Int J Adv Manuf Technol (2014) 70:1369–1376
DOI 10.1007/s00170-013-5380-4

ORIGINAL ARTICLE

Electrical discharge precision machining parameters optimization investigation on S-03 special stainless steel

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Received: 6 June 2013 / Accepted: 1 October 2013 / Published online: 22 October 2013

Abstract S-03 is a novel special stainless steel, which is widely used in precision aerospace parts and electrical discharge machining technology has the merit of high-accuracy machining. This paper aims to combine gray relational analysis and orthogonal experimental to optimize electrical discharge high-accuracy machining parameters. The four process parameters of gap voltage, peak discharge current, pulse width, and pulse interval are required to optimize in the fewest experiment times. The material removal rate and surface roughness are the objective parameters. The experiment were carried out based on Taguchi $L9$ orthogonal array, then we carried out the gray relational analysis to optimize the multi-objective machining parameter, finally, we verified the results through a confirmation experiment. The sequence of machining parameters from primary to secondary are as follows: discharge current 7A, pulse interval 100 μs, pulse width 50 μs, and gap voltage 70 V. Using the above machining parameters, we can obtain good surface roughness Ra1.7 μm, and material removal rate 13.3 mm^3/min. The machined work piece almost has no surface modification layer. The results show that combining orthogonal experiment and gray relational analysis can further optimize machining parameters, the material removal rate increased by 23.8 %, and the surface roughness almost has no change.

Keywords Electrical discharge machining (EDM) · Material removal rate (MRR) · Surface roughness (SR) · Taguchi method · Gray relational analysis · Special stainless steel

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1 Introduction

Electrical discharge machining (EDM) is an important process because it is often referred to as a 'non-contact' machining process via the thermomechanical effect regardless of the hardness of the work piece material [1–3]. EDM technology is a valuable and viable process method in molds, automobile, aerospace, and surgical industry fields. The work piece and the tool electrode submerged in electrical discharge dielectric liquid that are separated by a tiny gap. The local temperature within the discharge channel is sharply increased to more than 10,000 °C, which can make the tool electrode and work piece melt and vaporize as the point of discharge takes place. The melted material is flushed away by the working fluid. Therefore, it can make machining hard, high-strength, geometrically complex, and temperature-resistant materials.

EDM is a reliable, affordable, and accurate method, and it is used for processing intricate and complex parts. It mainly uses graphite or copper electrodes to erode the desired shape. The work piece does not get deformed through EDM machining; the finished product will not have burrs [4, 5].

Much research has been conducted in an attempt to improve material removal rate (MRR), reduce the surface roughness (SR) value and electrode wear rate (EWR), and make parameters optimization. Murray et al. have proposed using EDM technology machining single-crystal silicon through transmission electron microscopy [6]. Cryogenically cooled electrode has been researched on the machining characteristics in EDM [7–9]. Patel et al. have researched the role of weight percentage and size of silicon carbide particulate on EDM of aluminum-based composites [10]. Beri et al. have shown that powder metallurgy-processed electrodes can improve the EDM performance [11]. The EDM parameters on surface integrity, MRR, EWR, and multi-objective optimization method were studied by researchers [12–19]. The EDM debris was studied by many researchers [20–22]. Lee et al. have proposed using high purity germanium as wire electrical discharge machining electrode [23]. Gu et al. have proposed using

Table 1 Chemical composition of S-03 special steel (wt.%)

Element	Percentages
Carbon	≤0.03
Silicon	≤0.15
Manganese	≤0.15
Sulfur	≤0.01
Phosphorus	≤0.01
Aluminum	≤0.20
Chromium	11.5 to 12.5
Nickel	9.0 to 10.3
Molybdenum	0.5 to 0.8
Titanium	0.15 to 0.25
Ferrum	Balance

bundled electrical discharge electrode machining Ti6Al4V [24]. Kellens et al. studied the environmental assessment of EDM [25]. Zhang et al. adopted water-in-oil emulsion as EDM dielectric and researched the recast layer of the work piece surface [26]. Srivastava and Pandey researched the ultrasonic-assisted cryogenically cooled electrical discharge machining [27]. Kumar and Batra did the surface modification study by EDM method [28]. Electrochemical machining (ECM) technology has the merit of economical and high efficiency capabilities of manufacturing titanium and nickel-based alloys [29].

