Multi-objective Optimization of Dry EDM with Inconel 718 Using Grey Relational Analysis

A. S. Bhandare and U. A. Dabade

Abstract In dry EDM machining, hollow electrodes are applied to supply gaseous medium at the machining zone. In this paper, an attempt has been made with L_{27} orthogonal array using compressed air as a dielectric medium, for Inconel 718 workpiece material and with copper tool electrode, to study and investigate the effects of machining parameters like as gas pressure, discharge current, pulse on time and gap voltage to optimize the output variables such as material removal rate (MRR), surface roughness (SR) and tool wear rate (TWR) based on Taguchi grey relational array. Analysis of variance (ANOVA) was carried out to find the significance of process parameters on grey relational grade. Gas pressure at level 2 (2 bar), current at level 1 (13 A), pulse on time at level 3 (200 μs) and gap voltage at level 3 (60 V) were found to be the optimum parameters for this process.

Keywords Dry electric discharge machining (Dry EDM) · Material removal rate (MRR) · Surface roughness (SR) · Tool wear rate (TWR) · Grey relational analysis · Analysis of variance

1 Introduction

Electric discharge machining (EDM) is a non-traditional machining process in which material removal takes place through the process of controlled spark generation. This process generates a perfect replica of the tool shape on the workpiece by using controlled spark energy. By using thermal energy, workpiece is melted and vaporized, and the amount of removed material can be effectively controlled to produce complex and precise machine components. The electrical discharges generate impulsive pressure in combination with dielectric explosion to remove the melted material. By

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considering process advantages, it is also necessary to consider its impact on environmental issues which limits the versatility of process [1]. Different oil-based dielectric fluids used in EDM reflected as a primary source of pollution from the process. New eco-friendly dry EDM techniques get developed by replacing liquid dielectric using gases [1]. Hollow tool electrodes are used, and through which, defined velocity gas is supplied in the machining zone. Due to defined velocity gas in the machining region, it removes debris of machined material and also avoids extreme heating of electrode and workpiece material in the machining region which reduces thermal loading. It provides advantages compared to conventional EDM process are lesser tool wear, minimum discharge gap, lesser residual stresses, lower white layer and heat affected zone [2]. Dry EDM holds the potential for complex and precision-oriented machining applications with its unique identity.

2 Literature Review

Chakravorty et al. [3] tried with four simpler methods for multi-response optimization compared to GRA method for determination of optimal process conditions in EDM processes. They found that WSN and utility theory method provided effective optimization compared to GRA and other multi-response optimization techniques for EDM processes. Vikasa et al. [4] studied the influence of the input process parameters during EDM machining like pulse on time, off time, current and voltage over the surface roughness for an EN41 material by using Grey-Taguchi method, and they found that current provided most significance and after that voltage for surface roughness value. Mishra and Routara [5] compared optimization of the EDM process using Taguchi methodology and grey relational approach on EN-24 alloy steel with pulse on and off time dielectric pressure and current for material removal rate (MRR) coupled with tool wear rate (TWR) as response variables. They found for MRR pulse on time and input current provided most significance and after that pulse off time and for TWR pulse on time and current provided most significance and after that Pulse off time. For GRA approach, they found optimal parameters setting with pulse on time level 3, pulse off time level 3, current level 2 and dielectric pressure level 1. Purohit et al. [6] executed optimization of EDM machining of tool steel M2 with process parameters as tool rotation speed, voltage and spark time for metal removal rate (MRR), electrode wear ratio (EWR) and over cut (OC) as a response variables using grey relational approach with a L_9 orthogonal array. For GRA approach, they found electrode rotation speed was most significant parameter succeeded by voltage and the spark time. Khundrakpam et al. [7] investigated on near dry electrical discharge machining with pulse on time, off time, discharge current, gap voltage and tool rotating speed as process parameters for surface roughness as output variable with air plus deionized water as a dielectric mixture on EN-8 material under Grey-Taguchi approach. Under GRA approach, they observed that discharge current and pulse on time were the significant parameters in sequence. Priyadarshini and Pal [8] demonstrated parametric optimization of EDM for machining of Ti–6Al–4V alloy with copper as tool using L_{25} orthogonal array. After GRA, they found optimal parameter settings were current 10 A, pulse on time 10 μs, duty factor 9 and gap voltage 8 V.

