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Optimization by Grey Relational Analysis of EDM Parameters in Machining Al-15% SiC MMC Using Multihole Electrode

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Abstract: In this study the optimization of the Electrical Discharge Machining (EDM) process with multiple performance characteristics based on orthogonal array with the Grey relational analysis was studied. The Grey relational analysis theory was used to resolve the complicated interrelationships among the multiple performance characteristics. In the present study, attempt was made to find the optimal machining conditions under which a blind-hole can be drilled using a multihole electrode. The Taguchi method was used to determine the relations between machining parameters and process characteristics. In this study, the machining parameters, namely electrode polarity, discharge current, pulse on time, pulse off time and dielectric pressure were optimized with considerations of multiple performance characteristics including machining time, electrode wear and surface roughness. Experimental results showed that machining performance in the EDM process can be improved effectively through this approach.

Key words: Al-SiC, EDM, multihole electrode, grey relational analysis, optimization

INTRODUCTION

Aluminum metal matrix composites have gained significance in various engineering industries due to their high specific strength, stiffness and fatigue resistance, low density and thermal expansion coefficient. The need for these materials in automotive, defense and aerospace industries is high.

Machining of aluminum metal matrix composites by conventional processes generally resulted in excessive tool wear caused by the hard reinforcement, high cost of machining, unacceptable short tool life and the subsurface damage (Manna and Bhattacharya, 2005; Ozben *et al*., 2008; Muthukrishnan *et al*., 2008; Davim, 2003). Hence, non-conventional machining of composites started gaining importance, especially electrical discharge machining.

Machining aluminum metal matrix using EDM is one of the most extensively used non-conventional material removal processes. Its uniqueness, that is, the use of thermal energy to machine electrically conductive parts regardless of hardness has been its distinctive advantage. Another characteristic of EDM is the lack of direct contact between the electrode and the work piece, thus eliminating mechanical stress, chatter and vibration during machining (Ho and Newman, 2003).

Hocheng *et al*. (1997) conducted a preliminary study of material removal in EDM of SiC/Al. They investigated the material removal characteristics in single and continuous discharge. A correlation between the major machining parameters, electrical current and on time and the crater size produced by a singles spark plug was presented. For effective EDM, large electrical current and short on time were recommended. They also concluded that single pulse is better because in the continuous pulse, the discharge of SiC/Al is more irregular and the material removal rate is faster only at the beginning followed by being retarded due to existence of SiC particles in the gap.

Hung *et al*. (1994) investigated the feasibility of applying electrical discharge machining process for cast aluminium MMCs reinforced with silicon carbide particles. Feasibility of using the non-conventional EDM process for MMCs was confirmed and models based on two-level factorial experiments were developed. They concluded that the power level greatly affected the Material Removal Rate (MRR) and the recast layer. The current alone controlled the surface finish.

Wang and Yan (2000) optimized the blind hole drilling of AlO_3/6061 Al composite using rotary electro-discharge machining by using Taguchi methodology.

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Experimental results confirmed that the copper electrode with an eccentric through hole had the optimum performance. The polarity of the electrode largely affected either MRR or SR whilst the peak current mainly affected EWR. The increase of either the rotational speed of the electrode or the injection flushing pressure of the dielectric fluid, or the presence of two eccentric through holes in the electrode might result in higher MRR. They proposed semi-empirical expressions to simplify the evaluation of the MRR, EWR and SR with several parameters under various machining conditions.

Mohan *et al*. (2004) carried out investigation on electric discharge machining of Al-SiC MMCs using rotary tube electrode. Various input variables were used to assess the machinability. Peak currents were confirmed to have positive effects on the MRR, EWR and SR. The MRR, EWR and SR were more with positive polarity of the electrode than at negative. The electrode hole diameter and rotational speed had major effect on MRR, EWR and SR. Genetic algorithm was used to find optimum machining parameters.

Ghoreishi and Atkinson (2002) made a comparative experimental study of machining characteristics in vibratory, rotary and vibro-rotary electro-discharge machining. The effects high and low-frequency forced axial vibrations of the electrode, rotation of the electrode, and combinations of these methods in respect of MRR, tool wear rate and surface roughness in die sinking EDM with a flat electrode were compared. The combination of ultrasonic vibration and rotation of electrode leads to increases in MRR, TWR and SR. Thus, for optimum parameter settings, a compromise should be made between SR and MRR or TWR. This case was modeled by stepwise linear regression, significant parameters were found by ANOVA and optimum machining parameter settings were obtained using overlay contour plots.