Before we began this work, we have researched on composite electrolyte ECM S-03 special steel; the results demonstrated that the $NaClO_3$ and $NaNO_3$ electrolyte composition yielded better results than single-component $NaNO_3$ electrolyte [30]. Since the ECM technology is affect by electric field, flow field, magnetic field, and temperature field, it's difficult to acquire the desired geometrical precision. But, using ECM technology can improve machining efficiency in complex parts, which are manufactured by S-03 material. So we decide to adopt the EDM method to carry out the work piece's final fine machining.

However, there is no literature studied on EDM machining of S-03 stainless steel. The aim of this paper is to carry out EDM fundamental experiment research on S-03 special stainless steel. The experiments were designed using Taguchi $L9$ orthogonal array. Gap voltage, discharge current, pulse width, and pulse interval were the process parameters in this study. Moreover, the experimental data of SR and MRR were transferred to gray relational grade and were assessed to obtain the optimal machining parameters. Most of the application of Taguchi method is concentrated on the optimization of single response problem. However, the gray relational analysis based on gray system theory can be used for solving the complicated interrelationships among the multi responses. A gray relational grade is obtained to evaluate the multiple responses. As a result, optimization of the multiple responses can be converted into optimization of a single relational grade [31–40]. In short, there is an ample scope of applying the proposed methodology of gray relational analysis and Taguchi method with the orthogonal test and multi-objective parameters optimization. The goal is finding out suitable machining parameters for EDM high-accuracy machining S-03 special stainless steel.

2 Experimental work

As a novel material, S-03 is a special stainless steel, which is designed for new-type airplane engine turbine disk. It will be widely used in high-pressure liquid oxygen pump, high-pressure gas generator, and other important aerospace parts. Its composition is shown in Table 1. It takes into consideration the requirements of high and low temperatures. At low temperatures, its toughness is improved mainly by strengthening of martensite and the solid solution, and retaining a certain amount of austenite and sufficient Ni element. At high temperatures, it uses the intermetallic compounds to improve its strength. Owing to the special composition and structure, it not only improves the temperature usage range to between −253 and 500 °C, but also improves its toughness.

Fig. 1 The EDM machine and experiment setup

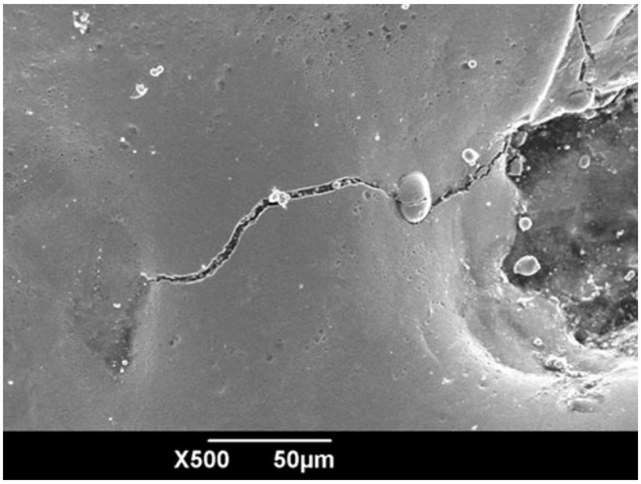

Fig. 2 The SEM of the EDM rough finish work piece

The material of work piece was S-03 with a dimension of 100×50×8 mm. The specimens were milled and ground to ensure parallelism before carrying out the experiments. In this study, the CNC ActSpark EDM machine is used and the experimental setup is shown in Fig. 1. A red copper rod with the diameter of 12 mm and the height of 100 mm was used as a tool electrode in this study. In addition, kerosene oil was employed as a dielectric fluid in this investigation.

