Vol. 2, Iss. 2 (2025) 61-70, DOI: 10.61552/JMES.2025.02.002

JMES

Journal of Management and Engineering Sciences

www.jmes.aspur.rs

Process Optimization during Electric Discharge Machining of Nickel-Chrome Alloy

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Keywords:

EDM
Grey-Taguchi`s methodology
Optimization
Performance measures

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Received: 11.05.2024.
Revised: 15.07.2024.
Accepted: 19.07.2024.

A B S T R A C T

This investigation involves the multi-response optimization of electrical discharge machining for Ni-22Cr-8Fe-Mn-Cu nickel-chrome alloy. The input parameters such as discharge current, pulse duration, pulse interval and flushing pressure were investigated and the material removal rate, electrode wear rate and radial overcut were explored. The experiments were performed as per L_{27} orthogonal array. Copper electrode was used as conductive tool during EDM of alloy inside a dielectric medium. Optimization was performed using Taguchi approach followed by Grey Relational Analysis. ANOVA has been performed to find significant parameters for responses. The Regression analysis was conducted to explore the dependency of performance measures on the controllable variables. Results reveled that pulse-off time and the interactions of the peak current with pulse-on time and pulse-off time are the most significant factors for the process performance. Results were validated by comparing the predicted and experimental grey relation grades.

1. INTRODUCTION

Nowadays, the industrial technology demands to utilize new materials such as super-alloys, composites, ceramics, etc. However, the machining of such materials is a big challenge. Electric Discharge Machining (EDM) is one of the un-conventional machining routes used to machine very hard materials [1-5]. This spark erosion process is developed in 1940, and is extensively used in mold and dies cutting applications [6,7]. In EDM, electrons and positive ions reach were reached at anode and cathode terminals respectively and possesses kinetic energy which generates heat. This heat is then converted into the thermal energy resulting from continuous series of electric discharges between the electrode and the work piece. This thermal energy generates a plasma between two electrodes and raises the temperature up to 8000-12000 °C [8] or as high as 20000 °C [9]. The spark frequency is used normally in the range

20000-30000 Hz [10]. The breakdown of plasma channel occurs, the pulsed DC supply is turned off, which suddenly reduces the temperature and allows the circulating fresh dielectric fluid expel away the eroded material in the form of small debris. The flushed metal solidifies into micro-spheres into the dielectric fluid [11]. EDM has no cutting force, there is no direct contact between the tool electrode and the work material, hence mechanical stress, noise and vibrations during machining are eliminated. Material removal rate depend on amount of pulse current, frequency of discharge, tool electrode material, work material, electrode polarity and type of dielectric fluid [12-15]. Sivaprakasam et al. [16] observed that material cutting rate and surface quality affected with the variation of discharge current. However, MRR and surface quality decreased with reducing the pulse on time. Torres et al [17] reported that higher material cutting rate is obtained using positive polarity while negative polarity caused better surface quality. Patela [18] concluded that all input factors possessed significant impact on the MRR and it increases slowly with respect to the electrode rotational speed. In EDM, the cryogenic treatment on workpiece improves surface quality and material removal rate and tool life [19]. Also, for different work materials, the cryogenic treatment of electrode increases tool life and reduces tool wear along with minor effect on surface quality and MRR [20-24] along with the improvement in the hardness and electrical conductivity of the electrode [25] and material removal rate [26] irrespective of electrode material Kumar et al. [27] observed that steel voltage, current and Pulse-on-time are the most influencing factors for the process performance measures i.e. MRR and EWR. In another research, TGRA and RSM optimization tools were used by Dutta et al [28] and reported that the end results are in-line with the existing literature model. Khan et al [29] found that pulse off time was found the most affecting parameter for surface finishing and microhardness of the work material. The results reported by Jangra et al [30] revealed that that the taper angle and pulse time are the important input factors affecting GRG means machining performance. Nowadays, parametric optimization using design of experiments (DOE) becomes essential in the manufacturing sector to achieve best manufacturing conditions with least cost [31]. The optimization techniques, based on DOE, can be applied to investigate the most effective optimal input conditions for responses [32-34]. For single objective optimization, Taguchi approach is the best solution. But, the multi objective optimization calls for other techniques viz. genetic algorithm, artificial neural network, grey relation analysis, etc. Among these, the grey relation analysis (GRA) is a best technique, which provides single optimized operating levels irrespective of number of performance measures.

