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An Experimental Study of WEDM Parameters on Inconel-625

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Abstract: Wire electrical discharge machining (WEDM) is a stochastic process in which a large number of parameters are involved. It's hard to choose correct settings of these parameters to maximize MRR and minimize surface roughness and overcut. To manufacture quality products at lowest cost in industries, optimization is a useful technique which can be applied to find out the best manufacturing conditions. This research work reports effects of machining parameters like pulse on time, pulse off time, servo voltage, peak current, wire feed rate and wire tension on surface roughness (SR),metal removal rate (MRR) and overcut while wire electrical discharge machining of Inconel-625. The experimentation is performed using Taguchi's L_{27} orthogonal array under different cutting conditions of machining parameters. Response surface methodology (RSM) is applied to develop mathematical models to correlate the interrelationships between various WEDM machining parameters with performance characteristics. ANOVA is used to determine the primary significant parameters affecting the performance characteristics.

Keywords: WEDM, MRR, surface roughness, overcut, Taguchi method, RSM, ANOVA

I. Introduction

Inconel-625 is a Nickel based super alloy. These alloys are very hard to machine conventionally owing to their high hardness, retain their strength at elevated cutting temperatures, low thermal coefficient of expansion and high chemical affinity with the tool materials. This leads to notch wear at the tool nose, abrasive wear of the tool, high diffusion wear rate, spalling on the tool rake face, degradation of tool material by seizure and cratering, high temperature at the tool tip and large thermal gradients in the cutting tool. These alloys finds wide applications in aircraft gas turbines, steam turbine power plants, reciprocating engines, metal processing, medical applications, heat treating equipment, nuclear power systems, chemical industries, pollution control equipment and coal gasification and liquefaction systems [1,2].

WEDM is one of the key non-conventional thermoelectric processes which provide an efficient solution for machining materials with high hardness, chemically reactive and which are difficult to machine using conventional methods. It finds major applications in aerospace, nuclear and automotive industries to cut intricate shapes in electrically conductive materials. Material removal mechanism is by melting, and evaporation caused by continuous, discrete sparks generated between wire and work piece in the existence of dielectric fluid. MRR, surface roughness, kerf width, overcut and wire wear ratio are the primary performance characteristics in WEDM.

Hewidy *et.al.* [3] developed mathematical models for correlating the inter-relationships between peak current, duty factor, wire tension and water pressure with MRR, wear ratio and surface roughness using response surface methodology while WEDM of Inconel 601 material. Kuppan *et.al.* [4] performed small deep hole drilling of Inconel 718. The process parameters considered for the study were peak current, pulse on time, duty factor and electrode speed and the responses were MRR and depth-averaged surface roughness. Response surface methodology was used to develop mathematical models for the output parameters, and optimization was carried out using desirability function approach. Rajesha *et.al.* [5] employed a copper electrode of a tubular cross section to machine holes on Inconel 718. Response surface methodology was used to perform the experiments to study the effect of duty factor, sensitivity control, pulse current, gap control and flushing pressure on

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MRR and surface roughness. Mathematical models were developed for the responses, and SEM analysis was carried out to study the influence of process parameters on tool wear and tool geometry. Rajyalakshmi and Vekata Ramaiah [6] presented multi-objective optimization of Inconel 825 using grey relational analysis. Experiments were carried out using L36 orthogonal array to study the effect of machining parameters on MRR, surface roughness and spark gap. Muthukumara *et.al.* [7] developed a mathematical model for radial overcut during EDM of Incoloy 800 using response surface methodology. The control factors considered for the study were pulse on time, pulse off time, current, and voltage. Torres *et.al.* [8] presented electrical discharge machining of Inconel 600 alloy using a copper electrode to study the effect of current intensity, duty cycle, pulse time and polarity on MRR, surface roughness, and electrode wear. From the results of experiments, they found that positive polarity results in higher MRR while negative polarity results in lower surface roughness. Aggrawal *et. al.* [9] carried out optimization for WEDM of Inconel 718 by employing desirability function approach and derived empirical models of for MRR and surface roughness using response surface methodology. Unune and Mali [10] fabricated microchannels on Inconel 718 with micro-WEDM. Experiments were conducted using Box-Behnken design to study the effect of gap voltage, capacitance, feed rate and vibrational frequency on MRR and kerf width. By applying statistical analysis, empirical models were developed for MRR and kerf width. Capacitance was found to be the major significant factor affecting the performance characteristics.