However, there are several machining parameters that should be considered in the EDM process. Before the high-accuracy process S-03 material, we did the S-03 material rough finish experiment. The fastest speed machining parameters are as follows: gap voltage 55 V, peak discharge current 50 A, pulse width 420 μs, pulse interval 180 μs, open-circuit voltage 100 V, and electrode lifting height 2 mm. The work piece is connected to the negative terminal of the power. The depth of every experiment is 5 mm and each experiment was done three times, then, we calculated the average value to ensure the authenticity of our experiment results. From the scanning electron microscope, the micro-cracks are obvious, which is shown in Fig. 2. The surface roughness is only Ra 10.5 μm.

In order to satisfy the demand of complex parts and improve the lifetime of aerospace components, we must reduce the process micro-cracks and improve surface roughness. So, we did the Taguchi experimental design and did the multi-objective parameters optimization. Through the experiment, we found that the process parameters such as gap voltage, peak discharge current, pulse width, and pulse interval have an obvious effect on S-03 steel. Table 2 presents the four process parameters and the levels of the machining parameters designed in the experiments.

Table 2 Experimental levels of machining parameters

Symbol	Control parameters	Level 1	Level 2	Level 3
A	Gap voltage (V)	60	70	80
B	Discharge current (A)	4	7	10
C	Pulse width (μs)	25	50	75
D	Pulse interval (μs)	20	60	100

Table 3 $L_9(3^4)$ orthogonal array, control parameters, and observed values

No.	Control factors				Observed values	
	A	B	C	D	Ra (μm)	MRR (mm^3/min)
1	1	1	1	1	2.4	8.5
2	1	2	2	2	2.2	10.7
3	1	3	3	3	3.5	13.8
4	2	1	2	3	1.6	10.5
5	2	2	3	1	2.0	11.9
6	2	3	1	2	3.7	12.6
7	3	1	3	2	1.8	10.3
8	3	2	1	3	1.9	11.6
9	3	3	2	1	4.2	13.4

The Taguchi experimental design of L9 (3^4) orthogonal array with four columns and nine rows and the results of experiments were shown in Table 3.

The MRR and the SR of the machined surface are the performance characteristics to evaluate the high-accuracy machining quality in this study. To measure the volume of the worn electrode and work piece removal, a precision balance (NL5003, China) was used. The surface roughness of the machined work piece was measured by a surface roughness tester (Form Taylor Hobson-μltra, UK). The machined holes are shown in Fig. 3.

3 Results and discussion

The gray analysis was first proposed by Dr. Deng in1982. Gray analysis has been broadly applied in evaluating or judging the performance of a complex project. It can be used for solving the complicated interrelationships among the multi responses. However, Taguchi method concentrated on the optimization of single-objective problems. A gray relational grade is obtained to evaluate the multiple responses. As a result, optimization of the multiple responses can be converted into optimization of a single relational grade [41]. The relation

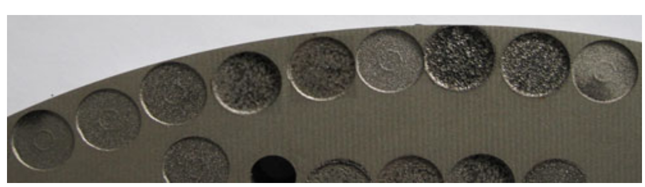

Fig. 3 The machined work piece with EDM

Table 4 Grey relational generating of MRR and SR

Number	SR Ideal sequence	MRR
	1	1
1	0.69	0
2	0.77	0.42
3	0.27	1
4	1	0.38
5	0.85	0.64
6	0.19	0.77
7	0.92	0.34
8	0.88	0.58
9	0	0.92

between the optimal objective and the machining parameters can be determined through the gray relational analysis. Based on this theory, the gray relational grade can be acquired to evaluate multiple performance characteristics, adopting discrete value to evaluate and find the relationship of these data. The sequences can be categorized into two types in this paper as follows:

For the-lower-the-better quality characteristics, the data preprocessing is calculated by

$$x_i^*(k) = \frac{\max x_i^{(0)}(k) - x_i^{(0)}(k)}{\max x_i^{(0)}(k) - \min x_i^{(0)}(k)} \tag{1}$$

For the-higher-the-better quality characteristics, data preprocessing is calculated by

