Experimental study on green electrical discharge machining in tap water of Ti–6Al–4V and parameters optimization

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Abstract Ti–6Al–4V is widely used in the aerospace, automobile, and biomedical fields, but is a difficult-to-machine material. Electrical discharge machining (EDM) is regarded as one of the most effective approaches to machining Ti–6Al–4V alloy, since it is a non-contact electro-thermal machining method, and it is independent from the mechanical properties of the processed material. This paper aims to combine grey relational analysis and Taguchi methods to solve the problem of EDM parameters optimization. From the viewpoint of health and environment, tap water as working fluid has good working environment, since it does not release harmful gas. The process parameters include discharge current, gap voltage, lifting height, negative polarity and pulse duty factor. The electrode wear ratio (EWR), material removal rate (MRR) and surface roughness (SR) as objective parameters are chosen to evaluate the whole machining effects. Experiments were carried out based on Taguchi L9 orthogonal array and grey relational analysis, and then verified the results through a confirmation experiment. Compared the machining parameters A1B1C3D2 with A1B2C2D2, MRR increased from 1.28 mm³/min to 2.38 mm³/min, EWR decreased from 0.14 to 0.10 mm³/min and SR decreased from Ra 2.37 μm to Ra 1.93 μm. The process parameters sequenced in order of relative importance are: the ratio of pulse width to pulse interval, discharge current, lifting height and gap voltage. The results showed that using tap water machining Ti–6Al–4V material can obtain high MRR, decrease the machining cost and have no harmful to the operators and the environment.

Keywords EDM · Ti–6Al–4V alloy · Material removal rate · Electrode wear rate · Surface roughness · Orthogonal experiment · Grey relational analysis

1 Introduction

Ti–6Al–4V alloy has exceptional merits such as high strength–weight ratio, good temperature stability and prominent corrosion resistance, which makes it widely used in aerospace, automobile, chemical and biomedical fields [1, 2]. However, it is a hard-to-cut material with its high melting and low thermal conductivity and it not suitable for traditional machining. Therefore, non-traditional machining methods such as electrical discharge machining (EDM) have been used to process this alloy. EDM is a non-traditional machining method, which is extensively used in machining hard, high-strength, complex geometry shape and temperature-resistant materials in a contactless manner. The material is melted and evaporated by the heat between electrode tool and work piece [3–9]. Recently, EDM technology made it widely used in machining the key parts such as aerospace and aeronautical components. Much research has been conducted in an attempt to improve the EDM material removal rate (MRR), surface roughness (SR), reduce the electrode wear rate (EWR) and seek optimal machining parameters.

Brass and bronze were used as electrode materials to machining D2 tool steel in tap water and deionized water, and the results showed that by using 75 % tap water and 25 % deionized water mixture, the dielectric can obtain the maximum MRR and the minimum EWR [10]. In order to obtain surface integrity of Ti–6Al–4V, graphite, electrolytic copper, aluminium and copper–tungsten material were researched as EDM electrodes [11–14]. EDM dielectric-water-in-oil, kerosene and
deionized water were studied to get high MRR and low EWR [15–18]. Powder-mixed EDM is one of the methods for improving the capabilities of EDM, which can reduce the gap between the tool and work piece, and make the machining more stable and improve the MRR [19–22]. Cryogenic cooling and treatment method can reduce EWR in Ti–6Al–4V and Ti 6246 alloy EDM [23, 24]. Ultrasonic, vibratory, rotary and magnetic field can also improve MRR in EDM [25–30]. The residual stresses and white layer have a great relationship with the type of the EDM dielectric [31, 32]. Machining performance in the EDM process can be improved effectively through optimal machining parameters [33–39]. Using kerosene as dielectric will discharge large amounts of solid, liquid and gaseous wastes, which result in serious environmental problems. These toxic substances can enter the body through inhalation and skin contact [8, 9].

