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Multi-Objective Optimization of Electric Discharge Machining for Inconel 718

Pushpendra S. Bharti, S. Maheshwari

***Abstract*—**Electric discharge machining (EDM) is one of the most widely used non-conventional manufacturing process to shape difficult-to-cut materials. The process yield, in terms of material removal rate, surface roughness and tool wear rate, of EDM may considerably be improved by selecting the optimal combination(s) of process parameters. This paper employs Multi-response signal-to-noise (MRSN) ratio technique to find the optimal combination(s) of the process parameters during EDM of Inconel 718. Three cases *v.i.z.* high cutting efficiency, high surface finish, and normal machining have been taken and the optimal combinations of input parameters have been obtained for each case. Analysis of variance (ANOVA) has been employed to find the dominant parameter(s) in all three cases. The experimental verification of the obtained results has also been made. MRSN ratio technique found to be a simple and effective multi-objective optimization technique.

***Keywords*—**EDM, material removal rate, multi-response signal-to-noise ratio, optimization, surface roughness.

I. Introduction

INCONEL 718 is a nickel based superalloy which finds wide applications in aerospace and nuclear industry. It is a difficult-to-cut material due to its mechanical and metallurgical properties. Machining of this material by conventional machines leads to several problems like shorter tool life and surface abuse. Researchers find non-traditional machining like EDM suitable to machine this alloy [1]. In EDM, metal removal takes place in effect of series of electric discharges between the tool (electrode) and the work piece both immersed in a dielectric liquid. With each electric discharge, extremely high temperature is generated that leads to very small amount of material vaporized from the surface [2]. Any material, irrespective of its hardness, can be machined on EDM.

EDM process performance (cutting speed and surface quality) depends on the proper combination(s) of input parameters. Therefore, the selection of optimal combination of parameters has always been important and a challenging task. Optimization of process parameters of EDM is a multi-objective optimization task as high value of Material Removal Rate (MRR) is desired along with low values of Surface Roughness (SR) and Tool Wear Rate (TWR). For this, researchers have employed different multi-objective optimization techniques like Genetic Algorithms (GA), Simulated Annealing (SA) and Grey Relation Analysis (GRA) [3]-[7]. These techniques are quite efficient but require a high level of computational facility and mathematical skills. MRSN technique is one of the simple techniques that may be employed without much of mathematical background and computational facility. In this technique, the optimal combination of input parameters is obtained by converting multiple responses into a single response. The work reported (on this technique) in literature is limited, and that has motivated the authors to employ this technique in the parametric optimization of EDM. Ramakrishnan and Karunamoorthy [8] employed this technique to obtain the optimized parametric combination during wire-EDM of heat treated tool steel. They considered two cases. In the first case, more weightage was given to MRR as compared to SR, and in the other case, SR was given more weightage than MRR. In both the cases, the wire wear ratio was given the same weightage. Ramakrishnan and Karunamoorthy [9] obtained the parametric combination of input parameters during wire-EDM of Inconel 718. They took two performance measures namely MRR and SR and obtained the parametric combination by assigning different weights in three different cases. Bharti et al. [10] obtained the best combination of input parameters by employing this technique during EDM of D2 steel. Two cases were taken and parametric combinations were obtained accordingly.

In this work, MRSN technique has been employed to get the optimal combination(s) of the process parameters during EDM of Inconel 718. The experiments have been designed as per L36 ($2^1 3^6$) orthogonal array. Seven input parameters (1 is of 2 levels, 6 are of 3 levels each) and three performance measures have been taken into account. The obtained results are reported.

II. Experimental Procedure

Taguchi's L36 (21×36) orthogonal array was used for the design of experiments. The input parameters and their levels are shown in Table I. MRR, SR, and TWR were taken as performance measures. Elecktra Plus S-50 ZNC oil die-sinking EDM was used for the experimental runs. Copper was taken as tool electrode. MRR (mm^3/min) in each experimental run was obtained by measuring the mass difference before and after the experiment, using the precision electronic digital weight balance with a 0.1 mg resolution. The center line average (CLA) surface roughness parameter R_a was used to quantify the SR. MRR (or TWR) are calculated by:

Pushpendra S. Bharti is with University School of Information and Communication Technology, Guru Gobind Singh Indraprastha Universty, New Delhi, India (corresponding author, phone: +91 9810478041, e-mail: psbharti@ipu.ac.in).