Koshy *et al*. (1993) suggested when the provision of holes in the electrode is impracticable, flushing of the working gap poses a major problem. Use of a rotating disk electrode was proposed as a more productive and accurate technique than use of a conventional electrode. Material removal rate, tool wear rate, relative electrode wear, corner reproduction accuracy and surface finish aspects of a rotary electrode were compared with those of a stationary one. The effective flushing of the working gap brought about by the rotation of the electrode remarkably improved material removal rate and machines surfaces with a better finish.

The Grey relational analysis proposed by Deng (1989) has been proved to effectively resolve the complicated interrelationships among multiple performance characteristics of the EDM process (Lin and Lin, 2002; Singh *et al*., 2004; Jung and Kwon, 2010). Lin and Lin (2002) proposed a new approach for the optimization of the electrical discharge machining process with multiple performance characteristics based on the orthogonal array with the Grey relational analysis. Optimal machining parameters were determined by the grey relational grade as the performance index. The machining parameters, namely work piece polarity, pulse on time, duty factor, open discharge voltage, discharge current and dielectric fluid are optimized with considerations of multiple performance characteristics including material removal rate, surface roughness and electrode wear ratio. Experimental results have shown that machining performance in the EDM process can be improved effectively through this approach.

Singh *et al*. (2004) used Grey relational analysis for optimization of EDM parameters on machining Al-10% SiC_P composites. Orthogonal array was employed with Grey relational analysis to optimize the multi response characteristics. The experimental result for the optimal setting shows that there is considerable improvement in the process. The application of this technique converts the multi response variable to single response Grey relational grade and therefore, simplifies the optimization procedure.

Jung and Kwon (2010) used Grey relational analysis for optimization of EDM parameters in machining micro-hole to a minimum diameter and maximum aspect ratio. They obtained optimum conditions of the machining parameters to machine a micro-hole of 40 μm average diameter and an aspect ratio of 10 by using the Grey relational analysis.

The goal of the present study was to determine the optimal machining parameters for the formation of a blind hole of 12 mm diameter and 5 mm depth under the given machining conditions. The Taguchi method was employed to elucidate the effect of the machining parameters on the characteristics of the EDM process. Additionally, Grey relational analysis was used to find the optimal machining parameters satisfying the multiple characteristics of the EDM process.

MATERIALS AND METHODS

EDM machine: The machine used for this work was SPARKONIX die-sinking EDM. Feed in the vertical direction was controlled by a servo drive. The dielectric fluid used was kerosene and the electrode suction flushing method was used. Removal of debris generated

Table 1: Electrical discharge machining conditions

Conditions	Description
Polarity of electrode	Positive and negative
Discharge current	4-12 A
Pulse on time	200-600 μsec
Pulse off time	20-60 μsec
Polarity of electrode	Positive and negative
Pressure of dielectric fluid	0.25-0.75 kgf cm^{-2}
Method of flushing	Suction

Table 2: Work material specifications

Workpiece material	6061 Al-MMC
Al (%)	92.7
Si (%)	7.0
Mg (%)	0.3
Reinforcement	15% SiC particles (by volume)
Particle size (μm)	22

Table 3: Machining parameters and their levels

Machining parameter	Symbol	Level 1	Level 2	Level 3
Polarity	A	+	-	
Discharge current	B	4	8	12
Pulse on time	C	200	400	600
Pulse off time	D	20	40	60
Dielectric pressure	E	0.25	0.5	0.75

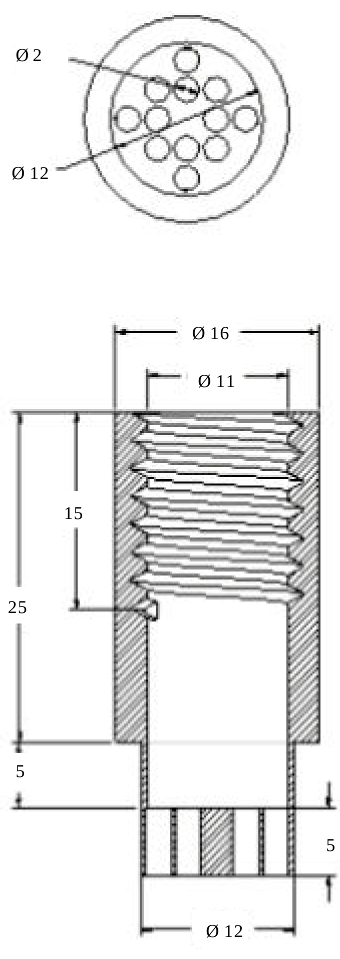

Fig. 1: Multihole electrode

during the machining process being indispensable to maintain smooth processing during electrical discharge machining, a multihole electrode was selected over electrode rotation and ultrasonic vibration techniques. The electrical discharge machining conditions are given in Table 1.