Here, an attempt is made with an objective to optimize the process variables for dry EDM machining of Inconel-718 for the multiple responses. In order to obtain optimum MRR, TWR, and SR work was attempted to determine the suitable testing parameters, with the application of statistical-based ANOVA coupled with GRA. Experiments were conducted to verify the combinations of optimal test parameters.

3 Steps for Grey Relational Analysis

In following section, procedure of grey relational analysis with corresponding equations to process the data is discussed.
Step 1: Normalization
Smaller-the-better

$$x_i^*(k) = \frac{\max x_i^{(o)}(k) - x_i^{(o)}(k)}{\max x_i^{(o)}(k) - \min x_i^{(o)}(k)} \tag{1}$$

Larger the better

$$x_i^*(k) = \frac{x_i^*(k) - \min x_i^0\ (k)}{\max x_i^0(k) - \min x_i^0\ (k)} \tag{2}$$

Step 2: Deviation sequence

$$\Delta 0_i(k) = \left| x_0^*(k) - x_i^*(k) \right| \tag{3}$$

Step 3: Grey Relational Coefficient

$$\gamma(x_0(k), x_i(k)) = \frac{\Delta_{\min} + \zeta\,\Delta_{\max}}{\Delta_{0i}(k) + \zeta\,\Delta_{\max}} \tag{4}$$

ζ is grey relational constant, here it is taken as 0.5.

Step 4: Grey Relational Grade

$$\gamma(x_0, x_i) = \frac{1}{m}\sum_{i=1}^{m} \gamma(x_0(k), x_i(k)) \tag{5}$$

Step 5: Determination of Optimal parameters
Here, grey relational grades are grouped by the factor level for each column in the orthogonal array, and its average is taken to judge optimal parameters
Step 6: Prediction of grey relational grade under optimum parameters

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{0} \left(\gamma^{-} - \gamma_m\right) \tag{6}$$

4 Experimental Set-up and Methodology

As it is dry EDM machining, a new attachment was developed on the existing CNC EDM machine for machining of Inconel 718 workpiece material with copper as electrode material and compressed air as dielectric medium.

Table 1 shows details of machining parameters selected for investigation, and Table 2 shows L_{27} orthogonal array with machining parameters and response variables. Experimental set-up is shown in Fig. 1.

Table 1 Levels of process parameters

Parameter	Levels		
	A	B	C
Gas pressure, GP (Bar)	1	2	3
Current (I) A	13	16	19
Pulse on time (POT) µs	100	150	200
Gap voltage (V)	40	50	60

Table 2 Taguchi L_{27} array with experimental parameters and evaluated response variables

Gas pressure (Bar)	Current (I) A	Pulse on time (POT) μs	Gap voltage (V)	MRR (mm^3/min)	TWR (mm^3/min)	R_a (μm)
1	13	100	40	0.0625	0.0019	1.2430
1	13	150	50	0.0726	0.0003	3.6160
1	13	200	60	0.0851	0.0006	2.0860
1	16	100	50	0.1231	0.0001	3.1760
1	16	150	60	0.1138	0.0017	3.2800
1	16	200	40	0.1347	0.0036	3.1860
1	19	100	60	0.1345	0.0135	4.9880
1	19	150	40	0.1429	0.0198	5.1040
1	19	200	50	0.1425	0.0019	3.8020
2	13	100	40	0.2103	0.0060	5.1440
2	13	150	50	0.1997	0.0094	3.7140
2	13	200	60	0.2001	0.0005	1.3560
2	16	100	50	0.2643	0.0002	4.0960
2	16	150	60	0.2851	0.0002	6.2250
2	16	200	40	0.2991	0.0043	2.2400
2	19	100	60	0.2841	0.0038	4.0100
2	19	150	40	0.3115	0.0037	2.7620
2	19	200	50	0.3721	0.0052	1.3300
3	13	100	40	0.2273	0.0003	3.4280
3	13	150	50	0.2136	0.0008	3.9420
3	13	200	60	0.3460	0.0011	2.2020
3	16	100	50	0.2143	0.0028	3.0700
3	16	150	60	0.2620	0.0002	3.4100
3	16	200	40	0.2752	0.0103	3.3600
3	19	100	60	0.2664	0.0031	1.5840
3	19	150	40	0.2756	0.0304	3.2560
3	19	200	50	0.3162	0.0140	1.8440

