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Optimization of machining parameters for EDM honeycomb ring using gray relation analysis

Gao Ji, Sun Yao*, Wang Di
School of Mechatronics Engineering, Shenyang Aerospace University, Shenyang, Liaoning 110136, (CHINA)
E-mail : sy547515291@163.com

ABSTRACT

Aiming at the complexity and unpredictability of EDM(electrical discharge machining) honeycomb ring, the Taguchi method with gray relation analysis was proposed to determine the EDM parameters with consideration of multiple performance characteristics.The main machining parameters pulse-on time(t_{on}), pulse-off time(t_{off}), peak current(I) and peak voltage(U) were selected to explore the effects of multiple performance characteristics on SR(surface roughness) and EWR(electrode wear rate).A series of experiments were conducted according to an orthogonal array L_{18} based on Taguchi method. The significant process parameters that affected MRR and SR were determined by the analysis of variance.The obtained optimal machining conditions were pulse-on time of 5μs, peak current of 10A, peak voltage of 1V, pulse-off time of 75.Under these conditions, the SR of 0.826and MRR of 1.913could be obtained.An additional experiment was conducted to verify the obtained optimal machining conditions.

KEYWORDS

EDM;
Honeycomb ring;
Taguchi method;
Gray relation analysis;
Optimization.

INTRODUCTION

Honeycomb seal can improve efficiency and stability of airplane and reduce energy consumption because of its good seal properties and rotor dynamic characteristics. Therefore, honeycomb rings have been widely used in various jet or vortex engines at home and abroad, such as U-2 plane, F16 fighter jets as well as a number of civil aircraft engine, since the 1980s[1, 2].Engine performance and service life are affected by honeycomb ring quality.Because of the special structure and materials of honeycomb ring, traditional mechanical processing method is difficult to achieve.

EDM has gained importance due to its capability to remove material with good accuracy and precision and lack of direct contact between the tool electrode and the workpiece[3].EDM accomplishes shapes that could hardly been achieved with any other conventional method, regardless the hardness of material and the complex of the part to be machined. Therefore, EDM was suitable for machining honeycomb with special shape and material. But the physical mechanism of EDM is complex and volatile, randomness and uncertainty.

Taguchi method is an efficient tool for the design of a high-quality manufacturing system based on orthogonal array experiments, which provides much-reduced variance for the experiment with optimum setting of process control parameters[4].The gray theory, first initiated by Dr.Deng in 1982, can provide a solution to a system in which the model is unsure or the information is incomplete[5].It avoids the inherent shortcomings of conventional statistical methods and requires limited data to estimate the behavior of an uncertain system.It also provides an efficient solution to the uncertain, multi-input and discrete data problem.The gray relation analysis based on this theory is applied in different manufacturing processes to effectively solve the complicated interrelationships among multiple performance characteristics and to determine the optimal parameter setting[6-10].

In this present paper, four independently controllable parameters pulse-on time(t_{on}), pulse-off time(t_{off}), peak current(I) and peak voltage(U) were varied to determine their effects on MRR and SR.An L_{25} orthogonal array based on the Taguchi method was utilized to plan the experiments.The data of experiments were transferred into gray relational grade and were assessed by analysis of variance (ANOVA) to determine the significant machining parameters and obtain the optimal levels of machining parameters for multiple performance characteristics.

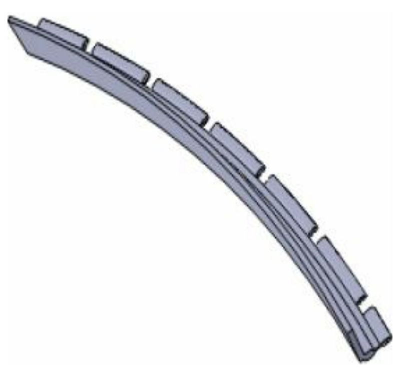


Figure 1 : 1/4 honeycomb ring

EXPERIMENTATION

The workpiece honeycomb ring

Honeycomb ring is typical thin-walled part with thickness of 0.03mm, shown in Figure 1.Meanwhile, the surface quality requirement of its structure is very strict, the processing requirements of the remelted layer thickness is less than 0.035mm, the runout on component benchmark is less than 0.05mm, $R_a \le 0.8mm \sim 1.6mm$, the requirements on the surface is no crack, no residual burr and no heat affected zone[11, 12].

