Multi-Response Optimization of Process Parameters in Electrical Discharge Machining Using Grey Relational Analysis and Taguchi Method

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Abstract
In the present investigation, the experiments were conducted on a CNC Electrical discharge machine for machining of AISI D2 steel with cylindrical copper rods as electrodes. Electrode rotation, voltage, current and spark gap are considered as process parameters to maximize the material removal rate and minimize the surface roughness. The optimization of process parameters was carried out using single objective taguchi optimization technique. The effects of each process parameter on the responses were studied individually using the signal to noise ratio graphs. The responses, MRR and Ra are mainly influenced by current followed by voltage, electrode rotation and spark gap. Grey relational analysis (GRA) is also extended for simultaneous multi-response optimization of the responses. Finally, confirmation experiments are further conducted to validate the results.

Keywords
EDM, Surface Roughness, MRR, Taguchi Method, Grey Relational Analysis

I. Introduction

Electrical Discharge Machining (EDM) is a common non-conventional metal removal process and has been used extensively in the tool and dies industry. In EDM, the mechanism involved in material removal is primarily electro-thermal via a series of successive discrete discharge or sparks between the electrode and the work piece. The material is eroded predominantly by melting of two conductors at instantaneous and very high temperature of 8000-12000ºC generated due to high current discharges through the dielectric medium [1]. Therefore, it has the advantage of allowing the work-piece to be full hardness before machining of EDM and hence minimizes dimensional variability due to post treatment. It is also useful for machining brittle materials as there is virtually no contact between the tool and the work piece. Basically, EDM is a process for eroding and removing material by transient action of electric sparks on electrically conductive materials. This process is achieved by applying consecutive spark discharges between charged work piece and electrode immersed in a dielectric liquid and separated by a small gap [2]. The schematic diagram and principle of working of EDM is shown in fig. 1. Usually, localized breakdown of the dielectric liquid occurs where the local electrical field is highest. Each spark melts and even evaporates a small amount of material from both electrode and work piece. Part of this material is removed by the dielectric fluid and the remaining part re-solidifies rapidly on the surfaces of the electrodes. The net result is that each discharge leaves a small crater on both work piece and electrode. Application of consecutive pulses with high frequencies together with the forward movement of the electrode towards the work piece, results with a form of a complementary shape of the electrode on the work piece.

Material Removal Rate (MRR) and surface roughness (Ra) are the most important responses in EDM which decide the cutting performance [3]. Several researchers carried-out various investigations for improving the process performance. Proper selection of machining parameters for the best process performance is still a challenging job. As EDM is very complex and stochastic process, it is very difficult to determine optimal parameters for best machining performance i.e., productivity and accuracy. In the present study, MRR and Ra have been considered as responses which are conflicts in nature. MRR reflects the productivity and Ra reflects the accuracy of the product.