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

Where $x_i^*(k)$ is obtained from gray relational analysis; max $x_i^{(0)}(k)$ is the maximum value of sequence $x_i^{(0)}(k)$; min$x_i^{(0)}(k)$ is the minimum value of the sequence $x_i^{(0)}(k)$; $x^{(0)}$ is the

Table 5 Grey relational coefficients and grades

Number	Gray relational coefficient		Grey relational grades	
	SR	MRR	Average value	Rank
1	0.72	0.44	0.58	9
2	0.78	0.58	0.68	7
3	0.52	1	0.76	4
4	1	0.58	0.79	1
5	0.84	0.69	0.78	2
6	0.50	0.78	0.64	8
7	0.91	0.54	0.73	5
8	0.87	0.66	0.77	3
9	0.47	0.91	0.69	6

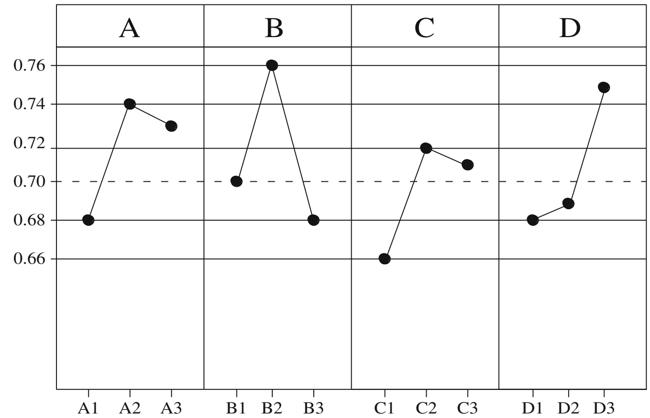

Fig. 4 Process parameters effects on grey relational grade

expectation value. Table 4 shows the data preprocessing results.

The gray relational coefficient can be calculated as:

$$\gamma(x_0(k), x_i^*(k)) = \frac{\min_i \min_j \left|x_0(k) - x_j^*(k)\right| + \zeta \max_i \max_j \left|x_0(k) - x_j^*(k)\right|}{\left|x_0(k) - x_i^*(k)\right| + \zeta \max_i \max_j \left|x_0(k) - x_j^*(k)\right|} \tag{3}$$

Where $x_0(k)$ is the ideal sequence;

$\Delta_{0i}(k) = |x_0(k) - x_i^*(k)|$ is the difference of the absolute value between $x_0(k)$ and $x_i^*(k)$;

$\Delta\max = \forall j^{\max} \in i\, \forall k^{\max} |x_0(k) - x_j^*(k)|$ is the largest value of Δ_{0i};

$\Delta\min = \forall j^{\min} \in i\, \forall k^{\min} |x_0(k) - x_j^*(k)|$ is the smallest value of Δ_{0i};

ζ is a distinguishing coefficient that is defined in the range between 0 and 1.

$$\Delta_v = \frac{1}{nm} \sum_{i=1}^{m} \sum_{j=1}^{n} \frac{1}{n} \left|x_0(k) - x_j{}^*(k)\right| = 0.4261 \tag{4}$$

$$\varepsilon_\Delta = \frac{\Delta_v}{\Delta_{\max}} = 0.4261 \tag{5}$$

$$\Delta_{\max} \le 3\Delta_v \tag{6}$$

$$1.5\varepsilon_\Delta < \zeta \le 2\varepsilon_\Delta \tag{7}$$

Table 6 Results of the confirmation experiment

Observer values	Orthogonal array	Optimal combination levels of machining parameters	
		Prediction	Experiment
Level	$A_2B_1C_2D_3$	$A_2B_2C_2D_3$	$A_2B_2C_2D_3$
SR (μm)	1.6	–	1.7
MRR (mm^3/min)	10.5	–	13.3
Grey relational grade	0.79	0.81	0.82