In the present study, machining performance of Inconel-625 has been evaluated on WEDM. Experiments were performed as per Taguchi's L_{27} orthogonal array to find out the effect of pulse on time, servo voltage, pulse off time, peak current, wire feed rate and wire tension on performance outputs such as MRR, surface roughness and overcut. ANOVA was performed to identify significant factor affecting the performance characteristics. Empirical models were developed for the responses using RSM technique to correlate the relationship between machining parameters and performance characteristics.

II.EXPERIMENTATION

A. Experimental set up and Material

The machine used to perform the experiments was 5-axis sprint cut (ELPUSE-40) wire electrical discharge machine manufactured by Electronica M/C Tool LTD, India. Fig. 1 shows the experimental set up.

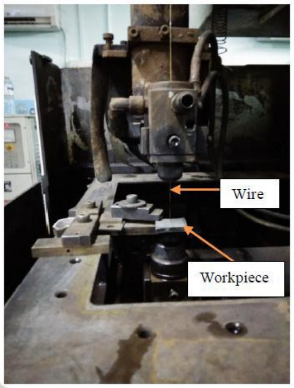

Fig. 1 Experimental set up

Inconel-625 has been used as a workpiece material for the present experimental investigation of dimensions 30 mm x 30 mm x 5 mm thickness. The chemical composition of the Inconel-625 is Ni-58%, Cr-20 to 23%, Fe-5% max, Mo-8 to10%, Nb & Ta-3.15 to 4.15%, Co-1% max, Mn & Si-0.5% max and traces of phosphorous, sulphur, aluminium and titanium. A 0.25 mm diameter Brass wire is used as a tool electrode to cut a profile along with a square block of 5 mm x 5 mm x 5 mm from the workpiece. Fig. 2 shows the workpiece after WEDM.

Fig. 2 Workpiece after WEDM

B. Design of Tests

In the present study, Taguchi method and RSM is used to plan the experiments and ANOVA is utilized for the subsequent analysis of data. The tests were performed as per L_{27} orthogonal plan. Six machining variables were considered for experimentation viz. pulse on time, servo voltage, pulse off time, peak current, wire feed rate and wire tension. Pilot tests were performed by changing one factor at a time and keeping other factors at some constant level. Parameters along with their levels are shown in Table 1. Each experiment was repeated thrice thus a total of 81 experiments were performed to minimize the experimental error. Apart from six machining parameters, other

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parameters were kept constant during machining are listed in Table 2. Table 3 indicates the results of experiments.

Table 1
Machining Variables and their Levels

Symbol	Variable	Unit	Levels		
			1	2	3
A	Pulse on Time	µs	110	114	118
B	Pulse off Time	µs	41	46	51
C	Servo Voltage	Volts	20	30	40
D	Peak Current	Amp	170	200	230
E	Wire Feed Rate	m/min	1	3	5
F	Wire Tension	Gram	2	5	8

Table 2
Constant Variables and their Values

Variable	Value
Flushing pressure	1 unit (15 Kg/cm^2)
Servo feed	2120 units
Dielectric	Distilled water of conductivity 22 µS/cm at 24°C

The performance characteristics selected for this study were MRR, surface roughness and overcut. The "lower-the-better (LB)" quality characteristic has been used for calculating the signal to noise ratio (S/N) of surface roughness and overcut, whereas "higher-the-better (HB)" quality characteristic for MRR. See Eq. 1 and 2.

$$\eta_{LB} = -10 \log \left[\frac{1}{n}\sum_1^n Yij^2\right] \quad (1)$$

$$\eta_{HB} = -10 \log \left[\frac{1}{n}\sum_1^n 1/Yij^2\right] \quad (2)$$

where Yij is the ith experiment at the jth test and n is the total number of repetitions.

Table 3
Taguchi's L_{27} Orthogonal Array with Performance Characteristics and Respective S/N Ratios