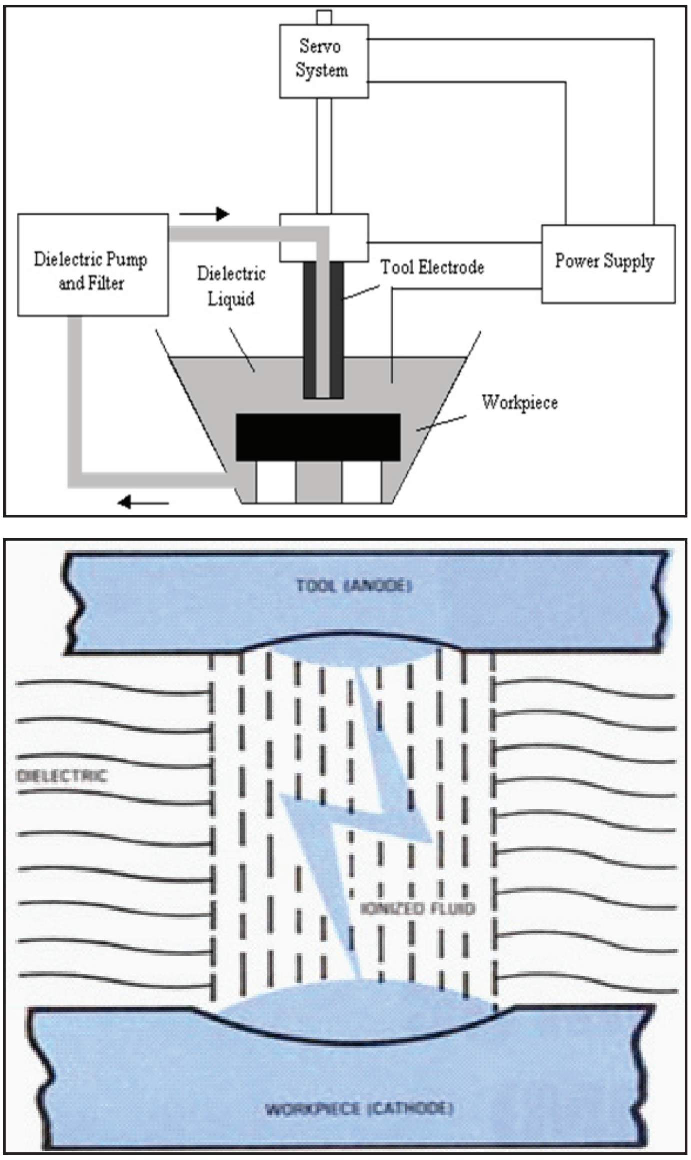

Fig. 1: Principle of Electrical Discharge Machining

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II. Experimental Details

The experiments were carried out on a standard EDM machine; model Sparkman (S-10) of sparkonix with straight polarity. AISI D2 steel (specimen of 80 mm x 25 mm x3mm,chemical composition of C-1.5%,Si-0.3%,Cr-12%,Mo-0.8%.V-0.9% and balance iron) hardened to 55-58 HRC was used as work piece material with SPARK2 oil (rust lick) as the dielectric fluid under jet flushing. The dielectric fluid was circulated by jet flushing and cylindrical Cu electrodes(diameter of 8 mm) was used for experimentation. EDM involves several control variables such as electrode rotation, voltage, current intensity, electrode material, duty cycle, flushing pressure, dielectric flow rate and spark gap. However, based on the literature survey and trail experiments, the variables namely, Electrode rotation (RPM), voltage (volts), current (amps) spark gap (mm) were considered as decision variables and MRR and Ra were considered as the output responses. The experimental process parameters and their levels selected for the study are listed in Table 1. MRR was calculated as the ratio of volume of material removed from work piece to the machining time and Ra was measured in perpendicular to the cutting direction using MITUTOYO surface roughness tester at a 0.8-mm cutoff value and measured at six different locations perpendicular to the direction of the machining on the surface of machined work piece and an average of these measurements is recorded as the response of Ra. The experiments are conducted twice to determine the S/N ratios as per Taguchi methodology. The experimental observations of the responses based on the L_{27} orthogonal array at different levels of parameters are listed in Table 2.

Table 1: Levels of Process Parameters

S.No	Process parameter	Symbol	Units	Levels		
				-1	0	1
1	Electrode rotation	x_1	RPM	250	500	750
2	Voltage	x_2	volts	80	120	160
3	Current	x_3	amps	4	8	12
4	Spark gap	x_4	mm	0.1	0.15	0.2

III. Taguchi's Method

Taguchi proposed that the engineering optimization of a process should be carried out in a three-step approach: system design, parameter design and tolerance design [4]. In the system design, the engineer applies scientific and engineering knowledge to produce a basic functional prototype design. This prototype design includes the product design stage and the process design stage. In the parameter design, the objective is to optimize the settings of the process parameter values. Finally the tolerance design is used to determine and analyze tolerances around the optimal setting recommended by the parameter design. The parameter design is the key step in the Taguchi method to achieve high quality without increasing cost and the same is adopted in this paper.