Green manufacturing aims at improving the efficiency and saving resources. Thus, optimization of process parameters is an essential requirement to achieve environmentally friendly EDM. The aim of this paper was to select optimum process parameters for Ti–6Al–4V alloy green EDM. The experiments were designed using a Taguchi L9 orthogonal array. Peak current, gap voltage, lifting height and pulse duty factor were the process parameters considered in this study. The experimental data of MRR, SR and EWR were transferred to grey relational grade and were assessed to determine the significant machining parameters. The goal of seeking high efficiency, high quality and no-pollution machining meets the modern industrial requirements.

### 2 Experiments research

The work piece material was Ti–6Al–4V alloy with the dimension of 50×50×8 mm. The sample was milled and ground to keep parallel before the experiments. The chemical composition of the alloy is shown in Table 1. 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 10 mm and the height of 100 mm was used as electrode in this study. In addition, tap water was employed as a dielectric fluid in this investigation.

However, there are several machining parameters to be considered in the EDM process. The process parameters such as discharge current, gap voltage, the ratio of pulse width to pulse interval and lifting height have a clear effect on the EDM performance of Ti–6Al–4V alloy. Table 2 presents the four process parameters and three levels of the machining parameters designed in the experiments. This experiments used a negative polarity electrode and the Taguchi experimental design of L9(3^4) orthogonal array with four columns and nine rows. The results of experiments were depicted in Table 3.

Each experiment was repeated three times with the average being taken. The MRR, EWR and SR of the machined surface are the performance characteristics to evaluate the machining quality in this study. The EWR (in cubic millimeter per minute) is defined by the volume of the electrode worn in the period of working time in minute. The MRR (in cubic millimeter per minute) uses the same measuring unit that accounts for the work piece removal volume under the working time. To measure the weight of the worn electrode and workpiece removal, a precision balance (NL5003, China) was used. In the experiments, the surface roughness of the machined work piece was measured by a surface roughness tester (Taylor Hobson, UK).

### 3 Optimal multi-objective EDM parameters

The relation between the objective parameters and the machining parameters can be determined through the grey relational analysis method. Based on this theory, the grey relational grade can be acquired to judge of multiple objective parameters, adopting discrete value to evaluate and find the relationship of these data. The sequences can be categorized into two types for our research.
Table 2: Experimental levels of the machining parameters

| Symbol | Control parameters | Level 1 | Level 2 | Level 3 |
|--------|--------------------|--------|--------|--------|
| A      | Discharge current(A)| 11     | 16     | 20     |
| B      | Pulse width/pulse interval (T_{off}/T_{on}) (μs)| 30:70  | 50:50  | 70:30  |
| C      | Gap voltage (V)    | 20     | 25     | 30     |
| D      | Lifting height (mm)| 3      | 6      | 9      |

For the higher-the-better MRR, data preprocessing is calculated by:

\[ x_i^*(k) = \frac{x_i^{(0)}(k) - \min x_i^{(0)}(k)}{\max x_i^{(0)}(k) - \min x_i^{(0)}(k)} \]  

(1)

For the lower-the-better EWR and SR, data preprocessing is calculated by:

\[ x_i^*(k) = \frac{\max x_i^{(0)}(k) - x_i^{(0)}(k)}{\max x_i^{(0)}(k) - \min x_i^{(0)}(k)} \]  

(2)

Where \( x_i^*(k) \) is obtained from grey relational analysis; \( \min x_i^{(0)}(k) \) is the minimum value of sequence \( x_i^{(0)}(k) \); \( \max x_i^{(0)}(k) \) is the maximum value of the sequence \( x_i^{(0)}(k) \); \( x^{(0)} \) is the expectation value. Table 4 shows the data preprocessing results.