In this investigation, electrical discharge machining on nickel-chrome alloy was performed using copper electrode and the influence of controllable variables (like discharge current, pulse duration, pulse interval and flushing pressure) on the process performance measures in form of material removal rate (MRR), Electrode Wear Rate (EWR) and Radial Overcut (ROC), was investigated. The optimization was performed initially using Taguchi approach followed by grey relational analysis.

2. MATERIALS AND METHODS

2.1 Workpiece Material

The nickel-chrome alloy (Ni-22Cr-8Fe-Mn-Cu) with dimension of 60 x 50 x 10 mm was chosen as work piece material and its composition is listed in Table 1. This material exhibits high corrosion and oxidation resistance at high temperature, high strength good workability. The applications of this material include high temperature spring, muffle furnace, heat exchanger tubes, chemical and food processing equipment, combustion chambers, etc.

Table 1. Composition of Nickel-Chromium alloy.

Ni	Cr	Fe	Mn	Cu	Si	C	S
63.9	24.3	8.91	1.01	0.98	0.509	0.11	0.013

2.2 Tool Material

Copper tool electrode (purity level-99.9 %) with 10 mm diameter and 25 mm length is chosen as tool material as it has better electrical conductivity.

2.3 Selection of input parameters

Four controllable input parameters having three levels each were selected to perform machining tests and the detail is shown in Table 2.

Table 2. Input parameters and their levels.

Parameters	Symbol	Unit	Level 1	Level 2	Level 3
Discharge current	I_d	A	4	7	10
Pulse duration	T_{on}	µs	60	90	120
Pulse interval	T_{off}	µs	45	70	95
Flushing Pressure	P_f	psi	4	7	10

2.4 Machine Tool Detail

Agie-Charmilles (FORM 300) die sink-EDM was used to perform experiments and the setup is shown in Figure 1. As a dielectric fluid, commercial grade oil for EDM process having specific gravity of 0.763 and freezing point as 94°C was employed. Copper electrode with positive polarity was used during machining. Pictorial view of copper electrode, workpiece and experimental set-up is shown in Figure 2.

Fig. 1. Pictorial view of EDM Machine used during experimentation.

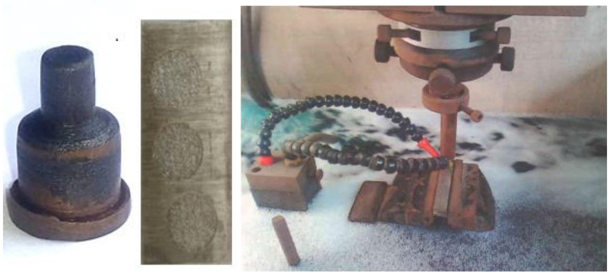

Fig. 2. Pictorial view of Cu electrode, workpiece and experimental Set-up.

2.5 Plan of Experiment and Observations

The process performance was evaluated in form of MRR, EWR and ROC. The experimental conditions were chosen according to L27 orthogonal array. The combinations of input parameters and corresponding responses are listed in Table 3.

Prior and after each run, the weights of workpiece and electrode were measured using electronic weighing machine (LC=0.001mg) and time for each run was recorded. MRR has been expressed the loss in weight of workpiece in unit time. Similarly, EWR has been evaluated in the form of loss in electrode weight in unit time for each run. The ROC, which is the radial oversize of the cutting hole in workpiece, was measures using instrumental profile projector. So as per the terminology of Taguchi method, "larger is better" type response for MRR and "lower is the better" type response for EWR and ROC has been chosen during analysis. The methodology used during the optimization of EDM for nickel-chrome alloy is shown in Fig. 3.

3. RESULTS AND DISCUSSION

3.1 Taguchi Analysis

Statistical analysis was performed using Taguchi approach.

3.1.1 Main effects plots

The main effects plots for MRR, EWR and ROC are shown in Fig. 4, Fig. 5 and Fig. 6 respectively. Results revealed that MRR increases with increasing discharge current and flushing pressure, while pulse duration and pulse interval shows opposite effect on it.