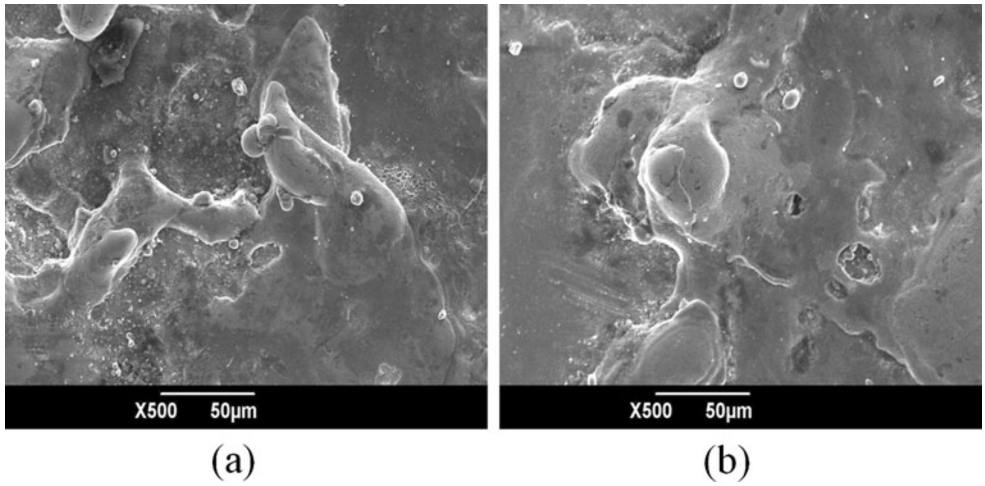

Fig. 5 The micrographs of work piece. **a** $A_2B_1C_2D_3$; **b** $A_2B_2C_2D_3$

In this paper, we selected ζ as 0.8. The gray relation coefficients of each performance characteristic are calculated using Formula (3), the results and gray relational grade are shown in Table 5. Experiment 4 shows the highest gray relational grade, indicating the optimal process parameter set of $A_2B_1C_2D_3$ has the best multiple performance characteristics among the nine experiments.

Since the experimental design is orthogonal, it is possible to separate the effects of each process parameter at different levels. For example, the mean of gray relational grade for the application voltage at level 1, 2 and 3 can be calculated by taking the average of the gray relational grade for the experiments1-3, 4–6 and 7–9, respectively. The mean of the gray relational grade for each level of other machining parameters can be computed in the similar method. Figure 4 shows the influence of process parameters on machining characteristics. It shows that the predicted optimal process parameter set is $A_2B_2C_2D_3$ based on the gray relational analysis. The mean value of the gray relational grade is 0.70. The process parameters sequenced in order of relative importance are as follows: peak discharge current, pulse interval, gap voltage, and pulse width.

Since the optimal EDM process parameter set is obtained, the confirmation tests are processed to verify the performance characteristics improvement. The results of the confirmation experiment are compared with the outcome of the orthogonal array and gray theory prediction of the design operating parameters. The estimated gray relational grade is calculated according to reference [32]. Table 6 shows the comparison of the experimental results between orthogonal array ($A_2B_1C_2D_3$) and gray theory prediction ($A_2B_2C_2D_3$) EDM parameters. The reason why the MRR from 10.5 to 13.3 mm^3/min improved by 23.8 % is that from $A_2B_1C_2D_3$ to $A_2B_2C_2D_3$, the peak current increased from 4A to 7A, the

