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Optimization of Electrical Discharge Drilling Process of Carbon Carbon Composite using Grey Relational Analysis

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Abstract—*This article addresses an approach based on the grey relational analysis for optimizing the process parameters for carbon-carbon composite with multiple performance characteristics. A grey relational grade obtained from the grey relational analysis is used to optimize the process parameters. Material removal rate and tool wear rate were selected as quality characteristics. Using these characteristics, the process parameters including pulse current, pulse-on-time, pulse-off-time and tool rotation are optimized. Carbon-carbon composite is used as workpiece. Carbon-carbon composite is a unique composite material consisting of carbon fibres reinforced in carbon matrix. Its low density, high thermal conductivity and outstanding mechanical properties at elevated temperature make it an ideal material for aircraft brakes, rocket nozzles and re-entry nose tips. The multi-response optimization of the process parameters on electrical discharge drilling of carbon carbon composite grey relational analysis is reported. Experimental results have been improved through this approach.*

1. INTRODUCTION

Carbon carbon composites are generic class of synthetic, pure carbon material consisting of fibres reinforced in a carbon matrix. These materials were first came into existence in the late 1950s when space shuttle programmes required thermal protection materials. Carbon-carbon composite is a unique composite material consisting of carbon fibres reinforced in carbon matrix. Its low density, high thermal conductivity and outstanding mechanical properties at elevated temperature make it an ideal material for aircraft brakes, rocket nozzles and re-entry nose tips [1]. It is highly brittle material which makes it difficult to machine with conventional machining processes. While drilling a hole of certain diameter drill bit with conventional drilling process, the cutting edge of the tool catches fibres and loses its sharpness. This tends to give fibre pullout and cracks in the composite material. This gives rise to need of advanced manufacturing process. Electrical discharge machining is one of the advanced manufacturing processes which is used to machine the material of high strength without applying any mechanical force between tool and workpiece. In EDM, material is removed with the help of electric spark. Material is removed from workpiece by the series of rapidly recurring current discharges between two electrodes, tool (cathode) and workpiece (anode) separated by dielectric liquid.

2. ELECTRICAL DISCHARGE DRILLING

Electric discharge machining is one of the most widely used unconventional processes which is capable to machine complex and intricate shapes for the hard to cut materials of any hardness. It is non-contact type machining process in which tool electrode does not come in contact with workpiece. The EDM process is based on extirpation of material through melting and evaporation. Both the tool electrodes (cathode) and workpiece (anode) are kept submerged in the dielectric and a high voltage DC current is supplied in the form of about 5 KHz frequency pulses. Further breaking down of dielectric occurs due to the supply of DC current which causes flow of electrons from cathode to anode. Due to bombardment of electrons at the anode surface, a high pressure plasma channel is formed between tool and workpiece. The formation and collapse of plasma channel causes material removal. The regularly occurring sparks owing melting and vaporization of tool and workpiece both. Electric discharge drilling is a collaborative hybrid machining process of EDM and conventional drilling. However, there is no contact between tool and workpiece as in case of conventional drilling. The material is removed by melting and evaporation and tool rotation assists the process by efficient expulsion of debris from machined areas at the same time.

3. EXPERIMENTAL

The material used in this investigation is carbon-carbon composite of size 120 mm × 100 mm × 2 mm. Copper is used as tool electrode of 8 mm diameter. The reason for selecting copper is its high electrical as well as thermal conductivity.

3.1. Experimental plan

It was decided to study the effect of input parameters, pulse current, pulse-on-time, pulse-off-time and tool rotation and response parameters material removal rate and tool wear rate. The range of input parameters was fixed as given in Table 1.

Table 1. Levels of input parameters

Input parameters	Level 1 (Low)	Level 2 (Medium)	Level 3 (High)
Pulse Current (A)	9	12	15
Pulse-on-time (μs)	90	120	150
Pulse-off-time (μs)	15	45	90
Tool rotation (rpm)	500	700	900

3.2. Planning experiments

In the present research, full factorial experimental design was used to analyze the effect of each factor on multiple responses. A full factorial designed experiment consists of all possible combinations of levels for all the factors. Pulse current, pulse-on-time, pulse-off-time and tool rotation were considered as input parameters. The different levels of these parameters are shown in Table 1.