Table 2: Experimental Observations of the Responses

S.No	x_1	x_2	x_3	x_4	MRR(mg/min)	Ra(μm)	S/N Ratio for	
							MRR	Ra
1	250	80	4	0.1	22.67	0.89	27.0586	1.011652
2	250	120	4	0.15	31.83	1.12	30.19002	-0.98575
3	250	160	4	0.2	33.96	1.22	30.73946	-1.72785
4	250	120	8	0.1	43.17	1.85	32.75949	-5.34347
5	250	160	8	0.15	51.45	1.91	34.22767	-5.62094
6	250	80	8	0.2	40.03	1.43	32.04748	-3.10677
7	250	160	12	0.1	122.9	2.81	41.79049	-8.97418
8	250	80	12	0.15	64.94	2.32	36.2502	-7.31049
9	250	120	12	0.2	109.9	2.63	40.8199	-8.39968
10	500	120	4	0.1	33.72	1.20	30.55774	-1.58483
11	500	160	4	0.15	41.07	1.69	32.27047	-4.55789
12	500	80	4	0.2	23.27	0.98	27.33531	0.175026
13	500	160	8	0.1	59.48	2.18	35.486	-6.76922
14	500	80	8	0.15	40.26	1.61	32.09729	-4.13719
15	500	120	8	0.2	53.55	1.96	34.57469	-5.84523
16	500	80	12	0.1	91.89	2.58	39.26532	-8.23246
17	500	120	12	0.15	126.9	2.89	42.06871	-9.21801
18	500	160	12	0.2	180.7	3.41	45.13915	-10.6551
19	750	160	4	0.1	42.61	1.72	32.59017	-4.71116
20	750	80	4	0.15	36.70	1.38	31.29331	-2.79781
21	750	120	4	0.2	34.20	1.23	30.67945	-1.79817
22	750	80	8	0.1	55.99	2.02	34.96218	-6.10741
23	750	120	8	0.15	66.90	2.33	36.5074	-7.34723
24	750	160	8	0.2	81.54	2.40	38.22721	-7.6043
25	750	120	12	0.1	173.1	3.21	44.76592	-10.1301
26	750	160	12	0.15	251.3	3.63	48.00385	-11.1982
27	750	80	12	0.2	128.9	2.97	42.20456	-9.45518

Taguchi method is a powerful design of experiments (DOE) [5] tool for engineering optimization of a process. The applications in which the concept of S/N ratio is useful are the improvement of variability reduction and the improvement of measurement. The S/N ratio (Signal to Noise ratio) characteristics can be divided into three categories when the characteristic is continuous, which are larger the better, smaller the better and nominal is the better. In the present paper, the MRR is to be maximized and Ra to be minimized. Hence smaller the better characteristics has been applied for the surface roughness and larger the better characteristics has been applied for the MRR.

(i) Smaller the better characteristics:

$S/N = -10 \log (1/n) \sum (Y_{ij}^2)$ (1)

(ii) Larger the better characteristics:

$S/N = -10 \log (1/n) \sum (1/Y_{ij}^2)$ (2)

Where Y_{ij} is observed data, n the number of replications. S/N ratios of the responses for each trail of experiment are listed in Table 2. S/N Ratio mean for the responses at different levels of process parameters are listed in Table 3. The effects of process parameters on mean S/N Ratio for MRR and Ra is shown in fig. 2 and fig. 3 respectively. From fig. 2, it can be seen that for MRR, S/N ratio increases for Electrode rotation, Voltage, Current and where as for Spark gap increases initially and then decreases. As MRR is the larger response is better, S/N ratio analysis suggests the (X_{13}, X_{23}, X_{33}, X_{42}) as best levels for maximum MRR. The values of optimum process parameters for maximum MRR are electrode rotation of 750 rpm, voltage of 160 volts, current of 120amps and spark gap of 0.2 mm. According to the results listed in Table 3, for MRR, current has the largest effect on the response followed by voltage, electrode rotation and spark gap. From Fig 3, it can be seen that for Ra, S/N ratio decreases for electrode rotation, voltage, current and where as for spark gap decreases initially and then increases. As Ra is the smaller response is better, S/N ratio analysis suggests the (X_{13}, X_{23}, X_{33}, X_{42}) as best levels for minimum Ra. The values of optimum process parameters for minimum Ra are electrode rotation of 750 rpm, voltage of 160 volts, current of 120amps and spark gap of 0.2 mm. According to the results listed in Table 3 for Ra, current has the largest effect on the response followed by voltage, electrode rotation and spark gap.