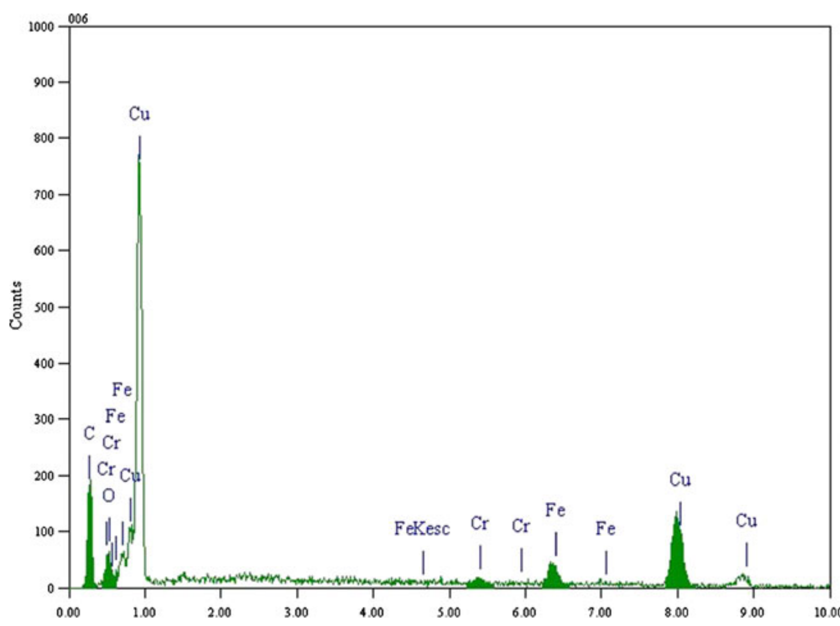

Fig. 6 Energy-dispersive x-ray spectroscopy of S-03 $A_2B_2C_2D_3$

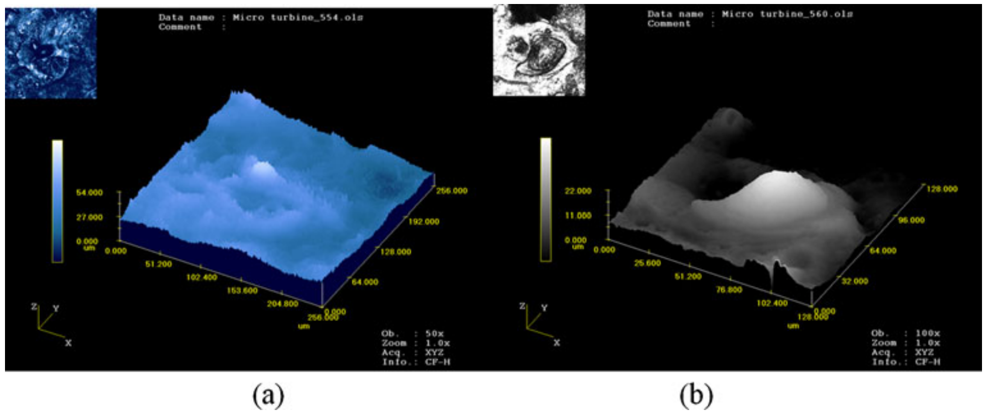

Fig. 7 Confocal laser scanning crater surface morphology. **a** $A_2B_1C_2D_3$, **b** $A_2B_2C_2D_3$

discharge energy is more and more larger. That is to say, the single discharge energy is changing too big, so the material removal rate becomes larger. Since the single discharge energy becomes larger, the single crater becomes bigger. So, the surface roughness value is becoming larger. Fortunately, using both $A_2B_1C_2D_3$ and $A_2B_2C_2D_3$ machining parameters, the SR value almost has no change. One reason can explain this phenomenon. The material was flushed away by melt or evaporation. If the discharge energy is small, a little material can be melted. But, if the discharge energy is large, most of the energy lost in material evaporation, there is only little energy used in the material melt. Another reason may also explain this phenomenon. With the development of discharge energy, more and more tool electrode material melted or evaporated, but it flushed into the work piece surface. So, the work piece surface roughness almost has no change.

The SEM micrograph in Fig. 5a shows the EDM surface topography with the orthogonal array parameters ($A_2B_1C_2D_3$) and the optimal gray theory prediction design ($A_2B_2C_2D_3$) is shown in Fig. 5b. Compared with Fig. 2, we can see that there are almost no micro-cracks in Fig. 4. Surface defects such as globules debris and melted drops are shown in Fig. 4. There are many micro-voids existed on the surface of the work piece.

In addition, energy-dispersive x-ray spectroscopy of S-03 of $A_2B_2C_2D_3$ is shown in Fig. 6. It indicates that Cu and O elements occurred when S-03 is machined using copper electrode with kerosene dielectric fluid. This can be attributed to the decomposition of the kerosene in the discharge gap due to the discharge energy. As we know, during the EDM process, both the tool electrode and work piece are melted and vaporized at the discharge point. Most of the melted material is flushed away by the working fluid, but there are some debris that went into another electrode surface. So, we can see Cu element on the work piece surface.