The main effect plot for EWR revealed that electrode wear increases with increasing the discharge current, but reduces with increasing the pulse interval. Moderate level of pulse duration and low level of flushing pressure is best suitable for minimum electrode wear. Moreover, EWR increases with decreasing the discharge current. However, pulse on time possessed inverse effect on it.

The main effect plot reveals that minimum overcut is obtained at low or high level of discharge current and moderate level of pulse interval. Also, overcut varies proportionally with respect to pulse on time and flushing pressure. Table 4 shows the best input parameters combinations for each response by employing the Taguchi approach.

Table 3. Experimental setup as per L_{27} OA and its responses.

Run No	I_d (A)	T_{on} (µs)	T_{off} (µs)	P_f (psi)	MRR (g/hr)	SNRA1	EWR (g/hr)	SNRA2	ROC (mm)	SNRA3
1	4	60	45	4	2552.1	68.1379	0.213	13.4324	0.024	32.5786
2	4	60	70	7	4289.7	72.6485	0.094	20.5374	0.090	20.9474
3	4	60	95	10	6037.0	75.6164	0.029	30.7520	0.214	13.4087
4	4	90	45	7	3610.3	71.1510	0.200	13.9794	0.065	23.7417
5	4	90	70	10	6334.5	76.0342	0.098	20.1755	0.213	13.4290
6	4	90	95	4	9288.9	79.3593	0.013	37.7211	0.363	8.8059
7	4	120	45	10	4617.3	73.2877	0.175	15.1392	0.152	16.3917
8	4	120	70	4	8817.9	78.9073	0.051	25.8486	0.237	12.5234
9	4	120	95	7	12451.8	81.9047	0.389	8.2010	0.371	8.6164
10	7	60	45	4	3543.3	70.9882	0.413	7.6810	0.122	18.2728
11	7	60	70	7	6008.6	75.5754	0.290	10.7520	0.280	11.0465
12	7	60	95	10	8466.8	78.5544	0.086	21.3100	0.061	24.2697
13	7	90	45	7	5151.5	74.2386	0.349	9.1435	0.255	11.8806
14	7	90	70	10	8907.5	78.9951	0.233	12.6529	0.406	7.8206
15	7	90	95	4	12673.6	82.0580	0.106	19.4939	0.059	24.5830
16	7	120	45	10	6660.3	76.4699	0.230	12.7654	0.222	13.0893
17	7	120	70	4	12466.7	81.9150	0.188	14.5168	0.399	7.9769
18	7	120	95	7	16627.5	84.4166	0.080	21.9382	0.103	19.7714
19	10	60	45	4	4688.1	73.4199	0.375	8.5194	0.325	9.7646
20	10	60	70	7	7558.1	77.5683	0.310	10.1728	0.026	31.6174
21	10	60	95	10	10885.0	80.7366	0.132	17.5885	0.196	14.1438
22	10	90	45	7	6391.6	76.1122	0.296	10.5742	0.338	9.4174
23	10	90	70	10	11454.0	81.1791	0.253	11.9376	0.061	24.2461
24	10	90	95	4	16093.0	84.1327	0.150	16.4782	0.178	15.0079
25	10	120	45	10	8743.6	78.8338	0.332	9.5772	0.379	8.4349
26	10	120	70	4	15671.8	83.9024	0.200	13.9794	0.077	22.2233
27	10	120	95	7	20167.9	86.0932	0.155	16.1934	0.240	12.4048