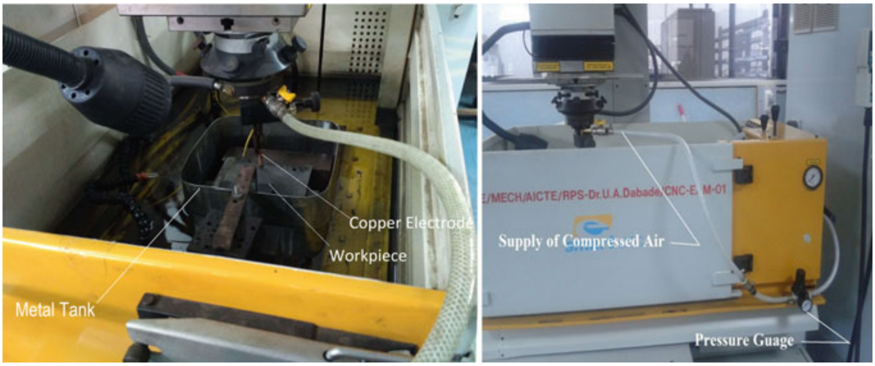

Fig. 1 Experimental set-up

5 Results and Discussion

The measured values of material removal rate (MRR), tool wear rate (TWR) and surface roughness are as shown in Tables 2, 3 and 4 show all the calculations derived from equations of grey relational analysis.

From the response and ANOVA Table 6, it is visible that pulse on time is most significant parameter for all response variables. It is pursued by gas pressure, gap voltage and current. All machining parameters have significant effect on GRG. The optimal factor setting is G2C1P3V3, i.e. gas pressure at level 2 (2 bar) current at level 1 (13 A), pulse on time at level 3 (200 μs), gap voltage at level 3 (60 V). The sequence of significance for all parameters is shown in Table 5.

Predicted (0.8054) and experimental value (0.8767) of GRG show good agreement as observed in Table 7. The improvement of 0.0742, i.e. 7.42% in grey relational grade is found from initial parameter combination, i.e. P3I3T1G3 to optimal parameter combination, i.e. P2I1T3G3.

6 Conclusion

- Multi-objective optimization of dry EDM process of Inconel 718 using grey relational analysis has been presented in this paper. Gas pressure, discharge current, pulse on time and gap voltage are the process parameters considered for investigation. Material removal rate (MRR), surface roughness (SR) and tool wear rate (TWR) are the response variables.

Table 3 Normalized data and deviation sequences

Normalized data			Deviation sequence		
MRR (mm^3/min)	TWR (mm^3/min)	R_a (μm)	MRR (mm^3/min)	TWR (mm^3/min)	R_a (μm)
0.0000	0.9416	1.0000	1.0000	0.0584	0.0000
0.0327	0.9948	0.5237	0.9673	0.0052	0.4763
0.0730	0.9827	0.8308	0.9270	0.0173	0.1692
0.1958	1.0000	0.6120	0.8042	0.0000	0.3880
0.1658	0.9462	0.5911	0.8342	0.0538	0.4089
0.2333	0.8850	0.6100	0.7667	0.1150	0.3900
0.2326	0.5567	0.2483	0.7674	0.4433	0.7517
0.2596	0.3513	0.2250	0.7404	0.6487	0.7750
0.2584	0.9391	0.4864	0.7416	0.0609	0.5136
0.4773	0.8069	0.2170	0.5227	0.1931	0.7830
0.4431	0.6946	0.5040	0.5569	0.3054	0.4960
0.4443	0.9884	0.9773	0.5557	0.0116	0.0227
0.6517	0.9964	0.4273	0.3483	0.0036	0.5727
0.7189	0.9964	0.0000	0.2811	0.0036	1.0000
0.7642	0.8603	0.7999	0.2358	0.1397	0.2001
0.7158	0.8783	0.4446	0.2842	0.1217	0.5554
0.8043	0.8825	0.6951	0.1957	0.1175	0.3049
1.0000	0.8324	0.9825	0.0000	0.1676	0.0175
0.5324	0.9918	0.5614	0.4676	0.0082	0.4386
0.4882	0.9764	0.4582	0.5118	0.0236	0.5418
0.9158	0.9664	0.8075	0.0842	0.0336	0.1925
0.4905	0.9123	0.6333	0.5095	0.0877	0.3667
0.6444	0.9963	0.5650	0.3556	0.0037	0.4350
0.6869	0.6638	0.5751	0.3131	0.3362	0.4249
0.6586	0.8994	0.9316	0.3414	0.1006	0.0684
0.6882	0.0005	0.5959	0.3118	0.9995	0.4041
0.8193	0.5400	0.8794	0.1807	0.4600	0.1206