Run	A	B	C	D	E	F	Surface Roughness (µm)	S/N ratio	Overcut (mm)	S/N ratio	MRR (mm^3/min)	S/N ratio
1	110	41	20	170	1	2	1.82	-5.2332	0.370	8.6212	33.30	29.9882
2	110	41	20	170	3	5	1.68	-4.3511	0.230	12.749	27.60	28.2153
3	110	41	20	170	5	8	1.60	-3.9551	0.265	11.523	26.60	27.712
4	110	46	30	200	1	2	1.76	-4.7944	0.402	7.9133	31.16	29.3075
5	110	46	30	200	3	5	1.70	-4.4375	0.224	13.007	28.43	28.6294
6	110	46	30	200	5	8	1.61	-4.0827	0.300	10.419	26.64	27.7466
7	110	51	40	230	1	2	1.79	-5.0095	0.340	9.3529	32.25	29.6556
8	110	51	40	230	3	5	1.58	-3.8283	0.380	8.4023	25.67	27.6978
9	110	51	40	230	5	8	1.52	-3.5025	0.168	15.492	24.53	27.6619
10	114	41	30	230	1	5	2.32	-7.3475	0.320	9.8773	55.00	34.5062
11	114	41	30	230	3	8	2.19	-6.9537	0.270	11.345	48.63	33.8563
12	114	41	30	230	5	2	1.85	-5.3749	0.167	15.528	33.70	30.2365
13	114	46	40	170	1	5	2.28	-7.1217	0.186	14.625	52.37	34.1899
14	114	46	40	170	3	8	1.79	-5.1215	0.179	14.958	32.92	29.7878
15	114	46	40	170	5	2	2.01	-6.0496	0.176	15.106	37.62	30.7563
16	114	51	20	200	1	5	1.95	-5.6816	0.286	10.872	34.00	30.4922
17	114	51	20	200	3	8	2.06	-6.3054	0.165	15.65	39.20	31.0776
18	114	51	20	200	5	2	1.97	-5.772	0.159	15.972	36.60	30.5405
19	118	41	40	200	1	8	2.51	-7.9132	0.352	9.0606	58.70	34.9792
20	118	41	40	200	3	2	2.04	-6.2784	0.172	15.303	38.90	30.9849
21	118	41	40	200	5	5	2.41	-7.5559	0.164	15.721	56.34	34.6794
22	118	46	20	230	1	8	2.10	-6.568	0.404	7.8794	44.37	31.6185
23	118	46	20	230	3	2	2.36	-7.4225	0.288	10.822	55.20	34.6204
24	118	46	20	230	5	5	2.25	-6.9922	0.200	14.108	50.90	33.9312
25	118	51	30	170	1	8	2.50	-7.7954	0.212	13.473	57.60	34.9689
26	118	51	30	170	3	2	2.31	-7.3226	0.163	15.755	54.50	34.4202
27	118	51	30	170	5	5	1.73	-4.592	0.180	14.892	29.20	29.0937

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Surface finish was measured on the surface of the square block in µm with the help of Mitutoyo make surface roughness tester SJ-210. MRR and overcut were calculated by using following equations:

$$MRR=\frac{Volume\ of\ material\ removed}{Cutting\ Time\ in\ min} \quad (3)$$

$$Overcut = \frac{Size\ of\ cut-D}{2} \quad (4)$$

Where, D = wire diameter in mm

The size of cut is the difference between dimensions of square on the work piece and square block. MRR was measured in mm^3/min and overcut in mm. Statistical analysis was performed by applying Minitab 16 software. Table 3 shows Taguchi's L_{27} orthogonal array along with the results obtained from the experiments corresponding S/N ratios.

III.RESULTS AND DISCUSSION

A. *Effect of machining variables on Surface finish*

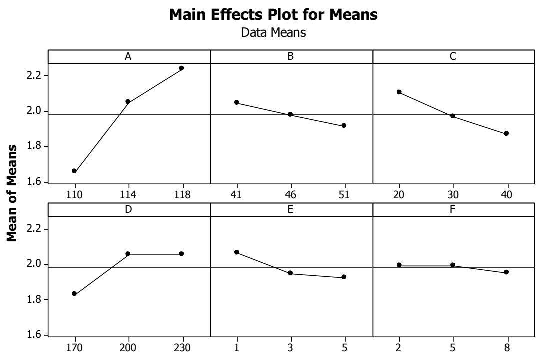

Fig. 3 Effect of machining parameters on surface roughness

From Fig. 3, it is observed that pulse on time and peak current increases more amount of heat energy is produced during machining. This results in more amount of melting and vaporization material creating large and deep craters on the workpiece surface and surface roughness decreases. As the pulse off time decreases, sparks produced increases which further increase the discharge energy. This results in creation of craters on the cut surface and surface roughness deteriorates. As servo voltage increases, discharge wait time increases. This leads to decrease in discharge energy per cycle and results in the better surface finish. At higher values of wire feed rate, surface finish improves owing to less duration of contact between wire and workpiece. Effect of wire tension was found to be negligible. Table 4 represents the results of ANOVA.