Materials: The work piece was 6061 Aluminium alloy reinforced with 15% of SiC particles (by volume). The work piece was a disc of diameter 70 and 12 mm thick. The specifications of the work piece are given in Table 2.

The electrode used was electrolytic copper rod with an array of 2 mm holes drilled in it was used as multihole electrode as shown in Fig. 1.

Experiments and results

Experimental condition The purpose of experiments was to form a blind hole of 12 mm diameter and 5 mm depth. From the results of preliminary experiments a multihole electrode with an array of 12 holes, each of diameter 2 mm was selected. To determine the machining conditions suitable for a hole of 12 mm diameter and 5 mm depth, the Taguchi method was used. The selected machining parameters, listed in Table 3, were polarity, discharge current, pulse on time, pulse off time and pressure of the dielectric fluid. An L_{18} ($2^1 \times 3^7$) orthogonal array was selected to determine the 18 trial conditions and their results are shown in Table 4.

The total time of machining can be given as:

$$\text{Total machining time} = T_1 + T_2 + T_3 \quad (1)$$

Where:

T_1 = Time for machining with multihole electrode
T_2 = Time for breaking the fins
T_3 = Time for finishing with solid electrode

Results of experiment: The experimental results are illustrated in Fig. 2 and the quantitative results for machining time, electrode wear and surface roughness are shown in Table 5.

Analysis of result according to the polarity: The machining time decreased from 26.76 min to 20.16 min for the sacrifice of electrode wear rate, which increased from 14.13 to 22.21 mg min^{-1} when the polarity of the tool changes from positive to negative. The reason may be that the transfer of energy during the charging process was more when the tool was kept at negative polarity than at the positive. The surface roughness decreased from 7.04 to 6.30 μm.

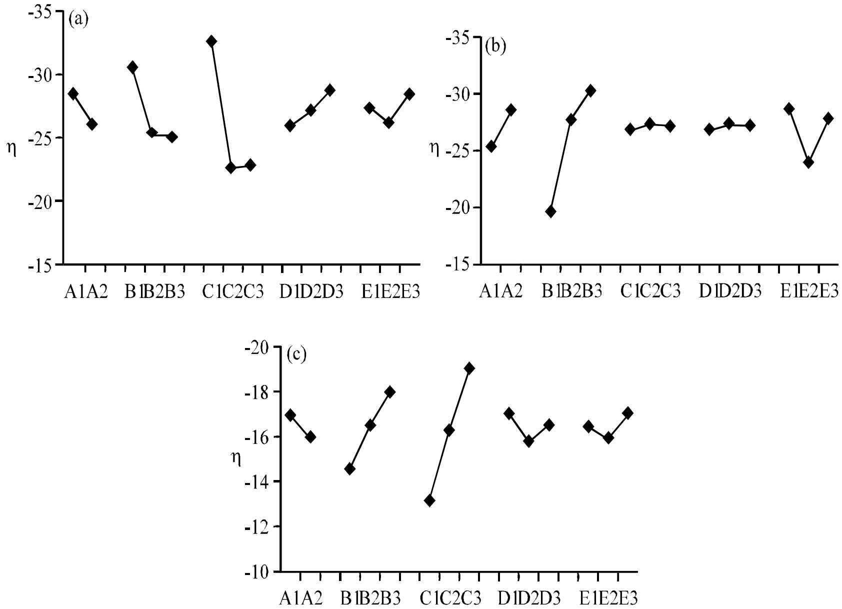

Fig. 2(a-c): Plots of factor effects (a) x = Machining time, (b) x = Electrode wear rate and (c) x = Surface roughness s/n ratio $\eta = -10\log_{10} x^2$