S. Maheshwari is with Manufacturing Process and Automation Division, Netji Subhas Institute of Technology, New Delhi, India (e-mail: ssaacchhiinn@gmail.com).

$$MRR = \frac{w_i - w_f}{\rho t} mm^3/min \quad (1)$$

where w_i and w_f are the initial and final weights of work piece (or tool material) in gram, ρ is the density of work piece in g/mm^3 and t is the machining time in seconds.

TABLE I
MACHINING PARAMETERS AND THEIR LEVELS

Input parameters	Unit	Levels and values		
		1	2	3
Shape factor (SF)	-	Square	Circular	-
Pulse-on-time (T_{on})	µs	50	100	150
Discharge current (I_d)	A	3	8	12
Duty cycle (ζ)	%	0.7	0.75	0.83
Gap voltage (V_g)	V	50	70	90
Flushing pressure (P)	kg/cm^2	0.3	0.5	0.7
Tool electrode lift time (T_L)	Sec	1	2	3

III. OPTIMIZATION BY MRSN

In MRSN technique, a multi-response SN ratio is determined to obtain the optimal combination of process parameters. The MRSN ratio is determined by integrating the quality loss for multiple performance characteristics. The multiple responses are converted into a single response by assigning weight to each SN ratio of quality loss function and summing the weighted SN ratios. The following steps are performed:

Step I. Determination of normalized quality loss for each performance characteristic.

The quality losses for each performance characteristics are normalized when the units of the multiple performance characteristics are different. Normalized loss function corresponding to each performance characteristic is determined by (2)

$$N_{ij} = \frac{L_{ij}}{\overline{L_i}} \quad (2)$$

where N_{ij} is the normalized loss function for the i^{th} performance characteristic in the j^{th} experiment, L_{ij} is the loss function for the i^{th} performance characteristic in the j^{th} experiment, and L_i bar is the average quality loss function for the i^{th} performance characteristic.

Step II. Determination of total normalized quality loss

A weighting method is applied to determine the total normalized quality loss by (3)

$$TN_j = \sum_{i=1}^{P} w_i N_{ij} \quad (3)$$

where w_i is the weighting factor for the i^{th} performance characteristic, P is the number of performance characteristic, and j is the number of experiments.

Step III. Determination of MRSN ratio

Total normalized loss function is converted into MRSN by (4)

$$MRSN = -10\log(TN_j) \quad (4)$$

After calculating MRSN, traditional Taguchi's method is employed to optimize the process parameters with the difference that MRSN is used in place of S/N.

Loss function can be expressed by (5)

$$L_{ij} = \exp\left\{\frac{-S/N}{10}\right\} \quad (5)$$

IV. RESULTS AND DISCUSSIONS

Table II shows the values of performance measures for each experimental run. In this work, three cases have been taken by observing the industrial requirement. Case1: High cutting efficiency, *i.e.* more weightage, is given to MRR as compared to SR and TWR. The weights taken are w_1=0.6, w_2=0.3, w_3=0.1. Case 2: High surface finish, i.e. more weightage, is given to SR as compared to MRR and TWR. The weights taken are w_1=0.3, w_2=0.6, w_3=0.1. Case 3: Normal machining i.e. equal weightage is given to MRR and SR. The weights taken are w_1=0.45, w_2=0.45, w_3=0.1. In all cases, w_1, w_2 and w_3 are weights for MRR, SR, and TWR, respectively. Giving more weightage to MRR does not mean that SR is ignored and vice-versa. Giving more weightage to MRR does not mean that SR is ignored and vice-versa. In this study, it is observed that the value of TWR is very small as compared to that of MRR, hence weightage given to TWR is 0.1. The values of MRSN for case 1, case 2, and case 3 are also reported in Table II.