Table 4

ANOVA for Surface Roughness

Source	DF	Seq SS	Adj MS	F	P	% Contribution
A	2	1.58162	0.790811	274.8	0.004*	64.52
B	2	0.07869	0.039344	13.67	0.068	3.21
C	2	0.25209	0.126044	43.8	0.022*	10.28
D	2	0.31287	0.156433	54.36	0.018*	12.76
E	2	0.10602	0.053011	18.42	0.050*	4.32
F	2	0.01042	0.005211	1.81	0.356	0.425
Error	14	0.1097	0.028862	9.02	1.555	4.477
Total	26	2.4514				
R-Sq = 99.8% R-Sq(adj) = 96.9%						
*P-value <0.05 indicates significant factor at 95% confidence level						

The results of ANOVA are represented in Table 5 and it is found that pulse on time is the major significant factor (contributing 64.52%), followed by peak current (contributing 12.76%), servo voltage (contributing 10.28%), wire feed rate (contributing 4.32%), pulse off time (contributing 3.21%) and wire tension (contributing 0.425%).

The regression equation for the surface roughness as a function of six machining parameters was developed and is given as follows:

$$\text{Surface roughness} = -69.7713+1.3195A+0.01796B+0.06624C-0.08478D+0.03506E-0.1668F-0.006354A^2+0.0002C^2-0.00001161D^2+0.02944E^2+0.002037F^2-0.000351AB-0.0003611AC+0.001129AD-0.001806AE+0.00125AF-0.0010BC+0.000126BD+0.00078BE-0.001444CE \quad (5)$$

B. *Effect of machining variables on MRR*

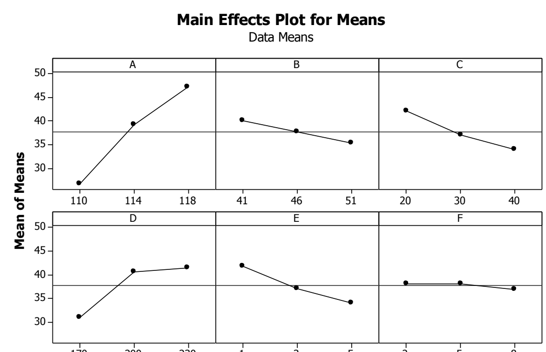

Fig. 4 Effect of machining parameters on MRR

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From Fig. 4, it is observed that pulse on time and peak current increases large amount of thermal energy is produced during machining. This results in more amount of heat transfer in the material resulting into melting and vaporization, and formation of bigger and dark holes on the cut surface and MRR boosts. As the pulse off time increases, sparks produced decreases which further reduce the thermal energy. This results in less amount of material removal from cut surface and MRR decreases. As servo voltage decreases, discharge wait time decreases. This leads to increase in the heat energy per cycle and results in the greater MRR. At greater values of wire feed rate, MRR reduces owing to less amount of material removal form workpiece. Effect of wire tension was found to be negligible. Table 5 shows the results of ANOVA.

Table 5

ANOVA for MRR

Source	DF	Seq SS	Adj MS	F	P	% Contribution
A	2	1901.26	950.632	590.9	0.002*	54.96
B	2	100.03	50.016	31.09	0.031*	2.89
C	2	304.18	152.089	94.54	0.010*	8.79
D	2	613.94	306.97	190.8	0.005*	17.75
E	2	279.62	139.808	86.91	0.011*	8.08
F	2	8.67	4.336	2.7	0.271	0.251
Error	14	251.72	63.732	38.61	0.259	7.273
Total	26	3459.41				
R-Sq = 99.9% R-Sq(adj) = 98.8%						
*P-value <0.05 indicates significant factor at 95% confidence level						

The results of ANOVA are represented in Table 5 and it is found that pulse on time is the major significant factor (contributing 54.96%), followed by peak current (contributing 17.75%), servo voltage (contributing 8.79%), wire feed rate (contributing 8.08%), pulse off time (contributing 2.89%) and wire tension (contributing 0.251%).