Table 4: Experimenter's log and experiment results

Trial No.	Polarity	Current (A)	Pulse on time (μsec)	Pulse off time (μsec)	Pressure (kg cm^{-2})	Machining time (min)	EWR (mg min^{-1})	SR (μm)
1	+	4	200	20	0.25	49.65	8.65	3.00
2	+	4	400	40	0.50	25.27	4.71	5.95
3	+	4	600	60	0.75	35.66	2.20	8.50
4	+	8	200	20	0.50	36.05	14.97	5.81
5	+	8	400	40	0.75	13.26	6.18	5.76
6	+	8	600	60	0.25	12.84	23.75	8.90
7	+	12	200	40	0.25	47.69	19.26	5.76
8	+	12	400	60	0.50	12.52	15.98	7.24
9	+	12	600	20	0.75	7.88	31.44	12.48
10	-	4	200	60	0.75	65.23	4.03	3.94
11	-	4	400	20	0.25	13.11	12.81	5.19
12	-	4	600	40	0.50	14.84	4.72	5.66
13	-	8	200	40	0.75	30.65	32.30	4.22
14	-	8	400	60	0.25	11.15	38.39	7.14
15	-	8	600	20	0.50	7.04	2.98	8.41
16	-	12	200	60	0.50	27.79	25.71	4.62
17	-	12	400	20	0.75	6.10	33.92	7.80
18	-	12	600	40	0.25	5.523	45.00	9.74

Table 5: Experimental results by Taguchi method

		Machining time (min)	EWR (mg min^{-1})	SR (μm)
Polarity	+	26.76	14.13	7.04
	-	20.16	22.21	6.30
	4	33.96	6.19	5.37
Discharge current	8	18.50	19.76	6.70
	12	17.92	28.55	7.94
	200	42.84	17.49	4.56
Pulse on time	400	13.57	18.66	6.51
	600	13.96	18.35	8.95
	20	19.88	17.46	7.12
Pulse off time	40	22.87	18.70	6.18
	60	27.53	18.34	6.72
	0.25	23.33	22.80	6.62
Pressure	0.5	20.59	11.51	6.28
	0.75	26.46	20.19	7.11

Analysis of result according to the discharge current: As the discharge current increased from 4 to 12 amps, the machining time considerably decreased from 33.96 to 17.92 min. The electrode wear rate and surface roughness increased from 6.19 to 28.55 mg min^{-1} and 5.37 μm to 7.94 μm, respectively. Those phenomena could be attributed to the increased input current lead to increased discharge energy. The increased discharge energy resulted in a larger sparks, which removed the debris generated quite effectively. In addition to that, debris removal at the machining gap is enhanced by forcing the dielectric fluid through the holes provided in the multihole electrode. The higher discharge energy resulted in accelerated tool wear and increased surface roughness.

Analysis of result according to the pulse on time: The machining parameters most influenced by the variation of pulse on time were the machining time and surface roughness. As the pulse on time increased from 200-600 μsec, the machining time decreased from 42.84 to 13.86 min. With increase in pulse on time, energy density on the work piece increased leading to reduced machining time. The improved flushing conditions by using the multihole electrode also lead to reduced machining time. The surface roughness increased from 4.56 to 8.95 μm. This was because of formation of larger crater on the surface of the work piece. The electrode wear rate slightly increased from 17.49 to 18.35 mg min^{-1}.

Analysis of result according to the pulse off time: The pulse off time variation slightly influenced the machining time and surface roughness. When the pulse off time varied from 20-60 μsec, the machining time increased from 19.88 to 27.53 min and surface roughness decreased from 7.12-6.72 μm. Increased pulse off time meant that the interval between discharges was long enough to recharge the circuit. As a result, the increment in pulse off time increased the machining time. The effective flushing with the multihole electrode reduced debris adherence with the work piece. This reduction in debris adherence improved the surface finish. The electrode wear rate marginally increased from 17.46 to 18.34 mg min^{-1}.

Analysis of result according to the dielectric pressure: As the dielectric pressure increased from 0.25 to 0.75 kg cm^{-2}, the machining time increased from 23.33 to 26.46 min. There was decrease in electrode wear rate from 22.80 to 20.19 mg min^{-1}. Those phenomena could be due to the cooling effect produced by the dielectric fluid during flushing Yilmaz and Okka (2010). Too much of cleaning of the gap often reduced discharge frequency because of the fast recovery of insulation resulted in increased machining time and decreased electrode wear rate. The surface roughness increased from 6.62 to 7.11 μm. The increased debris adherence due to cooling effect resulted in increased surface roughness.