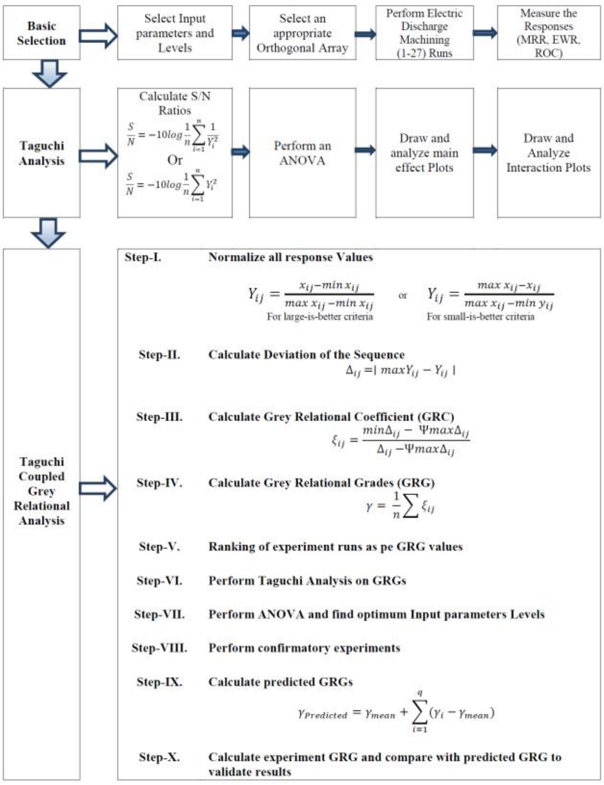

Fig. 3. Methodology used during electric discharge machining of Nickel-Chrome alloy [28-31].

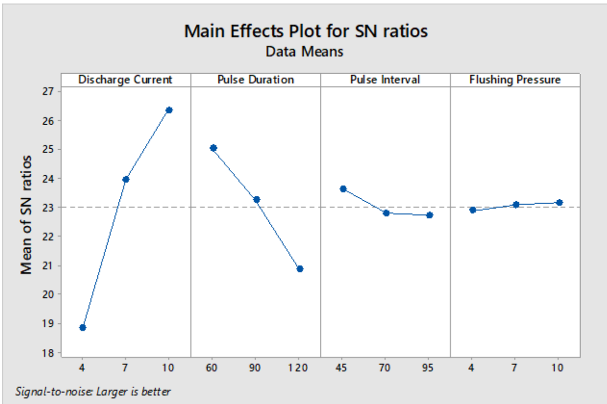

Fig. 4. Main effects plot graph for MRR.

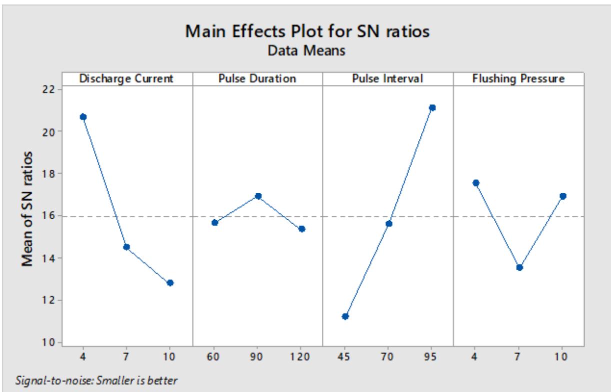

Fig. 5. Main effects plot for EWR.

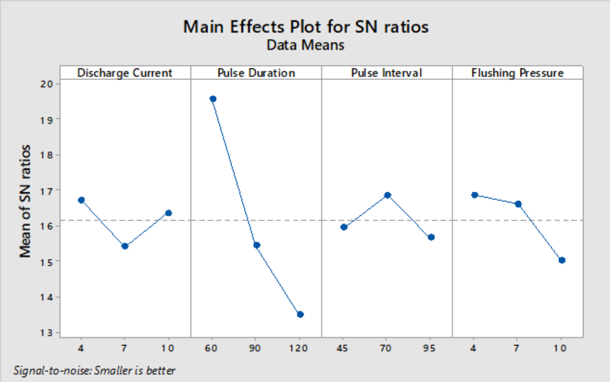

Fig. 6. Main effects plot for ROC.

Table 4. Best input parameters combinations suggested by Taguchi approach.

Parameter	I_d (A)	T_{on} (μs)	T_{off} (μs)	P_f (psi)
MRR	10	60	45	10
EWR	4	90	95	4
ROC	4	60	70	4

3.1.2 Analysis of Variance

The ANOVA for each response is shown in Table 5. Results revealed that discharge current is the most significant parameter for MRR that contributes 69.79% followed by pulse duration (20.50%) and interaction between current and pulse on time. Pulse off time and flushing pressure is insignificant. It has also been observed that pulse interval is the most significant parameter for electrode wear that contributes 33.26% to achieve minimum tool wear followed by discharge current (23.29%), while other parameters are insignificant and are having minor effect on it. Moreover, for dimensional accuracy (means overcut), the interactions between discharge Current*pulse Interval is the highest contributing factor (77.49%) among others while pulse interval is the significant parameter for it.