Honeycomb ring is made of nickle-based superalloys (GH3536) characterized by excellent resistance to oxidation, corrosiveness resistance, high thermal stability and fatigue, however, it is regarded as one of the most difficult-to-machine materials because of hard particle, work hardening and low thermal conductivity, the properties of GH3536 were shown in TABLE 1[13].

Experimental conditions and procedures

EDM is a process whereby unnecessary material is removed by the action of electrical discharges between the workpiece and the tool electrode. In this study, a series of experiments were performed on a CNC electrical discharge grinding machine "ZT-034 ", detailed processing parameters are shown in TABLE 2.

The concept of EDM honeycomb ring was illustrated in Figure 1.In the process of EDM, the honeycomb ring was fixed on the rotating table, and tool electrode was moved to machine the inner cambered surface.A relatively stable discharge gap (0.01~0.07mm

TABLE 1 : physical and mechanical properties of GH3536

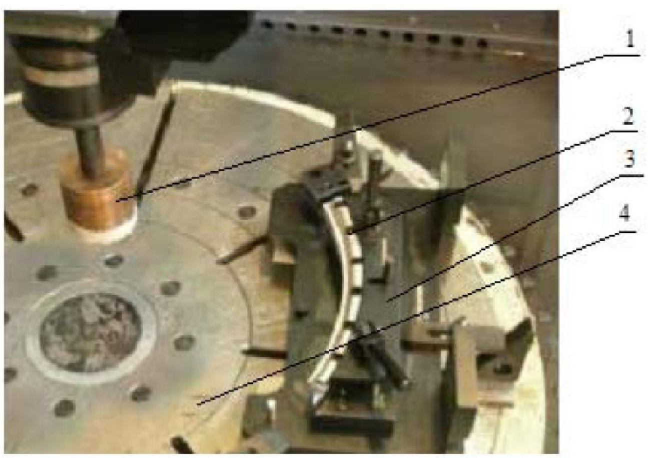
Physical property	Density g/cm^3	Melting point ℃	Thermal conductivity λ/(W/m℃)	Specific heat capacity J/kg℃	Modulus of elasticity GPa	Resistivity $\mu\Omega m$	Coefficient of linear expansion $a/10^{6} \cdot C^{-1}$
	8.28	1259~1381	13.38 (100℃)	372.6	199	1.18	12.1 (20~100℃)
Mechanical property	Heat treatment	σ_b MPa	σ_s MPa	δ %	HBS	Working temperature °C	
	Solution treatment	580~690	275~286	30	≥241	800~1200	

TABLE 2 : The detailed parameters of ZT-034

Process stage	Equipment model	Pulse-on time	Pulse-off time	Envelope width	Envelope interval	Low voltage current	High voltage current	Servo given
Finishing machining	ZT-034	50	100	1000	1000	8	1	70%
Unit		μs	μs	μs	μs	A	A	

Name	Machine input power	Max work current	Input power	Surface roughness	Electrode loss
Value	100	480	380	1.25	≤6%
Unit	KVA	A	VAC	μ m	

)was maintained between tool electrode and workpiece rotating in opposite direction to complete radial compensation processing. Clavate tool electrode was designed to not only facilitate chip removal and deionization but also enhance the machining precision of honeycomb ring[14].Copper with good electrical conductivity and low price was chosen as tool electrode material.The working liquid feed system was employed to ensure that the workpiece and tool electrode was completely immersed with kerosene of low viscosity and good deionization property.Positive polarity machining was applied to obtain high processing quality[15].



1—tool electrode 2—honeycomb 3— fixture 4— rotating table

Figure 2 : The concept of EDM honeycomb ring

The following independently controllable process parameters are identified to carry out the experiments: pulse-on time(t_{on}), pulse-off time(t_{off}), peak current(I) and peak voltage(U).Preferred levels, units and symbols are given in TABLE 3.