The sole crater machined by EDM is measured by confocal laser scanning microscope (Olympus OLS3000); we can see that the surface roughness $A_2B_1C_2D_3$ is almost the same as the $A_2B_2C_2D_3$, which is shown in Fig. 7. From Fig. 8a, we can see the cross-sectional side wall micrograph of samples machined with the orthogonal array parameters ($A_2B_1C_2D_3$) has much molten metal stuck in the side wall, but in Fig. 8b, there are almost no molten metal in the side wall in $A_2B_2C_2D_3$. So, the side surface roughness of $A_2B_2C_2D_3$ is better than $A_2B_1C_2D_3$. We also found that using $A_2B_1C_2D_3$ parameters machined hole is larger than using $A_2B_2C_2D_3$ parameters machined hole with the same electrode. The results demonstrate that $A_2B_2C_2D_3$ parameters machined hole has better machining

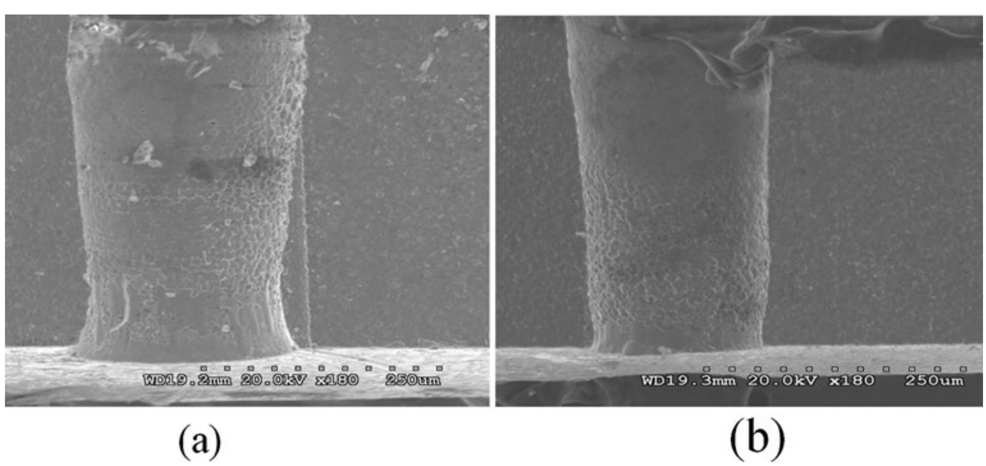

Fig. 8 The side wall morphology of machined hole. **a** $A_2B_1C_2D_3$, **b** $A_2B_2C_2D_3$

precision. From the experiment results, we can see that EDM S-03 material has the merit of high precision and it can do machining complex shape aerospace parts. Usually, EDM has low machining efficiency.

4 Conclusions

The novel special stainless steel S-03 material will be widely used in airplane engine, high-pressure pump, gas generator, and other automobile parts. The application of the Taguchi method and gray relational analysis is to improve the multiple performance characteristics of the MRR and SR in EDM. EDM technology can obtain high precision in processing S-03 material and has been reported in this paper. The effects on MRR and SR of S-03 material by gap voltage, peak discharge current, pulse width, and pulse interval were given. The following conclusions are obtained from the experimental results:

(1) Through the $L_9(3^4)$ Taguchi experiment and gray relational analysis, the optimal process parameters for EDM high-accuracy process S-03 material are gap voltage 70 V, peak discharge current 7A, pulse width 50 μs, and pulse interval 100 μs.
(2) The EDM high-accuracy process parameters sequenced in order of relative importance are: peak discharge current, pulse interval, gap voltage, and pulse width.
(3) The machining performance of the surface roughness decreases from 1.6 to 1.7 μm, which satisfied the demand of the product. Perfectly, the material removal rate increases from 10.5 to 13.3 mm^3/min, it is nearly improved by 27 %. At the same time, the side surface roughness of $A_2B_2C_2D_3$ is also better than $A_2B_1C_2D_3$.

Acknowledgments The work is partially supported by a grant from Shaanxi Provincial Department of Education Fund (Grant No. 2013JK1014). The authors would like to thank Professor Fan of Xi'an Technological University for her helpful suggestion and also Mr. Zhao for supplying the material of the work pieces. The authors also thank Mr. Li and Mr. Yang for their kind support for this research.

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