Table 5. ANOVA Table for response parameters.

Material removal rate							
Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Contribution
Discharge Current	2	265.126	265.126	132.563	242.31	0.000*	69.79%
Pulse Duration	2	77.888	77.888	38.944	71.19	0.000*	20.50%
Pulse Interval	2	4.594	4.594	2.297	4.2	0.072	1.21%
Flushing Pressure	2	0.354	0.354	0.177	0.32	0.735	0.09%
Discharge Current*Pulse Duration	4	23.635	23.635	5.909	10.8	0.007*	6.22%
Discharge Current*Pulse Interval	4	4.209	4.209	1.052	1.92	0.226	1.11%
Discharge Current*Flushing Pressure	4	0.802	0.802	0.201	0.37	0.825	0.21%
Residual Error	6	3.282	3.282	0.547			
Total	26	379.892					
Electrode wear rate							
Discharge Current	2	308.29	308.29	154.145	4.36	0.068	23.29%
Pulse Duration	2	12.33	12.33	6.163	0.17	0.844	0.93%
Pulse Interval	2	440.33	440.33	220.167	6.22	0.034*	33.26%
Flushing Pressure	2	83.96	83.96	41.978	1.19	0.368	6.34%
Discharge Current*Pulse Duration	4	96.81	96.81	24.202	0.68	0.628	7.31%
Discharge Current*Pulse Interval	4	42.96	42.96	10.74	0.3	0.866	3.24%
Discharge Current*Flushing Pressure	4	126.97	126.97	31.743	0.9	0.52	9.59%
Residual Error	6	212.28	212.28	35.381			16.03%
Total	26	1323.93					
Radial Overcut							
Discharge Current	2	8.18	308.29	154.145	4.36	0.068	0.61%
Pulse Duration	2	172.85	12.33	6.163	0.17	0.844	12.89%
Pulse Interval	2	7.1	440.33	220.167	6.22	0.034*	0.53%
Flushing Pressure	2	17.76	83.96	41.978	1.19	0.368	1.32%
Discharge Current*Pulse Duration	4	34.92	96.81	24.202	0.68	0.628	2.60%
Discharge Current*Pulse Interval	4	1038.81	42.96	10.74	0.3	0.866	77.49%
Discharge Current*Flushing Pressure	4	27.3	126.97	31.743	0.9	0.52	2.04%
Residual Error	6	33.59	212.28	35.381			2.51%
Total	26	1340.5					

*Significant parameter

3.1.3 Regression Analysis

The expression for regression analysis of MRR, TWR and ROC are shown in Equation 1, Equation 2 and Equation 3 that explains the dependency of each response factor on controllable input variables.

$$MRR\ (g/hr) = 14.69 + 2.048*I_d - 0.1220*T_{on} - 0.0405*T_{off} + 0.041*P_f \quad (1)$$

$$EWR\ (g/hr) = 0.346 + 0.01743*I_d - 0.000263*T_{on} - 0.003207*T_{off} - 0.00261*P_f \quad (2)$$

$$ROC\ (mm) = 0.049 + 0.0017*I_d + 0.00156*T_{on} - 0.00021*T_{off} + 0.0022*P_f \quad (3)$$

3.2 Taguchi-Grey Relational Analysis

In this experimental research, GRA was used for multiple objective optimization and results are listed in Table 6.

Table 6. Calculated Normalized Data, Grey Relation coefficients and Grey Relation Grades.