The grey relational coefficient can be calculated as:

\[ \gamma(x_0(k), x_i(k)) = \frac{\min \{ n | x_0(k) - x_i(k) \} + \zeta \max \{ n | x_0(k) - x_i(k) \}}{\| x_0(k) - x_i(k) \| + \epsilon \max \{ n | x_0(k) - x_i(k) \}} \]  

(3)

Where \( x_0(k) \) is the ideal value;
\[ \Delta_{\min} = \forall j \in i \forall k | x_0(k) - x_i^*(k) | \] is the smallest value of \( \Delta_{\min} \);
\[ \Delta_{\max} = \forall j \in i \forall k | x_0(k) - x_i^*(k) | \] is the largest value of \( \Delta_{\max} \);
\( \zeta \) is a coefficient that is defined in the range between 0 and 1.
\[ \Delta_k = \frac{1}{nm} \sum_{i=1}^{m} \sum_{j=1}^{n} \frac{1}{n} | x_0(k) - x_i^*(k) | = 0.4032 \]  

(4)

\[ \varepsilon = \frac{\Delta_k}{\Delta_{\max}} = 0.4032 \]  

(5)

\[ \Delta_{\max} \leq 3 \Delta_k \]  

(6)

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 grey relational grade for the discharge current at level 1, 2 and 3 can be calculated by taking the average of the grey relational grade for the experiments 1–3, 4–6 and 7–9, respectively. The mean of the grey relational grade for each level of other machining parameters

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 (mm³/min) | EWR (mm³/min) |
| 1   | 1   | 1   | 1   | 1   | 2.17    | 2.96          | 0.21          |
| 2   | 1   | 2   | 2   | 2   | 2.37    | 1.28          | 0.14          |
| 3   | 1   | 3   | 3   | 3   | 2.83    | 1.73          | 0.16          |
| 4   | 2   | 1   | 2   | 3   | 2.19    | 3.27          | 0.30          |
| 5   | 2   | 2   | 3   | 1   | 2.61    | 4.30          | 0.30          |
| 6   | 2   | 3   | 1   | 2   | 2.86    | 4.07          | 0.28          |
| 7   | 3   | 1   | 3   | 2   | 2.15    | 5.90          | 0.41          |
| 8   | 3   | 2   | 1   | 3   | 2.65    | 6.62          | 0.41          |
| 9   | 3   | 3   | 2   | 1   | 4.27    | 6.36          | 0.41          |

Table 4: Grey relational generating of MRR, EWR and SR

| Number | MRR | EWR | SR |
|--------|-----|-----|----|
| 1      | 1   | 1   | 1  |
| 2      | 0.32| 0.75| 0.96|
| 3      | 0   | 1   | 0.89|
| 4      | 0.09| 0.93| 0.68|
| 5      | 0.37| 0.41| 0.98|
| 6      | 0.56| 0.40| 0.78|
| 7      | 0.52| 0.47| 0.66|
| 8      | 0.86| 0.03| 1  |
| 9      | 0.95| 0.03| 0.76|
| 10     | 0   | 0   | 0  |
can be computed in a similar method. Figure 2 shows the influence of process parameters on machining characteristics. Based on the grey relational analysis, the predicted optimal process parameters set is A₁B₁C₃D₂. The mean value of the grey relational grade is 0.63. The process parameters sequenced in order of relative importance are the following: discharge current, the ratio of pulse width to pulse interval, gap voltage, and lifting height.

4 Confirmation experiment research

Since the optimal EDM process parameter set is obtained, the confirmation tests are used to check the performance characteristics improvement. The data of the confirmation experiment are compared with the data obtained by orthogonal array and grey theory prediction. The experimental comparison results between A₁B₂C₂D₂ and A₁B₁C₃D₂ are shown in Table 6. We can see that the MRR increased from 1.28 mm³/min to 2.38 mm³/min, the EWR decreased from 0.14 to 0.10 mm³/min and the SR decreased from 2.37 to 1.93 μm. The corresponding amelioration in MRR is 87.3 %, EWR reduced 25.7 % and surface roughness reduced 18.9 %, respectively.