ANOVA results and Mean MRSN ratio for case-1 are reported in Tables III and IV, respectively. By analyzing these two tables, it is evident that discharge current is the most significant factor, having percentage contribution of 79.51, followed by gap voltage, pulse-on-time, duty cycle and shape factor. Flushing pressure and tool electrode lift time are observed as insignificant factors. The mean MRSN ratio of parameters A to G is maximum at A2, B3, C3, D1, E2, F2 and G3. Hence combination A2B3C3D1E2F2G3 is recommended as the optimal factor/level combination for case 1. Since in case 1, more weightage is given to MRR as compared to SR, the levels of pulse-on-time and discharge current are identified as B3 and C3. Higher level of discharge current and pulse-on-time induce more spark energy which results in high MRR.

TABLE II
DESIGN OF EXPERIMENT OF 36($2^1 \times 3^6$) ARRAY WITH DIFFERENT EXPERIMENTAL PARAMETRIC LEVELS AND PERFORMANCE MEASURES AND MRSN RATIOS FOR THREE CASES

Exp.	SF	T_{on} (μs)	I_d (A)	ζ	V_g (V)	P (kg/	T_L	MRR	SR	TWR	Case-1	Case-2	Case-3
1.	1	1	1	1	1	1	1	4.52	4.25	0.029	-1.0964	0.2626	-0.4699
2.	1	2	2	2	2	2	2	25.18	7.3	0.699	0.9331	0.0252	0.4554
3.	1	3	3	3	3	3	3	36.63	9.46	0.940	0.4950	-0.7608	-0.1781
4.	1	1	1	1	1	2	2	4.76	6.145	0.111	-1.2924	-0.4058	-0.8717
5.	1	2	2	2	2	3	3	30.61	7.9	0.923	0.6522	-0.3700	0.1111
6.	1	3	3	3	3	1	1	49.03	8.55	0.378	1.9399	0.3340	1.0632
7.	1	1	1	2	3	1	2	2.71	5.05	0.074	-2.8737	-1.2171	-2.1239
8.	1	2	2	3	1	2	3	29.91	9	0.396	1.3377	-0.0037	0.6154
9.	1	3	3	1	2	3	1	35.27	11.07	0.301	1.2672	-0.4129	0.3464
10.	1	1	1	3	2	1	3	1.91	5.36	0.015	-4.0113	-2.0894	-3.1558
11.	1	2	2	1	3	2	1	11.25	7.03	0.102	0.7827	0.5067	0.6425
12.	1	3	3	2	1	3	2	34.49	10.73	0.159	1.6327	-0.1107	0.6741
13.	1	1	2	3	1	3	2	27.89	8.05	0.310	1.6484	0.4125	0.9866
14.	1	2	3	1	2	1	3	55.51	9.8	0.239	2.0673	0.1819	1.0230
15.	1	3	1	2	3	2	1	2.73	4.92	0.007	-2.7758	-1.0674	-2.0051
16.	1	1	2	3	2	1	1	17.21	7.16	0.162	1.4709	0.7178	1.0781
17.	1	2	3	1	3	2	2	30.86	9.63	0.522	1.0006	-0.3558	0.2697
18.	1	3	1	2	1	3	3	7.45	5.2	0.047	0.2108	0.7902	0.4908
19.	2	1	2	1	3	3	3	17.09	6.33	0.228	1.4952	0.9054	1.1903
20.	2	2	3	2	1	1	1	47.45	10	0.595	1.1470	-0.4288	0.2880
21.	2	3	1	3	2	2	2	4.94	4.29	0.021	-0.8067	0.4571	-0.2206
22.	2	1	2	2	3	3	1	12.04	5.76	0.175	1.0347	0.9189	0.9764
23.	2	2	3	3	1	1	2	42.08	7.25	0.385	2.1156	0.7382	1.3725
24.	2	3	1	1	2	2	3	4.36	4.67	0.015	-1.2406	0.0693	-0.6348
25.	2	1	3	2	1	2	3	39.59	7.09	0.723	1.3808	0.2372	0.7715
26.	2	2	1	3	2	3	1	4.00	6.11	0.059	-1.7356	-0.6353	-1.2202
27.	2	3	2	1	3	1	2	14.54	8.31	0.020	1.2630	0.4674	0.8470
28.	2	1	3	2	2	2	1	16.72	6.88	0.219	1.3524	0.6917	1.0095
29.	2	2	1	3	3	3	2	3.38	5.82	0.030	-2.1940	-0.8539	-1.5754
30.	2	3	2	1	1	1	3	31.83	7.28	0.087	2.6149	1.2102	1.8560
31.	2	1	3	3	3	2	3	34.94	6.9	0.278	2.2840	1.0027	1.5963
32.	2	2	1	1	1	3	1	4.96	4.49	0.065	-0.8950	0.2950	-0.3406
33.	2	3	2	2	2	1	2	22.61	7.03	0.069	2.2245	1.1639	1.6619
34.	2	1	3	1	2	3	2	38.64	7.19	0.401	2.0101	0.7026	1.3073
35.	2	2	1	2	3	1	3	2.60	6.03	0.015	-3.0301	-1.4654	-2.3179
36.	2	3	2	3	1	2	1	25.66	7.32	0.303	1.7284	0.6453	1.1531