The methodology of Taguchi for four factors at five levels was used for the implementation of the plan of orthogonal array experiments.An L_{25} orthogonal array with 4 columns and 25 rows is employed in this work, shown in TABLE 4.And experiments were carried out according to the arrangement of the orthogonal array.

The evaluation and measurement of MRR and SR

MRR was calculated by using the volume loss from the work piece divided by the time of machining.The calculated weight loss is converted to volumetric loss in cubic millimeter per minute as Eq(1).

$$\mathbf{MRR} = \frac{\Delta \mathbf{V_w}}{\mathbf{T}} = \frac{\Delta \mathbf{W_w}}{\rho_w \mathbf{T}} \quad (1)$$

where ΔV_w is the volume loss from the work piece, ΔW_w is the weight loss from the work piece, T is the

TABLE 3 : Process parameters and their levels

Parameters	Level					
	unit	1	2	3	4	5
t_{on}:pulse-on time	μs	5	10	15	20	25
I:peak current	A	2	6	10	14	18
U:peak voltage	v	1	5	9	13	17
t_{off}:pulse-off time	μs	25	50	75	100	125

TABLE 4 : Experimental layout using L_{25} orthogonal array

Experiment no.	Process parameters				Multiple performance characteristics	
	t_{on} (μs)	I (A)	U (V)	t_{off} (μs)	SR (μm)	MRR ($mm^3/\min$)
1	1	1	1	1	0.872	0.960
2	1	2	2	2	0.952	1.326
3	1	3	3	3	1.142	1.400
4	1	4	4	4	1.057	1.560
5	1	5	5	5	1.284	1.454
6	2	1	2	3	1.655	0.902
7	2	2	3	4	1.591	1.428
8	2	3	4	5	1.126	1.372
9	2	4	5	1	1.265	1.474
10	2	5	1	2	1.533	1.302
11	3	1	3	5	1.479	1.112
12	3	2	4	1	1.472	1.316
13	3	3	5	2	1.385	1.874
14	3	4	1	3	1.463	1.798
15	3	5	2	4	1.612	1.466
16	4	1	4	2	1.971	1.682
17	4	2	5	3	2.029	2.440
18	4	3	1	4	2.227	2.568
19	4	4	2	5	1.701	2.364
20	4	5	3	1	1.867	1.854
21	5	1	5	4	1.945	1.602
22	5	2	1	5	1.839	1.944
23	5	3	2	1	2.101	2.232
24	5	4	3	2	1.500	1.794
25	5	5	4	3	2.438	0.960

duration of the machining process, and $\rho_w = 8.28\ g/cm^3$ is the density of the work piece.

SR was measured at three different positions and average SR(Ra) value was taken using a surf test measuring instrument (TR200).

GRAY RELATIONAL ANALYSIS

Gray relational analysis is an improved method for identifying and prioritizing main system factors and is helpful for variable independence analysis. Therefore, the relationships between the machining performance characteristics and the machining parameters can be determined using gray relational analysis[16].

Gray relational generating

Gray relational analysis adopted discrete measurements to evaluate the distance between two sequences and then explored the extent of their relationships. If the sequence range is excessively large and the stand value is too enormous, it will induce the effect of some factors to be ignored[17]. Therefore, the raw experimental data are normalized at first. The normalized results x_{ij},

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for higher-the-better performance characteristic can be expressed as:

$$x_{ij} = \frac{y_{ij} - \min_j y_{ij}}{\max_j y_{ij} - \min_j y_{ij}} \quad (2)$$

For lower-the-better performance characteristic x_{ij} can be expressed as:

$$x_{ij} = \frac{\max_j y_{ij} - y_{ij}}{\max_j y_{ij} - \min_j y_{ij}} \quad (3)$$

Where y_{ij} is the *i*th performance characteristic in the *j*th experiment.

Gray relational coefficient

The gray relational coefficient is determined to express the relationship between ideal and actual normalized experimental data.Besides, the gray relational coefficient can be calculated as :

$$\xi_{ij} = \frac{\min_i \min_j \left|x_i^0 - x_{ij}\right| + \zeta \max_i \max_j \left|x_i^0 - x_{ij}\right|}{\left|x_i^0 - x_{ij}\right| + \zeta \max_i \max_j \left|x_i^0 - x_{ij}\right|} \quad (4)$$

where x_i^0 is the ideal normalized result for the *i*th performance characteristics, and ζ is a distinguishing coefficient, which is defined in the range of $0 \le \zeta \le 1$.Generally ζ can be adjusted to fit the practical requirements and it is normally set at 0.5[18].