Run No.	Normalization (Y)			Deviation sequences (Δ)			Grey Relation Coefficients (ξ)			Grey Relation Grades (γ)	Rank
	EWR	MRR	ROC	EWR	MRR	ROC	EWR	MRR	ROC		
1	0.500	0.000	1.000	0.500	1.000	0.000	0.500	0.333	1.000	0.61111	6
2	0.798	0.099	0.827	0.203	0.901	0.173	0.712	0.357	0.743	0.60391	8
3	0.960	0.198	0.503	0.040	0.802	0.497	0.926	0.384	0.501	0.60374	9
4	0.533	0.060	0.893	0.468	0.940	0.107	0.517	0.347	0.823	0.56244	14
5	0.788	0.215	0.505	0.213	0.785	0.495	0.702	0.389	0.503	0.53114	16
6	1.000	0.382	0.113	0.000	0.618	0.887	1.000	0.447	0.360	0.60259	10
7	0.595	0.117	0.665	0.405	0.883	0.335	0.552	0.362	0.599	0.50428	17
8	0.905	0.356	0.442	0.095	0.644	0.558	0.840	0.437	0.473	0.58335	13
9	0.060	0.562	0.092	0.940	0.438	0.908	0.347	0.533	0.355	0.41176	22
10	0.000	0.056	0.743	1.000	0.944	0.257	0.333	0.346	0.661	0.44685	20
11	0.308	0.196	0.330	0.693	0.804	0.670	0.419	0.383	0.427	0.41003	23
12	0.818	0.336	0.903	0.183	0.664	0.097	0.733	0.429	0.838	0.66660	4
13	0.160	0.148	0.395	0.840	0.852	0.605	0.373	0.370	0.453	0.39848	24
14	0.450	0.361	0.000	0.550	0.639	1.000	0.476	0.439	0.333	0.41614	21
15	0.768	0.575	0.908	0.233	0.425	0.092	0.683	0.540	0.845	0.68934	2
16	0.458	0.233	0.482	0.543	0.767	0.518	0.480	0.395	0.491	0.45511	19
17	0.563	0.563	0.018	0.438	0.437	0.982	0.533	0.534	0.337	0.46810	18
18	0.833	0.799	0.793	0.168	0.201	0.207	0.749	0.713	0.707	0.72325	1
19	0.095	0.121	0.212	0.905	0.879	0.788	0.356	0.363	0.388	0.36891	27
20	0.258	0.284	0.995	0.743	0.716	0.005	0.402	0.411	0.990	0.60110	11
21	0.703	0.473	0.550	0.298	0.527	0.450	0.627	0.487	0.526	0.54667	15
22	0.293	0.218	0.178	0.708	0.782	0.822	0.414	0.390	0.378	0.39410	25
23	0.400	0.505	0.903	0.600	0.495	0.097	0.455	0.503	0.838	0.59832	12
24	0.658	0.769	0.597	0.343	0.231	0.403	0.593	0.684	0.554	0.61026	7
25	0.203	0.351	0.071	0.798	0.649	0.929	0.385	0.435	0.350	0.39017	26
26	0.533	0.745	0.861	0.468	0.255	0.139	0.517	0.662	0.783	0.65388	5
27	0.645	1.000	0.435	0.355	0.000	0.565	0.585	1.000	0.469	0.68469	3

Maximum value of Grey relational grade is obtained in experiment number 18. Since the value of GRG represents all responses instantaneously, the optimization is further extended by applying Taguchi approach on the GRG values considering it as "larger is better" type criteria. The ANOVA for GRG is shown in Table 7. It is noted that pulse interval and the interactions of discharge current with pulse duration and pulse interval are most significant parameters to obtained maximum GRG value (means optimal response values). Also, the interaction of discharge current with pulse interval contributes 45% followed by pulse interval (35.37%) and interaction between discharge current and pulse interval (9.12%), while other parameters contribute the least to achieve optimum value of GRG.

Table 7. ANOVA for GRGs.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Contribution
Discharge Current	2	2.8016	2.8016	1.4008	3.6	0.094	3.33%
Pulse Duration	2	0.0589	0.0589	0.0295	0.08	0.928	0.07%
Pulse Interval	2	29.7539	29.7539	14.8769	38.22	0.000*	35.37%
Flushing Pressure	2	1.6663	1.6663	0.8331	2.14	0.199	1.98%
Discharge Current*Pulse Duration	4	7.6691	7.6691	1.9173	4.93	0.042*	9.12%
Discharge Current*Pulse Interval	4	37.8497	37.8497	9.4624	24.31	0.001*	45.00%
Discharge Current*Flushing Pressure	4	1.979	1.979	0.4948	1.27	0.377	2.35%
Residual Error	6	2.3357	2.3357	0.3893			2.78%
Total	26	84.1142					

Table 8. Response Table for S/N ratios for GRGs.