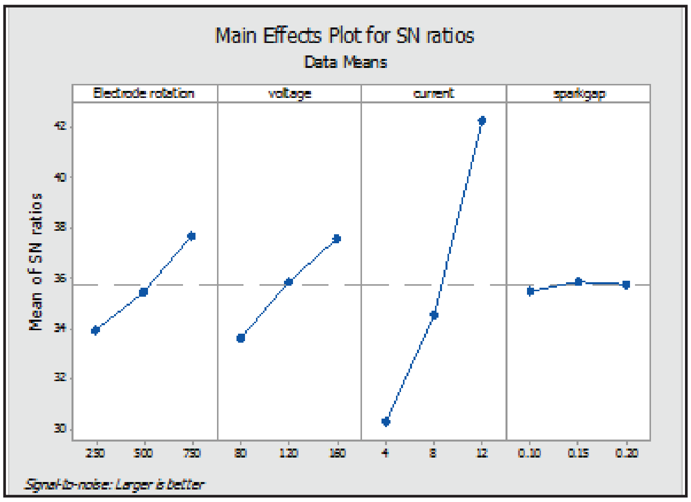

Fig. 2: The Effects of Process Parameters on Mean S/N Ratio for MRR

Table.3. S/N Ratio mean for MRR and Ra

Level	MRR(larger is the better)			Ra(Smaller is the better)				
	x_1	x_2	x_3	x_4	x_1	x_2	x_3	x_4
1	33.96	33.62	30.28	35.47	-4.495	-4.44	-1.886	-5.649
2	35.42	35.86	34.54	35.86	-5.647	-5.628	-5.764	-5.908
3	37.69	37.6	42.26	35.74	-6.869	-6.869	-9.286	-5.379
Delta	3.73	3.98	11.98	0.39	2.299	2.429	7.4	-0.528
Rank	3	2	1	4	3	2	1	4

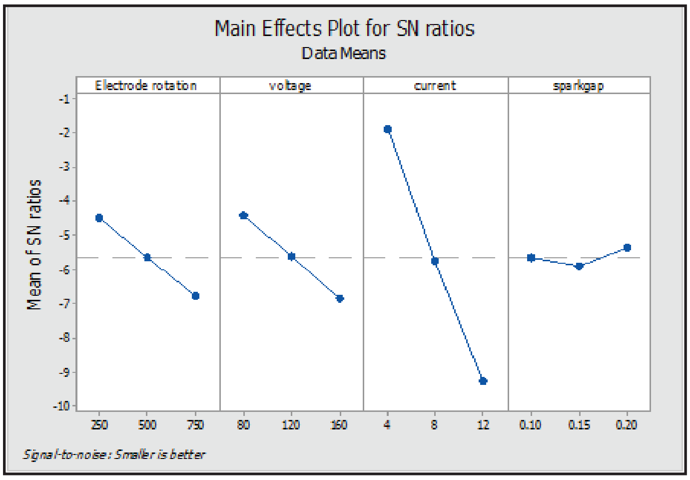

Fig. 3: The Effects of Process Parameters on Mean S/N Ratio for Ra

IV. Grey Relation Analysis

Grey Relational Analysis (GRA) technique is used to solve the problems of the systems that are complex and multivariate. GRA is an alternate method for traditional statistical methods which deals with the small sample size and uncertainty conditions and can be applied in optimization of multiple quality characteristics [6]. In this method, multi response performance characteristics can be converted in to a single grey relation grade.GRA is normalization based evolution technique in which the quality characteristics of the measured data are first normalized ranging from 0 to 1. This process is known as grey relational generation. In the present study, the S/N ratios obtained for metal removal rate, surface roughness have to be normalized in the range between 0 and 1.