TABLE III
ANALYSIS OF VARIANCE FOR MRSN IN CASE-1

Source	Degrees of freedom	Sum of squares	Mean square	F-ratio	Percentage contribution
Shape factor (A)	1	1.50	1.5	16.22	1.36
Pulse-on-time(B)	2	1.91	0.95	10.32	1.73
Discharge current(C)	2	87.56	43.78	473.56	79.59
Duty cycle(D)	2	1.57	0.78	8.49	1.42
Gap voltage(E)	2	5.18	2.59	28.01	4.70
Flushing pressure(F)	2	0.13	0.06	0.70	0.11
Tool electrode lift time (G)	2	0.11	0.05	0.59	0.10
Error	22	2.03	0.09		10.94
Total		110.01			100

ANOVA results and Mean MRSN ratio for case 2 are shown in Tables V and VI, respectively. By analyzing these two tables, it is evident that discharge current is most significant factor having a percentage contribution as 30.81 followed by shape factor, pulse-on-time, gap voltage and duty cycle. Flushing pressure and tool electrode lift time are observed as insignificant factors. The mean MRSN ratio of parameters A to G is maximum at A2, B2, C2, D1, E2, F2 and G1. Hence combination A2B2C2D1E1F2G1 is recommended as the optimal factor/level combination for case-2. It is observed that the significant factor level of pulse-on-time, discharge current and gap voltage reduces from B3 to B2, from C3 to C2 and from E2 to E1 respectively when we go from case-1 to case-2. This is because low discharge current, lesser pulse-on-time, and low gap voltage induce less spark energy, and as a result surface finish improves and MRR decreases.

ANOVA results and Mean MRSN ratio for case 3 are shown in Tables VI and VIII, respectively. By analyzing these two tables, it is evident that discharge current is most significant factor followed by gap voltage, shape factor and pulse-on-time. Duty cycle, flushing pressure, and tool electrode lift time are observed as insignificant factors. The mean MRSN ratio of parameters A to G is maximum at A2, B3, C2, D1, E1, F1, and G3. Hence, combination A2B3C2D1E1F1G3 is recommended as the optimal factor/level combination for case 3.