Level	Discharge Current	Pulse Duration	Pulse Interval	Flushing Pressure
1	0.5571454*	0.5398788	0.4590494	0.5593777*
2	0.5193217	0.5336447	0.5406619	0.5321955
3	0.5386776	0.5416211*	0.6154334*	0.5235715
Delta	0.0378238	0.0079764	0.1563839	0.0358062
Rank	2	4	1	3

* Significant Level

Table 9. Results of responses using initial and optimal parameters.

Response Parameters	Initial Input Parameters	Optimum Input Parameters	
		Predicted	Experimental
Setting Level	I_p=4A, T_{on}=60µs, T_{off}=45µs, P_f=4psi	I_p=4A, T_{on}=120µs, Toff=95µs, P_f=4psi	
Electrode wear rate (g/hr)	0.213		0.12
Material Removal Rate (g/hr)	2552.1		12058.1
Radial overcut (mm)	0.024		0.105
Grey Relation Grade	0.61111	0.6154334	0.62477
Improvement in GRG = 0.01366			

Fig. 7 illustrates that the optimal combination of input conditions is discharge current of 4A, pulse duration of 120µs, pulse interval of 95µs and flushing pressure of 4psi. Table 8 shows the significant level for each controllable input factors. Based on the delta value, all these factors can be ranked.

A "non-linear regression equation" for GRG is shown in Equation 4. This equation indicates that how all responses depend on the controllable input parameters.

$$GRG= 0.380 - 0.00308*I_d + 0.000029*T_{on} + 0.003128*T_{off} - 0.00597*P_f \quad (4)$$

The confirmatory tests are conducted and responses are recorded as shown in Table 9. The predicted grey relation grade ($\gamma_{Predicted}$) is also calculated to validate the results. A significant improvement in the GRG has been observed. It has also been observed that the experimental

GRG differs by 1.52 % only from the predicted GRG. This confirms validation of the results obtained by employing Taguchi coupled grey relational analysis.

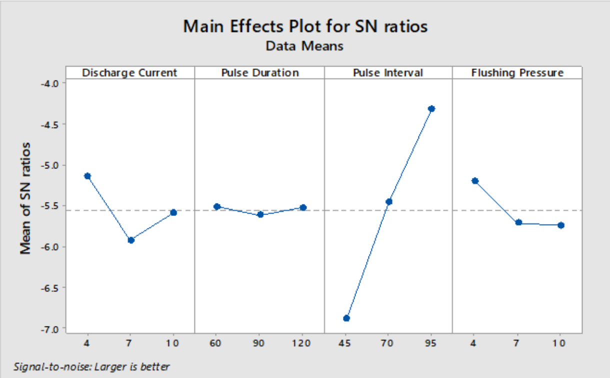

Fig. 7. Main effects plot for GRG.

4. CONCLUSIONS

In this study, parametric optimization of EDM for nickel-chrome alloy is carried out. The process optimization is performed using GRA. During machining, discharge current, pulse interval, pulse duration and flushing pressure were chosen as input parameters and process performance was measured in form of MRR, EWR and ROC.

1. To conclude, as per findings of Taguchi approach, discharge current is the most significant parameter for MRR followed by pulse duration and interaction between current and pulse on time. Similarly, for electrode wear, also, the pulse interval is the most significant parameter for electrode wear and radial over cut.
2. The non-linear regression models explain the reliant of responses on the input parameters.
3. As per results of grey relation analysis, pulse interval and the interactions of discharge current with pulse duration and pulse interval have the strongest impact on the performance measures. The interaction between discharge current and pulse interval contributes the most (45%) followed by pulse interval (35.37%) and interactions of discharge current and pulse interval (9.12%) to obtain optimal response values.
4. The common optimal set of input conditions for all responses is discharge current 4A, pulse duration 120µs, pulse interval 95µs and flushing pressure 4psi.
5. A significant improvement in the GRG value of 0.01366 (means optimal results) are obtained by employing Taguchi-GRA. Also, the value of predicted GRG and experimental GRG is very close to each other (differs by 1.52% only) that indicates validation of the results.

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