Gray relational grade

The gray relation grade that is obtained by averaging the gray relational coefficients associated with each performance characteristic.It can be expressed as:

$$\gamma_j = \frac{1}{n}\sum_i^n w_i \xi_{ij} \quad (5)$$

where γ_j is the gray relational grade for the *jth* experiment, w_i is the weighting factor for the *i*th performance characteristic, and *n* is the number of performance characteristics.

The optimization of machining parameters associated with the complex multiple performance characteristics can be converted into the optimal resolution of single gray relational grade.And the optimal level of the process parameters is the level with the highest gray relational grade.

INFLUENCE OF PROCESS PARAMETERS ON MRR AND SR

The purpose of the ANOVA is to investigate which process parameters significantly affects the MRR and SR.This is completed by separating the total variability of the response, which is measured by the sum of squared deviations from the total mean of the response, into contributions by each EDM process parameter and the error.The results of ANOVA were furnished in TABLE 5 and 6.

According to TABLE 5, pulse-on time was the most dominant effect factor on MRR, and it was followed by peak current, peak voltage and pulse-off time.The MRR mainly depends on the energy, a higher pulse-on time generates high thermal energy, which produces a large MRR.The peak current and peak voltage have positive effect on MRR, and the MRR increase with them.Pulse-off time is inversely proportional to MRR, with the in-

TABLE 5 : Results of the ANOVA for MRR

Source	Degrees of freedom	Sum of squares	Mean squares	F value	Prob>F	Contribution(%)
t_{on}	4	3.07080	0.76770	14.7247	0.001	59.57
I	4	1.62420	0.40604	7.7879	0.007	31.51
U	4	0.24397	0.06099	1.1699	0.392	4.73
t_{off}	4	0.21597	0.05399	1.0356	0.446	4.19
Error	8	0.41710	0.05214			
Total	24	5.57200				

TABLE 6 : Results of the ANOVA for SR

Source	Degrees of freedom	Sum of squares	Mean squares	F value	Prob>F	Contribution(%)
t_{on}	4	2.95690	0.73923	19.3206	0.003	81.80
I	4	0.30766	0.07691	2.0102	0.186	8.51
U	4	0.02916	0.00729	0.1905	0.937	0.81
t_{off}	4	0.32112	0.08028	2.0982	0.173	8.88
Error	8	0.30609	0.03826	19.3206		
Total	24	3.92090				

crease of pulse-off time, the number of discharge pluses per unit time decrease, as a result, MRR is low.

It could be found from TABLE 6 that pulse-on time had the most dominant effect on SR, and it was ranked by pulse-off time, peak current and peak voltage.SR increase as the pulse-on time.It is due to the fact that a higher pulse-on time make a single pulse discharge time and energy increase and enlarge discharge craters.A lower pulse-off time make a single pulse discharge cycle decrease and pulse discharge frequence increase, the refinement can obtain a lower SR.If the pulse-off time is lower than the critical value, deionization is not sufficient and the stability is reduced, so SR will increase. The increase of peak current and peak voltage cause a larger single pulse discharge energy and larger discharge craters, so SR increases as well.

DETERMINATION OF OPTIMAL PROCESS PARAMETERS ON MRR AND SR

The normalized results for MRR and SR were listed in TABLE 7, in this work, the MRR was desired to obtain a higher value, namely, higher-the-better feature and the SR exhibited the feature of lower-the-better.Consequently, the gray relational coefficients for each experiment can be calculated according to Eq(4).In calculating the gray relational grades, the weighting for both performance characteristics was set as 1:1, each characteristics had equal importance or relative weighting.After averaging the corresponding gray relational coefficients, the gray relational grades were obtained.