Table 4 Grey relational grade

Grey relational coefficients				Rank
MRR (mm^3/min)	TWR (mm^3/min)	R_a (μm)	GRG	
0.3333	0.8953	1.0000	0.7429	5
0.3408	0.9897	0.5121	0.6142	18
0.3504	0.9665	0.7472	0.6880	9
0.3834	1.0000	0.5631	0.6488	14
0.3748	0.9028	0.5501	0.6092	19
0.3947	0.8129	0.5618	0.5898	21
0.3945	0.5299	0.3995	0.4413	26
0.4031	0.4351	0.3922	0.4101	27
0.4027	0.8914	0.4933	0.5958	20
0.4889	0.7213	0.3897	0.5333	23
0.4731	0.6207	0.5020	0.5319	24
0.4736	0.9773	0.9566	0.8025	3
0.5894	0.9928	0.4661	0.6828	11
0.6401	0.9928	0.3333	0.6554	13
0.6796	0.7816	0.7142	0.7251	6
0.6376	0.8042	0.4738	0.6385	17
0.7187	0.8097	0.6212	0.7165	7
1.0001	0.7489	0.9663	0.9051	1
0.5167	0.9838	0.5327	0.6778	12
0.4942	0.9548	0.4800	0.6430	15
0.8559	0.9370	0.7220	0.8383	2
0.4953	0.8507	0.5769	0.6410	16
0.5844	0.9927	0.5348	0.7039	8
0.6149	0.5978	0.5406	0.5844	22
0.5942	0.8325	0.8796	0.7688	4
0.6159	0.3333	0.5531	0.5008	25
0.7346	0.5207	0.8056	0.6870	10

Table 5 Sequence of significance

Factors	Level 1	Level 2	Level 3	Max–Min	Rank
Gas pressure	0.5934	**0.6879**	0.6717	0.0945	2
Current	**0.6747**	0.6489	0.6293	0.0454	4
Pulse on time	0.6417	0.5983	**0.7129**	0.1146	1
Gap voltage	0.6090	0.6611	**0.6829**	0.0739	3
Mean grey relational grade = 0.6510					

Bold values in the table indicates optimal parameter setting is G2C1P3V3, i.e., Gas pressure at level 2 (2 bar), current at level 1 (13 amp), pulse on time at level 3(200 μs), gap voltage at level 3 (60 V)

Table 6 *F* and *P* values of ANOVA for parameters

Source	DF	Adj SS	Adj MS	F	P
Gas pressure (Bar)	2	0.046003	0.023002	2.21	0.139
Current (I) A	2	0.009309	0.004654	0.45	0.647
Pulse on time (POT) μs	2	0.060206	0.030103	2.89	0.082
Gap voltage (V)	2	0.025960	0.012980	1.25	0.312
Error	18	0.187661	0.010426		
Total	26	0.329139			

Table 7 Confirmation table

	Exp. No. 4	Optimal	
	Initial (P3I3T1G3)	Predication (P2I1T3G3)	Experimental (P2I1T3G3)
MRR	0.2644		0.3119
TWR	0.0031		0.0009
SR	1.5840		1.3459
GRG	0.8025	0.8054	0.8767

- For multi-objective optimization, grey relational analysis is used because of its simplicity to solve complex problems with simple mathematical equations. Gas pressure at level 2 (2 bar), current at level 1 (13 A), pulse on time at level 3 (200 μs) and gap voltage at level 3 (60 V) were found as the optimum parameters for the process.
- Good agreement between predicted (0.8054) and experimental values (0.8767) of grey relational grade was found during the investigation.

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