The total number of experiments for studying 4 factors at 3 levels is 3^4=81 experiments.

3.3. Experimental setup

A SPARKONIX make Z-axis numerically controlled EDM machine has been used for performing the experiments. A separate attachment for giving rotation to tool electrode is mounted on the servo head of EDM

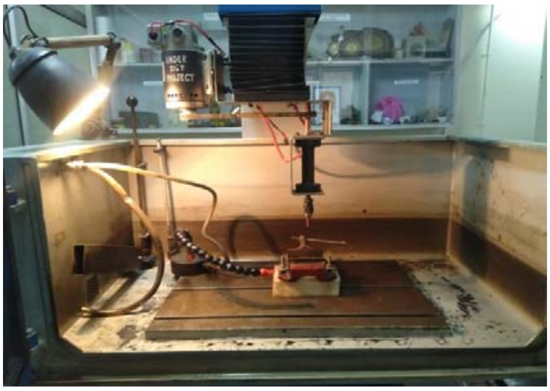

Figure 1: Experimental setup for Electrical Discharge Drilling setup mounted on servo head

4. GREY RELATIONAL ANALYSIS METHOD

Optimization of process parameters is the key step in the Taguchi methods to achieve high quality with increase in cost. Optimization of multi response characteristics is more complex as compared to optimization of single performance characteristics. The higher-the-better performance for one factor may affect the performance because another factor may demand lower-the-better characteristics. For these multi-response optimization characteristics, grey relational analysis optimization methodology is used.

In the grey relational analysis,[2] experimental results were first normalized and then the grey relational coefficients were calculated from the normalized experimental data. Then the grey relational grade was computed by averaging the grey relational coefficient corresponding to each process response [5]. The overall evaluation of the multiple process response is based on the grey relational grade. As a result, optimization of complicated process responses can be converted into optimization of a single grey relational grade. The optimization of the process was performed in following steps:

(a) Normalizing the experiments results of MRR and TWR for all the trials.
(b) Performing the grey relational generating and to calculate the grey relational coefficient.
(c) Calculating the grey relational grade by averaging the grey relational coefficient.
(d) Finding the ranks of grey relational grade and consider the input parameters of higher grey relational grade as optimal level of process parameter.

3.4. Normalizing the experimental results

A normalization of the experimental results for the response parameter i.e. MRR and TWR is performed in the range between 0 and 1, this is known as grey relational generating as given in Table 2. For 'larger-the-better' characteristics like material removal rate, the original sequence can be normalized as:

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

$x_i^*(k)$and$x_i(k)$ are the sequence after the data preprocessing and comparability sequence respectively, k=1 for MRR; i=1,2,3…,81 for experiments numbers 1 to 81.

For 'smaller-the-better' characteristics like TWR, the original sequence can be normalized as:

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

Table 2: The sequences of each performance characteristic after data processing

Expt. No.	MRR	TWR	Expt No.	MRR	TWR
1	0.6460	0.8357	36	0.5652	0.8736
2	0.5466	0.8373	37	0.4255	0.9131
3	0.9596	0.6477	38	0.4876	0.8183
4	0.7360	0.7694	39	0.5031	0.8420
5	0.3075	0.8578	40	0.4255	0.9210
6	0.4503	0.9258	41	0.5497	0.8341
7	0.0000	0.7978	42	0.5497	0.8420
8	0.5932	0.8547	43	0.7516	0.7709
9	0.5404	0.0000	44	0.5342	0.8736
10	0.3991	0.8949	45	0.5652	0.9052