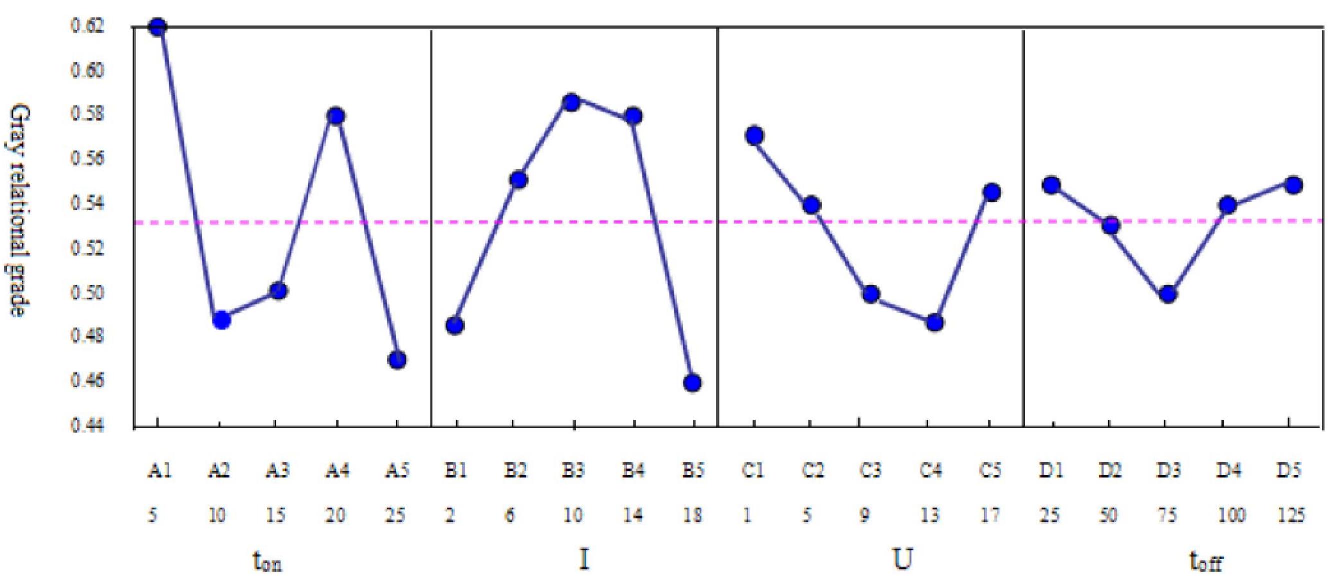

Figure 3 : Response graph of gray relational grade

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TABLE 7 : Gray relational generation of SR and MRR

Number	SR	MRR
	Ideal sequence	
	1	1
1	1.0000	0.0348
2	0.9489	0.2545
3	0.8276	0.2989
4	0.8819	0.3950
5	0.7369	0.3313
6	0.5000	0.0000
7	0.5409	0.3157
8	0.8378	0.2821
9	0.7490	0.3433
10	0.5779	0.2401
11	0.6124	0.1261
12	0.6169	0.2485
13	0.6724	0.5834
14	0.6226	0.5378
15	0.5275	0.3385
16	0.2982	0.4682
17	0.2612	0.9232
18	0.1347	1.0000
19	0.4706	0.8776
20	0.3646	0.5714
21	0.3148	0.4202
22	0.3825	0.6255
23	0.2152	0.7983
24	0.5990	0.5354
25	0.0000	0.0348

TABLE 8 presented the results of gray relational coefficients, grades and their ranks.The results indicated that experiment number 8 had the largest relational grade.It could be expected that the levels of each machining parameter were superior to obtain a better multiply performance characteristics.