The SEM micrograph of surface topography with the orthogonal array parameters (A₁B₂C₂D₂) is shown in Fig. 3a and the optimal grey relation analysis theory predicted design (A₁B₁C₃D₂) is shown in Fig. 3b. We can see that the latter cracks are smaller than the former. Surface defects such as globules debris and melted drops are unclear except for crater scattering in A₁B₁C₃D₂. Figure 3 also shows that many microvoids existed on the surface of the sample machined.

In addition, energy-dispersive X-ray spectroscopy of Ti–6Al–4V alloy of A₁B₁C₃D₂ is shown in Fig. 4. It indicated that the oxide form of TiO occurs when Ti–6Al–4V alloy is machined using copper electrode with tap water dielectric fluid. As illustrated in Fig. 4, the working area was occupied by the tap water droplets which can be easily vaporized and subsequently reacted with the melted material. The melted Ti metal is oxidized by oxygen decomposed from water.

The sole crater machined by EDM with tap water is measured by Confocal laser scanning microscope (OLYMPUS OLS3000), we can see that the surface roughness of A₁B₂C₂D₂ machining parameters in Fig. 5a is worse than the optimal grey theory prediction design (A₁B₁C₃D₂) shown in Fig. 5b. From Fig. 6a, we can see the cross-

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**Table 5** Grey relational coefficients and grades

| Number | Grey relational coefficient | Grey relational grades |
|--------|----------------------------|------------------------|
|        | MRR | EWR | SR | Average value | Rank |
| 1      | 0.42 | 0.67 | 0.93 | 0.68 | 3 |
| 2      | 0.33 | 1   | 0.82 | 0.72 | 1 |
| 3      | 0.35 | 0.88 | 0.61 | 0.61 | 6 |
| 4      | 0.44 | 0.46 | 0.96 | 0.62 | 5 |
| 5      | 0.53 | 0.45 | 0.70 | 0.56 | 7 |
| 6      | 0.51 | 0.49 | 0.60 | 0.53 | 8 |
| 7      | 0.79 | 0.34 | 1   | 0.71 | 2 |
| 8      | 1   | 0.34 | 0.68 | 0.67 | 4 |
| 9      | 0.91 | 0.33 | 0.33 | 0.53 | 9 |

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Fig. 2 Process parameters effects on grey relational grade

![Fig. 2](image-url)
sectional side wall micrograph of samples machined with the orthogonal array parameters (A₁B₂C₂D₂) has much molten metal in the side wall, but in Fig. 6b, there is almost no molten metal in the side wall. So, the SR of A₁B₁C₃D₂ is better than A₁B₂C₂D₂. We found that using A₁B₂C₂D₂ parameters machined hole is larger than using A₁B₁C₁D₂ parameters. The results demonstrate that A₁B₁C₃D₂ parameters machined hole has better machining precision.

5 Conclusions

The manufacturing industry was considered as one of the main sources of environmental pollution. How to minimize the pollution is an important topic for manufacturers all over the world. The novel EDM Ti–6Al–4V with tap water was explored. The application of the Taguchi method and grey relational analysis to improve the multiple performance of the EWR, MRR and SR in the EDM has been reported in this paper. There are three conclusions gained as follows:

1. The optimal process parameters are 11 A discharge current, 30 V gap voltage, 3 mm lifting height, 30 μs pulse duration and 30 % duty factor.
2. The machining performance of the EWR decreased from 0.14 to 0.10 mm³/min, the MRR increased from 1.28 to 2.38 mm³/min, and the SR decreased from Ra 2.37 μm to Ra 1.93 μm. The corresponding improvement in MRR is 87.3 %, EWR reduced 25.7 %, and SR reduced 18.9 %, respectively.
3. It was indicated that the method of combining Taguchi and grey relational analysis was efficient and effective for multi-objective parameters optimization in green electrical discharge machining Ti–6Al–4V with tap water. Using tap water machining, Ti–6Al–4V alloy has high MRR, has no harm to operators and the environment, and also decreases the whole cost.
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Acknowledgments

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