TABLE IV
MEAN MRSN RATIO TABLE FOR CASE-1

Machining parameters	Mean S/N			Selected level	Optimum Level/factor combination
	Level-1	Level-2	Level-3		
Shape factor (A)	0.1882	0.5971		2	
Pulse-on-time(B)	0.2836	0.1818	0.7128	3	
Discharge current(C)	-0.3783	0.7344	0.8220	3	
Duty cycle(D)	0.8832	-0.2938	0.5888	1	A2B3C3D1E2F2G3
Gap voltage(E)	0.5132	0.5565	0.1084	2	
Flushing pressure(F)	0.5816	0.6240	-0.0275	2	
Time interval(G)	-0.4051	0.4549	1.1284	1	

TABLE V
ANALYSIS OF VARIANCE FOR MRSN IN CASE-2

Source	Degrees of freedom	Sum of squares	Mean square	F-ratio	Percentage contribution
Shape factor (A)	1	2.60	2.60	0.65	12.19
Pulse-on-time(B)	2	1.31	0.65	0.16	6.14
Discharge current(C)	2	6.58	3.29	0.83	30.81
Duty cycle(D)	2	0.85	0.42	0.10	4.00
Gap voltage(E)	2	1.15	0.57	0.14	5.40
Flushing pressure(F)	2	0.15	0.07	0.01	0.72
Time interval(G)	2	0.19	0.09	0.02	0.89
Error	22	87.14	3.96		39.20
Total		21.23			100

TABLE VI
MEAN MRSN RATIO TABLE FOR CASE-2

Machining parameters	Mean S/N			Selected level	Optimum Level/factor combination
	Level-1	Level-2	Level-3		
Shape factor (A)	-0.1979	0.34		2	
Pulse-on-time(B)	0.1783	0.2321	-0.1972	2	
Discharge current(C)	-0.4883	0.5500	0.1516	2	
Duty cycle(D)	0.2856	-0.0694	-0.0030	1	A2B2C2D1E1F2G1
Gap voltage(E)	0.3035	0.0418	-0.1321	1	
Flushing pressure(F)	-0.0104	0.1502	0.0734	2	
Time interval(G)	0.1523	0.0853	-0.0244	1	

TABLE VII
ANALYSIS OF VARIANCE FOR MRSN IN CASE-3

Source	Degrees of freedom	Sum of squares	Mean square	F-ratio	Percentage contribution
Shape factor (A)	1	2.14	2.14	4.60	4.04
Pulse-on-time(B)	2	1.37	0.68	1.47	2.59
Discharge current(C)	2	34.90	17.45	37.54	66.04
Duty cycle(D)	2	1.18	0.59	1.26	2.23
Gap voltage(E)	2	2.79	1.39	3.00	5.27
Flushing pressure(F)	2	0.15	0.07	0.16	0.28
Time interval(G)	2	0.09	0.04	0.09	0.17
Error	22	10.22	0.46		19.34
Total		52.85			100

V. EXPERIMENTAL VERIFICATION

The results of confirmatory experiments are shown in Tables IX-XI for case-1, case-2, and case-3, respectively. The results show that there is considerable improvement in MRR, SR, and TWR with respect to the initial settings of input parameters. The purpose of initial setting is to see the improvement in performance measures at optimum values with respect to the initial settings. Since case-1 represents the high cutting efficiency (i.e. more weightage is given to MRR as compared to SR), improvement in MRR (i.e. 27.47%) is more than improvement in SR (i.e. 10.61%). Case-2 represents the high surface finish (i.e. more weightage is given to SR as compared to MRR), so improvement in SR (i.e. 19.31%) is more than improvement in MRR (i.e. 12.98%). In case-3, improvement in MRR and SR is 18.23% and 12.88%, respectively. Improvement in TWR is less in case-1 (i.e. 7.02%) as compared to case-2 (i.e. 14.25%) and case-3 (10%). This is because settings of input parameters in case-1 lead to high MRR and high TWR.