TABLE 8 : Gray relational coefficients and grades

Number	Gray relational coefficient		Gray relational grade	
	SR	MRR	Value	Rank
1	1.0000	0.3413	0.6707	2
2	0.9073	0.4014	0.6544	3
3	0.7436	0.4163	0.5800	8
4	0.8089	0.4525	0.6307	6
5	0.6552	0.4278	0.5415	13
6	0.5000	0.3333	0.4167	24
7	0.5213	0.4222	0.4718	19
8	0.7551	0.4105	0.5828	7
9	0.6658	0.4323	0.5491	11
10	0.5422	0.3969	0.4696	20
11	0.5633	0.3639	0.4636	21
12	0.5662	0.3995	0.4829	17
13	0.6042	0.5455	0.5749	9
14	0.5699	0.5196	0.5448	12
15	0.5141	0.4305	0.4723	18
16	0.4160	0.4846	0.4503	22
17	0.4036	0.8669	0.6353	5
18	0.3662	1.0000	0.6831	1
19	0.4857	0.8033	0.6445	4
20	0.4404	0.5384	0.4894	16
21	0.4219	0.4630	0.4425	23
22	0.4474	0.5718	0.5096	15
23	0.3892	0.7126	0.5509	10
24	0.5549	0.5183	0.5366	14
25	0.3333	0.3413	0.3373	25

The response of the gray relational grades associated with the levels of each machining parameter and the effects of each each machining parameters was summarized in TABLE 9.The total mean value of the gray relational grade is found to be 0.5354.Pulse-on time has been found to have maximum effect on the response.In addition, the response graph of gray relational grades were shown in Figure 3.

From the analysis of results presented in TABLE 9

TABLE 9 : Response table for gray relational grades

Machining parameters	symbol	Gray relational grade						
		Level 1	Level 2	Level 3	Level 4	Level 5	Delta	Rank
t_{on} pulse-on time	A	0.6155	0.4980	0.5077	0.5805	0.4754	0.1401	1
I:peak current	B	0.4888	0.5508	0.5943	0.5811	0.4620	0.1323	2
U:peak voltage	C	0.5756	0.5478	0.5083	0.4968	0.5487	0.0788	3
t_{off} pulse-off time	D	0.5486	0.5372	0.5028	0.5491	0.5484	0.0458	4
Total mean value of the gray relational grade = 0.5358								

and Figure 3, the optimal combinational levels of machining parameters associated with multiple performance characteristics from EDM honeycomb rings were as follows: pulse-on time at level 1(t_{on}=5 μs), peak current at level 3(I=10A), peak voltage at level 1(U=1V), pulse-off time at level 3(t_{off}=75) for minimizing SR and maximizing MRR, respectively.The EDMed surfaced micrograph was shown in Figure 4, the smoother surface due to lower discharge current (10 A) and lower pulse-on time (5 μs).

Figure 4 : The SEM micrographs of GH3536 in optimum condition

CONFIRMATION EXPERIMENT

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

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{p} (\bar{\gamma}_j - \gamma_m) \qquad (6)$$

where γ_m is the total mean of gray relational grade, $\bar{\gamma}_j$ is the mean of the gray relational grade at the optimum level and p is the number of machining parameters that significantly affects the multiple performance characteristics.Based on Eq(6), the results of the confirmation experiment using optimal machining parameters shown in TABLE 10.The SR was reduced from1.057 to 0.826 μm and MRR was enhanced from1.560 to 1.913 $mm^3/\min$ .It was clearly presented

TABLE 10 : Results of confirmation experiment

	Initial machining parameters	Optimal machining parameters	
		Prediction	Experiment
Level	$A_1B_4C_4D_4$	$A_1B_3C_1D_3$	$A_1B_3C_1D_3$
Surface roughness(SR)	1.057		0.826
Material removal rate(MRR)	1.560		1.913
Gray relational grade	0.6307	0.6808	0.7502
Improvement of the gray relational grade = 0.1195			

that multiply performance characteristics in EDM honeycomb ring were greatly improved through this work.

CONCLUSIONS

(1) ANOVA results indicated that the pulse-on time, peak current, peak voltage and pulse-off time were significant machining parameters that obviously affected the multiple performance characteristics in the EDM honeycomb ring.Moreover, the optimal combinational levels of machining parameters based on gray relational grades associated with multiply performance characteristics in the EDM honeycomb ring process as follows: 5 μs pulse-on time (t_{on}), 10A peak current (I), 1V peak voltage (U), 75pulse-off time (t_{off}).As a result, optimization of the complicated multiple performance characteristics can be greatly simplified through this approach.

(2) The corresponding confirmation tests show that the improvement of SR and MRR from the initial condition to optimal condition is 21.85%and 22.63%, respectively.

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