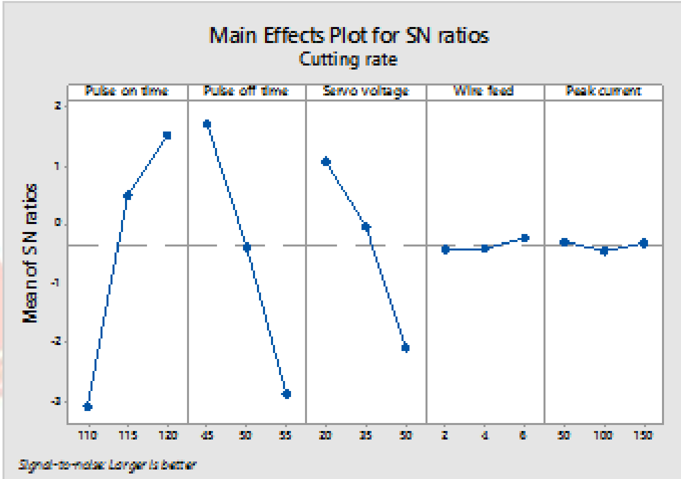

Figure 4.2: Effects of process parameters on cutting rate (S/N data)

The signal-to-noise (S/N) ratio is used to represent the quality characteristic and larger S/N ratio is better for cutting rate and illustrated in the figure 4.2.

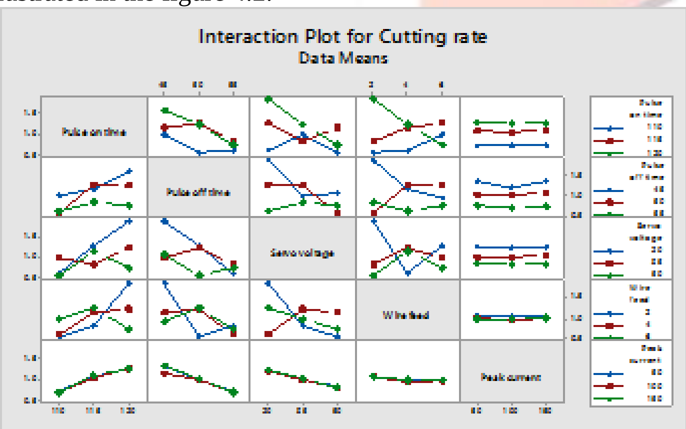

Figure 4.3: Effects of process parameters interactions on cutting rate

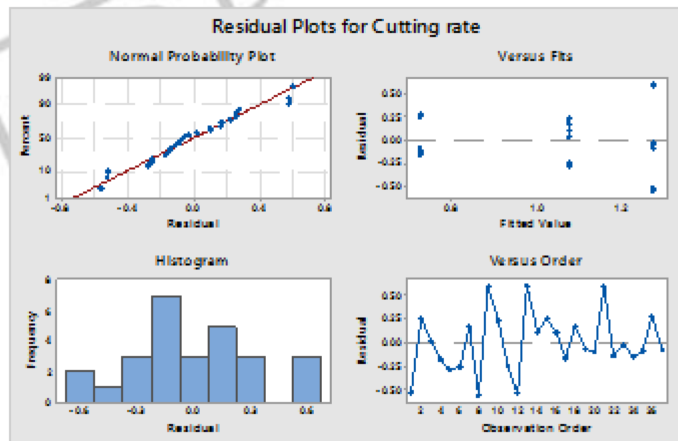

Figure 4.4: Residual plots for cutting rate

Residual plots are used to evaluate the data for the problems like non-normality, non-random variation, non-constant variance, higher order relationships, and outliers. This layout is essential to check whether the model meets the expectation of the analysis.

- The residual plot in the graph for normal probability plot indicates the data are normally distributed and variables are influencing the response.
- The residuals versus fitted value indicate the variation is constant.
- The Histogram proved the data are not skewed and no outline exists.
- The residual versus order of the data indicates that there are systematic effects in the data due to time or data collection order.

Table 5: Response table for cutting rate

Level	Pulse on time	Pulse off time	Servo voltage	Wire feed	Peak current
1	-3.08546	1.71171	1.08196	-0.42482	-0.29668
2	0.50092	-0.38580	-0.04248	-0.40660	-0.44913
3	1.53076	-2.89112	-2.09327	-0.22237	-0.30797
Delta	4.61622	4.60283	3.17523	0.20245	0.15245
Rank	1	2	3	4	5

The response table 5 illustrates the average of each response characteristic for each level of each factor. The table includes ranks based on delta statistics, which compare the relative magnitude of efforts. The delta statistic is the highest minus the lowest average for each factor. Minitab 17 assigns ranks based on delta values; rank 1 to highest delta value, rank 2 to the second highest and, so on. The ranks indicate the importance of each factor to the response. The ranks and the delta values show that pulse on time have the greatest effect on cutting rate and is followed by pulse off time, servo voltage, wire feed and peak current in that order.

Table 6: Analysis of variance for cutting rate

Source	Sum of Squares	Df	Mean Square	F Value	p-value Prob> F	Percentage contributions
Model	3.75	10	0.38	26.69	< 0.0001	
A-pulse on time	1.14	2	0.57	40.43	< 0.0001	29.72
B-pulse off time	1.46	2	0.73	51.91	< 0.0001	38.16
C-servo voltage	1.08	2	0.54	38.50	< 0.0001	28.31
D-wire feed	0.10	2	0.051	3.65	0.0495	2.68
E-peak current	0.043	2	0.021	1.53	0.2469	1.13
Residual Error	0.22	16	0.014			
Total	3.98	26				100

The results of the ANOVA are represented in the table 6, and from the table, it is clear that pulse off time is the major influencing factor (contributing 38.16 % to performance measures), followed by pulse on time (contributing 29.72 %), servo voltage (contributing 28.31 %), wire feed (contributing 2.68 %) and peak current (contributing 1.13 %).

4.1 Regression equation for cutting rate

Regression coefficients of the second order equation are obtained by using experimental data. The regression equation for the cutting rate as a function of five input process parameters was developed and is given below.

$$\text{Cutting Rate} = 1.01115 + 0.236892 * A + -0.250625 * B + -0.331181 * C + -0.249635 * D + 0.0132292 * E + 0.225069 * AB + 0.021875 * AC + 0 * AD + -0.000416667 * AE + -0.0606597 * BC + 0.205208 * BD + -0.00125 * BE + 0 * CD + -0.00291667 * CE + 0.0025 * DE + -0.117135 * A^2 + 0 * B^2 + 0 * C^2 + 0 * D^2 + 0.00578125 * E^2$$

5. Conclusion:

On the basis of experimental results and their analysis, the general conclusions drawn for this work are presented below:

- Regression Equation has been successfully used to develop the mathematical models for Cutting Rate and Gap Voltage.
- The main significant factors that affect the Cutting Rate are Pulse on time, Pulse off time and servo voltage.
- The main significant factor that affects the Gap Voltage is servo voltage.

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