TABLE VIII
MEAN MRSN RATIO TABLE FOR CASE-3

Machining parameters	Mean S/N			Selected level	Optimum Level/factor combination
	Level-1	Level-2	Level-3		
Shape factor (A)	-0.0582	0.4289		2	
Pulse-on-time(B)	0.1912	-0.0564	0.4212	3	
Discharge current(C)	-0.3328	0.4446	0.4442	2	
Duty cycle(D)	0.4983	-0.2316	0.2894	1	A2B3C2D1E1F1G3
Gap voltage(E)	0.3343	0.2648	-0.0431	1	
Flushing pressure(F)	0.3683	0.2496	-0.0619	1	
Time interval(G)	-0.4345	0.2853	0.7052	3	

TABLE IX
RESULTS OF CONFIRMATORY EXPERIMENTS FOR CASE-1

	Initial setting	Optimum values		Improvement
		Predicted	Experimental	
Level	A1B1C2D1E2F3G2	A2B3C3D1E2F2G3	A2B3C3D1E2F2G3	
MRR	38.63	-	49.25	27.47%
SR	7.19	-	6.5	10.61%
TWR	0.40	-	0.37	7.02%

TABLE X
RESULTS OF CONFIRMATORY EXPERIMENTS FOR CASE-2

	Initial setting	Optimum values		Improvement
		Predicted	Experimental	
Level	A2B1C2D1E2F3G2	A2B2C2D1E1F2G1	A2B2C2D1E1F2G1	
MRR	38.63	-	43.65	12.98%
SR	7.19	-	5.80	19..31%
TWR	0.40	-	0.34	14.25%

TABLE XI
RESULTS OF CONFIRMATORY EXPERIMENTS FOR CASE-3

	Initial setting	Optimum values		Improvement
		Predicted	Experimental	
Level	A1B1C1D1E1F1G1	A2B3C2D1E1F1G3	A2B3C3D1E2F2G3	
MRR	38.63	-	45.67	18.23%
SR	7.19	-	2.35	12.88%
TWR	0.40	-	0.36	10%

VI. CONCLUSIONS

In this work, MRSN ratio technique has been employed to obtain the optimal combination(s) of input parameters for the best cutting performance. MRSN ratio technique is found very simple, systematic, and effective. As per industrial requirement, three cases were taken viz. high cutting efficiency (case-1), high surface finish (case- 2) and normal machining (case-3). A2B3C3D1E2F2G3, A2B2C2D1E2F2G1 and A2B3C2D1E1F1G3 are recommended as the optimum factor /level combinations for case-1, case-2, and case-3, respectively. Predicted results have been experimentally verified and the improvement in MRR (with respect to initial setting of input parameters) is found as 27.47%, 12.98%, and 18.23% in case-1, case-2, and case-3, respectively. Surface finish has also been improved considerably (with respect to initial setting of input parameters) which is as 10.61%, 19.31%, and 12.88% in case-1, case-2, and case-3, respectively. ANOVA results indicate that that discharge current is the most dominant parameter in all three cases.

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Pushpendra S. Bharti was born at Uttar Pradesh, India in 1977. He obtained B.Sc. (Engg.) in Mechanical Engineering from Dayalbagh Educational Institute, Agra, India in 1998. He obtained M.E. in Production Engineering from Motilal Nehru National Institute of Technology, Allahabad, India in 2000. He obtained Ph.D. from Guru Gobind Singh Indraprastha University, New Delhi, India in 2012. His areas of research are Non-conventional manufacturing Process, Robotics and Manufacturing Automation.

He is working as Associate Professor with University School of Information and Communication Technology, Guru Gobind Singh Indraprastha University, New Delhi, India.

S. Maheswari was born at Madhya Pradesh, India in 1969. He obtained B.E. in Production and Industrial Engineering from Motilal Nehru National Institute of Technology, Allahabad, India in 1992. He obtained M.Tech. in Industrial Metallurgy from Indian Institute of Technology, Roorkee, Indiain 1993. He obtained Ph.D. from Indian Institute of Technology, Delhi, India in 1997. His areas of research are Non-conventional Manufacturing Process, Welding Technology and Manufacturing Automation.

He is working as Professor and Head with Manufacturing Process and Automation Division, Netaji Subhas Institute of Technology, New Delhi, India.