Determination of machining condition

Grey relational analysis: The original reference sequence and the sequence for comparison can be represented as X_0 (k) and X_i (k), I = 1, 2, …, m; k = 1, 2, …, n, respectively. Here, m is the total number of experiments, while n is the total number of observation data. If the target value of the original sequence is 'the-larger-the-better', then the original sequence is normalized according to:

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

If it is the-smaller-the-better, then the original sequence is normalized as:

$$X_i^0(k) = \frac{\max X_i^0(k) - X_i^0(k)}{\max X_i^0(k) - \min X_i^0(k)} \tag{3}$$

In the case where there is a specific value, the original is normalized as:

$$X_i^0(k) = 1 - \frac{\left|X_i^0(k) - OB\right|}{\max\{X_i^0(k) - OBOB - x_i^0(k)\}} \tag{4}$$

Here, OB is the target value.

Grey relational coefficient and grey relational grades: The grey relational co-efficient is defined as follows:

$$\gamma(X_0^*(k), X_i^*(k) = \frac{\Delta_{min} + \xi\Delta_{max}}{\Delta_{oi(k)} + \xi\Delta_{max}} \tag{5}$$

$$0 < \gamma(X_0^*(K), X_i^*(K) \le 1$$

$\Delta_{oi}(k)$ is the deviation sequence of the reference sequence X_0* and the comparability sequence X_i*, that is:

$$\Delta_{oi(k)} = |X_o^*(k) - X_i^*(k)|$$

$$\Delta_{max} = \max_{\forall j \in i}\max_{\forall k}|X_o^*(k) - X_j^*(k)| \tag{6}$$

$$\Delta_{min} = \min_{\forall j \in i}\min_{\forall k}|X_o^*(k) - X_j^*(k)|$$

where, ξ is the distinguishing coefficient, ζ∈ [0,1].

A Grey relational grade is a weighted some of the Grey coefficient and is defined as:

$$\gamma(X_o^*, X_i^*) = \sum_{k=1}^{n}\beta_k\gamma(X_o^*(k), (X_i^*(k) \tag{7}$$

$$\sum_{k=1}^{n}\beta_k = 1$$

Here the Grey relational grade γ (X_0*, X_i^*) represents the level of correlation between the reference and the comparability sequence. If a particular comparability sequence is more important to the reference sequence than the other comparability sequence, the Grey relational grade for that comparability sequence and the reference sequence will exceed that for the other Grey relational grades.

Evaluated Grey relational coefficient and grades: The experimental results for the machining time, electrode wear rate and surface roughness are listed in Table 5. Since smaller values for those parameters were desirable, the data sequence had the-smaller-the-better characteristic. Hence, Eq. (3) is employed for the data processing, the results of which are listed in Table 6. Eq. 5 was utilized to determine the Grey relational coefficient and Eq. (7) was used to find the Grey relational grade. The results are tabulated in Table 7. In this case, the reference sequences were set to 1, that is, $X_i^*(k) = 1$ and the distinguishing coefficient ζ was set to 0.5.

Table 6: Experimental results after normalization process

Machining time	Electrode wear rate	Surface roughness
0.2609	0.8493	1.0000
0.6693	0.9413	0.6888
0.4953	1.0000	0.4204
0.4887	0.7016	0.7036
0.8704	0.9069	0.7094
0.8775	0.4964	0.3782
0.2938	0.6013	0.7094
0.8828	0.6781	0.5527
0.9605	0.3169	0.0000
0.0000	0.9572	0.9008
0.8729	0.7520	0.7690
0.8440	0.9412	0.7194
0.5792	0.2967	0.8718
0.9058	0.1545	0.5633
0.9746	0.9817	0.4293
0.6271	0.4507	0.8296
0.9903	0.2589	0.4937
1.0000	0.0000	0.2890

Table 7: Calculated grey relational co-efficient and grade

Grey relational co-efficient			
Machining time	Electrode wear rate	Surface roughness	Grey relational grade
0.4035	0.7685	1.0000	0.7240
0.6019	0.8950	0.6164	0.7044
0.4976	1.0000	0.4631	0.6536
0.4944	0.6262	0.6278	0.5828
0.7942	0.8430	0.6324	0.7565
0.8032	0.4982	0.4457	0.5823
0.4145	0.5564	0.6324	0.5344
0.8101	0.6083	0.5278	0.6488
0.9268	0.4226	0.3333	0.5609
0.3333	0.9211	0.8345	0.6963
0.7974	0.6684	0.6840	0.7166
0.7621	0.8947	0.6405	0.7658
0.5430	0.4155	0.7960	0.5848
0.8414	0.3716	0.5338	0.5823
0.9082	0.7588	0.7270	0.7980
0.5728	0.4765	0.7459	0.5984
0.9810	0.4029	0.4969	0.6269
1.0000	0.3333	0.4129	0.5821