11	0.6242	0.7938	46	0.6429	0.9052
12	0.7143	0.7425	47	0.2547	0.9289
13	0.9627	0.7180	48	0.9224	0.7314
14	0.6506	0.8294	49	0.3634	0.8183
15	0.4239	0.8799	50	0.7826	0.8341
16	0.5093	0.8578	51	0.5963	0.8341
17	0.6273	0.8104	52	0.5652	0.8183
18	0.4099	0.8894	53	0.5963	0.8499
19	0.4720	0.8736	54	0.8758	0.7788
20	0.8913	0.7630	55	0.6429	0.7472
21	0.2547	0.9447	56	0.8913	0.6603
22	0.6584	0.7156	57	0.6584	0.7788
23	0.7516	0.7867	58	0.4720	0.8657
24	0.5497	0.8183	59	0.3944	0.9052
25	0.3168	0.8973	60	0.6429	0.8262
26	0.6429	0.8973	61	0.3634	1.0000
27	0.7516	0.7314	62	0.6118	0.8341
28	1.0000	0.6682	63	0.6584	0.9210
29	0.2857	0.8657	64	0.4565	0.8499
30	0.8292	0.6998	65	0.8758	0.6919
31	0.5342	0.9210	66	0.5652	0.8894
32	0.3478	0.9368	67	0.6429	0.8657
33	0.7360	0.7630	68	0.2547	0.9052
34	0.7360	0.8499	69	0.7360	0.7709
35	0.5807	0.8025	70	0.6739	0.8183
71	0.4255	0.8657			
72	0.6739	0.8104			
73	0.5497	0.9052			
74	0.7360	0.8183			
75	0.3012	0.9368			
76	0.5186	0.8657			
77	0.4720	0.8420			
78	0.5963	0.8025			
79	0.6894	0.7077			
80	0.9068	0.7630			
81	0.4099	0.9289			

3.5. Computing the grey relational coefficients

The grey relational coefficients are calculated to express the relationship between the ideal and the actual experimental results. The grey relational coefficient can be expressed as:

$$\xi_i(k) = \frac{\Delta_{min}+\zeta\Delta_{max}}{\Delta_{oi}(k)+\zeta\Delta_{max}} \quad (3)$$

Where $\Delta_{oi}(k)$ is the deviation sequence of the reference sequence $x_0^*(k)$ and the comparability sequence is $x_i^*(k)$, ζ distinguishing coefficient.

3.6. Computing the grey relational grades

The grey relational grade corresponding to each performance characteristics is to be computed and the overall evaluation of the multi response characteristics is based on the grey relational grade, which is given as follows:

$$\alpha_i = \frac{1}{m}\sum_{k=1}^{m} \xi_i(k) \quad (4)$$

Where α_i the grey relational grade for the i_{th} experiment and m is the number of performance characteristics. The higher grey relational grade represents that the corresponding experimental result is closer to the ideally normalized value as shown in Table 3. In the present work, experiment 28 has the best multi response characteristics among the 81 experiments conducted.

The mean of the grey relational grade for each level of the machining parameter can be calculated by averaging the grey relational grades as summarized in Table 4. The larger the value of grey relational grade, the better is the multi response characteristics. According to the results shown in Table 4, for machining of carbon carbon composite, pulse-off-time (T_{off}) has the largest effect. Pulse-on-time (T_{on}) on second and is followed by tool rotation and pulse current (I_p). From the response table for the grey relational grade (Table 4), the optimal parameter setting is to maintain pulse current at level 3, pulse on-time at level 3, pulse off-time at level 1 and tool rotation at level 3 for maximizing MRR and for minimizing TWR among the 81 experiments.

Table 3: Grey relational coefficient and grey relational grade

Expt. No.	GRC (MRR)	GRC (TWR)	GRG	Rank
1	0.5855	0.7527	0.6691	29
2	0.5244	0.7545	0.6394	57
3	0.9253	0.5867	0.7560	5
4	0.6545	0.6843	0.6694	27
5	0.4193	0.7786	0.5989	78
6	0.4763	0.8707	0.6735	25
7	0.3333	0.7120	0.5227	80
8	0.5514	0.7748	0.6631	36
9	0.5210	0.3333	0.4272	81
10	0.4542	0.8264	0.6403	55
11	0.5709	0.7081	0.6395	56
12	0.6364	0.6601	0.6482	49
13	0.9306	0.6394	0.7850	2
14	0.5887	0.7456	0.6671	30
15	0.4646	0.8064	0.6355	62
16	0.5047	0.7786	0.6416	54
17	0.5730	0.7251	0.6490	47
18	0.4587	0.8189	0.6388	58
19	0.4864	0.7982	0.6423	53
20	0.8214	0.6785	0.7499	6
21	0.4015	0.9004	0.6510	46
22	0.5941	0.6375	0.6158	75
23	0.6680	0.7010	0.6845	21
24	0.5261	0.7335	0.6298	67
25	0.4226	0.8296	0.6261	69
26	0.5833	0.8296	0.7065	15
27	0.6680	0.6506	0.6593	40
28	1.0000	0.6011	0.8006	1
29	0.4118	0.7883	0.6000	77
30	0.7454	0.6249	0.6851	20
31	0.5177	0.8636	0.6906	17
32	0.4340	0.8878	0.6609	39
33	0.6545	0.6785	0.6665	33
34	0.6545	0.7691	0.7118	12