The regression equation for the surface roughness as a function of six machining parameters was developed and is given as follows:

$$MRR = -1255.28+25.12A+0.42B-1.80C-2.74D+27.28E-11.22F-0.14A^2+0.01B^2+0.01C^2+0.88E^2-0.03F^2+0.02AB+0.03AC+0.04AD-0.23AE+0.1AF-0.03BC-0.01BD-0.12BE-0.05CE \quad (6)$$

C. Effect of machining variables on Overcut

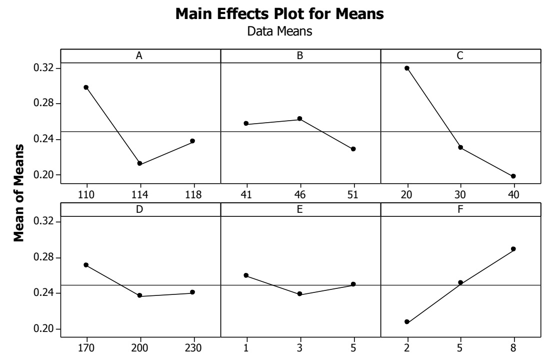

Fig. 4 Effect of machining parameters on MRR

Fig. 4 shows that with increase in pulse on time overcut first declines quickly then rises very slightly. As pulse off time increases, the overcut first enhances and then decreases. With the increment in peak current and servo voltage, decrement in the value of overcut is observed. Increase in wire tension value leads to higher overcut. The effect of wire feed is not very significant. Table 6 indicates the results of ANOVA.

Table 6

ANOVA for Overcut

Source	DF	Seq SS	Adj MS	F	P	% Contribution
A	2	0.03488	0.017443	86.05	0.011*	19.16
B	2	0.00600	0.003002	14.81	0.063	3.30
C	2	0.07116	0.035584	175.5	0.006*	39.09
D	2	0.00655	0.003277	16.17	0.058	3.60
E	2	0.00184	0.000922	4.55	0.18	1.01
F	2	0.03006	0.015034	74.17	0.013*	16.52
Error	14	0.03153	0.007986	38.39	0.397	17.32
Total	26	0.18206				
R-Sq = 99.9% R-Sq(adj) = 98.8%						
*P-value <0.05 indicates significant factor at 95% confidence level						

The results of ANOVA are represented in Table 6 and it is found that servo voltage is the major significant factor (contributing 39.09%), followed by pulse on time (contributing 19.69%), wire tension (contributing 16.52%), peak current (contributing 3.60%), pulse off time (contributing 3.30%) and wire feed rate (contributing 1.01%).

The regression equation for the overcut as a function of six machining parameters was developed and is given as follows:

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Overcut = $54.1655-0.853A-0.0558B+0.004C-0.0438D+0.2401E+0.1814F+0.0035A^2-0.0008B^2+0.0003C^2+0.0074E^2+0.0071F^2+0.0008AB-0.004AC+0.0002AD-0.0025AE-0.0021AF+0.0005BC+0.0021BE-0.0032CE$ (7)

IV. CONFIRMATION EXPERIMENTS

Three confirmation experiments for each response characteristic have been conducted to validate the experimental results and the average value has been reported in Table 7.

For calculation of CI_{CE}, the following equations have been used:

$$CI_{CE} = \sqrt{F\alpha(1, fe)\left\{\left(\frac{1}{\eta eff}\right) + \left(\frac{1}{R}\right)\right\} Ve} \quad (8)$$

Where $F\alpha\ (1,f_e)$ = the F-ratio at a confidence level of (1-α) against DOF 1 and error DOF

Ve = Error variance

$$\eta_{eff} = \frac{N}{(1 + Total\ DOF\ used\ in\ estimating\ mean)} \quad (9)$$

N = Total number of Experiments

R = 3 (No. of repetitions for confirmatory experiment)

V. CONCLUSIONS

In this study, the effect and optimization of six machining parameters on three performance characteristics namely surface roughness, MRR and overcut is reported using Taguchi's experimental design. To find out major significant parameter affecting the performance characteristics, ANOVA analysis was performed. Mathematical models are developed to establish the interrelationship between machining parameters and performance characteristics. Following conclusions are drawn from this research work:

- The major significant factors that affect surface roughness are pulse on time, servo voltage, peak current and wire feed rate.
- For MRR, the major significant factors are pulse on time, pulse off time, servo voltage, peak current and wire feed rate.
- For overcut, the major significant factors are pulse on time, servo voltage and wire tension.
- Mathematical models were developed using regression analysis for performance characteristics so that we can determine the values of performance characteristics at any values of machining parameters.

Table 7

Results of Confirmation Experiments

Response	Optimum Set of Variables	Optimal value	Experimental value	CI_{CE}
Surface Roughness, µm	A1B3C3D1E3F3	1.3406	1.32	1.1935<1.3406<1.4877
MRR, mm^3/min	A3B1C1D3E1F1	61.7512	64.8647	55.8945<61.7512<67.6079
Overcut, mm	A2B3C3D2E2F1	0.119	0.117	0.055<0.119<0.183

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