ANOVA results of grey relational grades: Table 8 lists the results of the analysis of variance (ANOVA) for the machining time, electrode wear rate and surface roughness using the calculated values for the Grey relational coefficients and Grey relational grades of Table 7. The Table 8 figures show that the contribution of discharge current was the most significant, with 63.72% contribution. The significant factors were the dielectric pressure with 10.85% and pulse on time with 10.03% contribution. These three parameters controlled the machining time, electrode wear rate and surface roughness simultaneously and effectively.

Based on the above discussion, the optimal machining parameters are the electrode polarity at level 2, discharge current at level 1, pulse on time at level 2, pulse off time at level 1 and dielectric pressure at level 2.

Confirmation tests: Once the optimal level of the machining parameters was selected, the final step was to predict and verify the improvement of the performance characteristics using the optimal level of machining parameters. The estimated grey relational grade $\hat{\gamma}$ using the optimal level of the machining parameters can be calculated as:

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{q} (\bar{\gamma}_i - \gamma_m) \tag{8}$$

where, γ_m is the total mean of the grey relational grade, $\bar{\gamma}_i$ is the mean of the grey relational grade at the optimal level and q is the number of machining parameters that significantly affects the multiple performance characteristics.

Table 8: Results of analysis of variance (ANOVA)

Factor	Level 1	Level 2	Level 3	Sum of squares	df	Variance	F	Contribution (%)
Polarity (A)	0.6386	0.6608		0.0022	1	0.0022	1.93	2.06
Discharge current (B)	0.7135	0.6472	0.5919	0.0686	2	0.0343	29.87	63.72
Pulse on time (C)	0.6201	0.6726	0.6565	0.0108	2	0.0054	4.70	10.03
Pulse off time (D)	0.6676	0.6547	0.6269	0.0052	2	0.0026	2.26	4.81
Pressure (E)	0.6203	0.6824	0.6465	0.0117	2	0.0058	5.09	10.85
Error				0.0092	8	0.0011		8.53
Total				0.1077	17			100

Table 9: Results of machining performance using initial and optimal machining parameters

	Initial machining parameters	Optimal machining parameters: Prediction	Optimal machining parameters: Experiment
Setting level	$A_1B_2C_3D_3E_1$	$A_2B_1C_2D_1E_2$	$A_2B_1C_2D_1E_2$
Machining time (min)	12.84	-	8.64
Electrode wear rate (mg min^{-1})	23.80	-	9.00
Surface finish (μm)	8.895	-	4.780
Grey relational grade	0.5823	0.7980	0.7971
Improvement of the Grey relational grade = 0.2148			

Based on Eq. 8, the estimated grey relational grade using the optimal machining parameters can then be obtained. Table 9 shows the results of the conformational experiment using the optimal machining parameters. As shown in the Table 9, machining time was decreased from 12.84 to 8.64 min, electrode wear rate was improved from 23.8 to 9 mg min^{-1} and surface roughness was improved from 8.895 to 4.780 μm. It was clearly shown that the multiple performance characteristics in the EDM process were greatly improved through this study.

CONCLUSIONS

In this study attempt was made to find the optimal machining conditions for drilling of a blind hole of 12 mm diameter and 5 mm depth. The Taguchi method was employed to determine the relations between the machining parameters and the process characteristics. The machining parameters affecting the blind hole drilling were revealed by executing 18 experiments. To determine the machining parameters affecting the machining time, the electrode wear rate and surface roughness.

Grey relational analysis was used. The discharge current was found to be the most significant controlling parameter. The dielectric pressure and pulse on time were the significant factors affecting the process characteristics.

The obtained optimal machining conditions were electrode polarity negative, discharge current 4 amps, pulse on time 400 μsec, pulse off time 10 μsec and dielectric pressure 0.5 kg cm^{-2}. Under these conditions machining time was 8.64 min, electrode wear rate was 9 mg min^{-1} and surface roughness was 4.78 μm.

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