For larger the better

$X_{ij} = (Y_{ij} - \min (Y_{ij})) / (\max (Y_{ij}) - \min (Y_{ij}))$ (3)

For smaller the better

$X_{ij} = (\max (Y_{ij}) - Y_{ij}) / (\max(Y_{ij}) - \min(Y_{ij}))$ (4)

Where X_{ij} is the normalized S/N ratio, Y_{ij} is the S/N ratio determined from the experiment for each trail, max Y_{ij} and min Y_{ij} are the corresponding maximum and minimum values of S/N ratios. Grey relational coefficient (GC) is determined to represent the relationship between the desired and actual data. It can be determined as follows [7]

$$GC_{ij} = (\Delta_{min}+\mu\ \Delta_{max})/\ (\Delta_{ij}+\mu\ \Delta_{max}) \quad (5)$$

The responses are both larger and smaller characteristics, μ assumed to be 0.5 and Δ_{min}, Δ_{max} are the minimum and maximum absolute difference from the target value. Grey relational grade (G) can be determined as the mean average of grey relational coefficients of responses for each trail of experiment. The higher value of grey relational grade represents the better solution and closer to the optimal response of the process. Normalized S/N ratio, grey relation coefficient, grey relation grade and rank of each trail are listed in Table 4. The rank of each experiment trail has been listed in a way that the higher grey relation grade is given as rank 1 and so on as the higher grey relation grade will have better multi response characteristics. Hence, from Table. 5 it is evident that experiment trail 26 has the optimal parameters setting for better multi response characteristics. The response table for Grey relation grade means at different levels of process parameters is listed in Table 5 and it indicates the level of co relational between the reference sequence and obtained sequence. The higher rank for a process parameter is given based on the higher value of maximum and minimum difference of the average means (delta value) of a particular parameter on the response. It is evident from table 5 that, current (Rank 1) is the most significant process parameter among the remaining on the responses and followed by voltage, electrode rotation and spark gap as per the rank order .The optimal combination of process parameters on the response has been obtained from Table 5 as level 3 of electrode rotation, level 3 of voltage, level 3 of current and level 2 of spark gap. (X_{13}, X_{23}, X_{33}, and X_{42}).The numerical values of optimal process parameters are electrode rotation of 750 rpm, voltage of 160 volts, current of 120amps and spark gap of 0.2 mm. The grey relation grade for multi performance response is shown in fig .4.

V. Confirmation Test

The experiments have been conducted with optimal setting process parameters for the confirmation of the results [8]. The equation for the predicted Grey relation analysis multi performance response is given as:

$$Y_{predicted} = Ym + \sum^{n}_{i=1}(Yn-Ym) \quad (6)$$

Where $Y_{predicted}$ is predicted grey relation grade to validate the responses of the EDM process. Yn is the mean grey relation grade at optimum level, n is the number of factors and Ym is the total mean grey relation grade. The predicted of grey relation grade ($Y_{predicted}$)obtained is 0.938.The responses at the optimal setting of the confirmation experiments are obtained as MRR of 251.3 mg/min , Ra of 3.63 µm and grey relational grade of 0.914.The value of the grey relational grade is improved by 2.62% from the predicted mean value.