35	0.5439	0.7169	0.6304	66
36	0.5349	0.7982	0.6666	32
37	0.4653	0.8520	0.6586	41
38	0.4939	0.7335	0.6137	76
39	0.5016	0.7599	0.6307	65
40	0.4653	0.8636	0.6644	35
41	0.5261	0.7509	0.6385	59
42	0.5261	0.7599	0.6430	52
43	0.6680	0.6858	0.6769	23
44	0.5177	0.7982	0.6580	42
45	0.5349	0.8406	0.6878	18
46	0.5833	0.8406	0.7120	11
47	0.4015	0.8755	0.6385	60
48	0.8656	0.6506	0.7581	4
49	0.4399	0.7335	0.5867	79
50	0.6970	0.7509	0.7239	9
51	0.5533	0.7509	0.6521	45
52	0.5349	0.7335	0.6342	64
53	0.5533	0.7691	0.6612	38
54	0.8010	0.6933	0.7472	7
55	0.5833	0.6642	0.6238	72
56	0.8214	0.5955	0.7085	14
57	0.5941	0.6933	0.6437	51
58	0.4864	0.7883	0.6373	61
59	0.4522	0.8406	0.6464	50
60	0.5833	0.7421	0.6627	37
61	0.4399	1.0000	0.7199	10
62	0.5629	0.7509	0.6569	43
63	0.5941	0.8636	0.7288	8
64	0.4792	0.7691	0.6242	70
65	0.8010	0.6188	0.7099	13
66	0.5349	0.8189	0.6769	24
67	0.5833	0.7883	0.6858	19
68	0.4015	0.8406	0.6211	74
69	0.6545	0.6858	0.6701	26
70	0.6053	0.7335	0.6694	28
71	0.4653	0.7883	0.6268	68
72	0.6053	0.7251	0.6652	34
73	0.5261	0.8406	0.6834	22
74	0.6545	0.7335	0.6940	16
75	0.4171	0.8878	0.6524	44
76	0.5095	0.7883	0.6489	48
77	0.4864	0.7599	0.6232	73
78	0.5533	0.7169	0.6351	63
79	0.6169	0.6311	0.6240	71
80	0.8429	0.6785	0.7607	3
81	0.4587	0.8755	0.6671	31

Table 4. Response table for the Grey relational grade

Parameters	Symbols	Level 1	Level 2	Level 3
Pulse current (Ip)	A	0.6605	0.6618	0.6626
Pulse-on-time (Ton)	B	0.6458	0.6661	0.6730
Pulse-off-time (Toff)	C	0.6789	0.6377	0.6436
Tool rotation (rpm)	D	0.6335	0.6610	0.6845

Average grey relational grade: 0.6616

5. RUNNING CONFIRMATION EXPERIMENT

The estimated grey relational grade ά using the optimal level of the machining parameters can be calculated as:

$$ά = \alpha_m + \sum_{i=1}^{q}(\bar{\alpha}_i - \alpha_m) \qquad (5)$$

whereα_m is the total mean of the grey relational grade, $\bar{\alpha}_i$is the mean of the grey relational grade at the optimal level and qis the number of the machining parameters that significantly affects the multiple response characteristics.

Based on equation (5), the estimated grey relational grade using the optimal machining parameters can be found out even if the setting not available in experimental design.

Table 5: Results of response performances indicating the initial and optimal settings

	Initial parameters	Optimal parameters
Setting level	$A_3B_3C_1D_2$	$A_3B_3C_1D_3$
MRR (mg/min)	6.8	6.1
TWR (mg/min)	4.7	4.8
GRG	0.8006	0.8133

6. CONCLUSIONS

A grey relational grade obtained from the grey relational analysis was used to optimize the process parameters of electrical discharge drilling process for carbon carbon composites with multi performance characteristics. The application of this technique converts the multi response variable to a single response grey relational grade and, therefore, optimization of complicated multiple performance characteristics can be greatly simplified. The experimental result for the optimal setting shows that there is considerable improvement in the process.

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