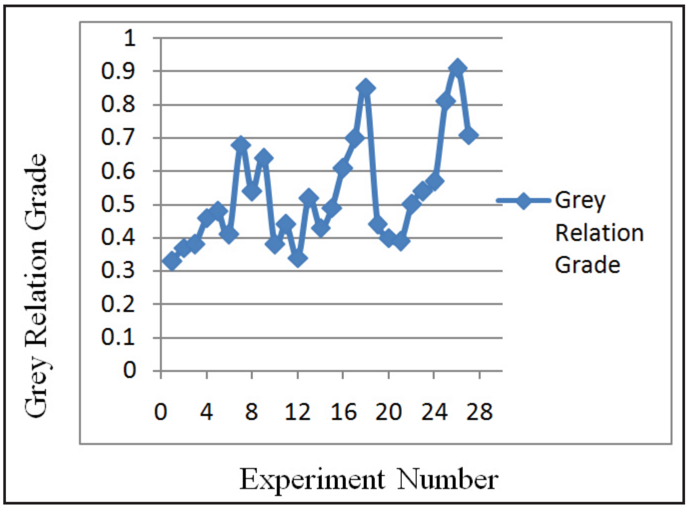

Fig. 4: Grey Relation Grade for Multi Performance Response

VI. Conclusion

Multi- response optimization of process parameters in electrical discharge machining using grey relational analysis and Taguchi method was experimentally investigated in this paper. The responses, MRR and Ra are mainly influenced by current followed by voltage, electrode rotation and spark gap .The optimal values of process parameters are electrode rotation of 750 rpm, voltage of 160 volts, current of 120amps and spark gap of 0.2 mm. The responses MRR and surface roughness are optimized using single objective taguchi method and multi-objective grey relational analysis and the same has been validated with the confirmation test.

Table 4: S/N Ratios and Grey Relation Coefficients with Grey Relation Grade

S.No.	S/N Ratio		Normalized S/N Ratio		Grey Relation Coefficient(GRC)		Grey Relation Grade(G)	Rank
	MRR	Ra	MRR	Ra	MRR	Ra		
1	27.0586	1.011652	0.00000	0.0000	0.33333	0.33315	0.33	27
2	30.19002	-0.98575	0.14950	0.1628	0.37023	0.37391	0.37	25
3	30.73946	-1.72785	0.17574	0.2236	0.37757	0.39171	0.38	23
4	32.75949	-5.34347	0.27218	0.5197	0.40723	0.51004	0.46	16
5	34.22767	-5.62094	0.34228	0.5424	0.43188	0.52214	0.48	15
6	32.04748	-3.10677	0.23819	0.3365	0.39626	0.42973	0.41	20
7	41.79049	-8.97418	0.70335	0.8170	0.62763	0.73211	0.68	6
8	36.2502	-7.31049	0.43884	0.6808	0.47118	0.61034	0.54	11
9	40.8199	-8.39968	0.65701	0.7700	0.59313	0.68492	0.64	7
10	30.55774	-1.58483	0.16706	0.2118	0.37511	0.38815	0.38	24
11	32.27047	-4.55789	0.24883	0.4553	0.39963	0.47862	0.44	18

12	27.33531	0.175026	0.01321	0.0677	0.33630	0.34909	0.34	26
13	35.486	-6.76922	0.40235	0.6365	0.45552	0.57901	0.52	12
14	32.09729	-4.13719	0.24057	0.4209	0.39700	0.46334	0.43	19
15	34.57469	-5.84523	0.35884	0.5608	0.43815	0.53235	0.49	14
16	39.26532	-8.23246	0.58279	0.7563	0.54513	0.67231	0.61	8
17	42.06871	-9.21801	0.71664	0.8370	0.63827	0.75416	0.70	5
18	45.13915	-10.6551	0.86323	0.9547	0.78521	0.91696	0.85	2
19	32.59017	-4.71116	0.26410	0.4679	0.40456	0.48445	0.44	17
20	31.29331	-2.79781	0.20218	0.3112	0.38526	0.42059	0.40	21
21	30.67945	-1.79817	0.17287	0.2293	0.37675	0.39349	0.39	22
22	34.96218	-6.10741	0.37734	0.5822	0.44537	0.54481	0.50	13
23	36.5074	-7.34723	0.45112	0.6838	0.47670	0.61259	0.54	10
24	38.22721	-7.6043	0.53323	0.7048	0.51719	0.62881	0.57	9
25	44.76592	-10.1301	0.84541	1.0000	0.76384	0.84993	0.81	3
26	48.00385	-11.1982	1.00000	0.9117	1.00000	0.8166	0.91	1
27	42.20456	-9.45518	0.72312	0.8564	0.64360	0.77693	0.71	4

Table 5: Response table of the average grey relation grade

Parameter level	electrode rotation	voltage	current	spark gap
1	0.4767	0.4744	0.3856	0.5256
2	0.5289	0.5311	0.4889	0.5444
3	0.5956	0.5956	0.7267	0.5311
Delta	0.1189	0.1211	0.3411	0.0189
Rank	3	2	1	4
Total mean grey relation grade=0.5336				

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