Experimental investigation on simultaneous machining of EDM and ECM of Ti6Al4V with different abrasive materials and particle sizes

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Abstract
In view of the difficult machining characteristics of titanium alloys and the limitations of sequential EDM/ECM machining, taking NaN O3 salt solution with low conductivity as the working fluid, the simultaneous machining of EDM and ECM (SEDCM) assisted by abrasive particles was carried out. Firstly, the effects of the electrical conductivity of the working fluid, the abrasive material, and particle size on material removal rate (MRR), tool wear rate (TWR), surface roughness (Ra), and surface morphology of SEDCM were investigated. Then, SiC abrasive with particle size of 50 μm was selected to add in the working fluid of SEDCM, owing to the unique properties of SiC in comparison with Al and Cu abrasive particles. The effect of process parameters, such as peak current, pulse on time, abrasive concentration, and gap voltage, was optimized using Taguchi-based grey relational analysis. The multi-objective optimization of MRR, TWR, and Ra was converted into the optimization of a single grey relational grade. Finally, based on the grey relational grade, the optimal combination of process parameters was predicted and verified by experiments. The results show that the comprehensive machining effect is better when the conductivity of working medium is 300 μS/cm, as long as other electrical parameters and experimental conditions are the same. Compared with Cu and Al abrasives, SiC abrasive has the lowest tool wear rate and the best surface quality, even with the worst material removal rate. Moreover, MRR, TWR, and Ra were obviously improved at the optimal parametric combination of peak current 1.5A, pulse on time 15 μs, abrasive concentration 5 g/L, and gap voltage 40 V by implementing Taguchi-based grey relational analysis.

Keywords Electrical discharge machining (EDM) · Electrochemical machining (ECM) · Hybrid machining · Abrasive materials · Abrasive sizes · Titanium alloy

1 Introduction
Micro-parts or micro-structures of titanium alloy are widely used in aviation, aerospace, weapons, precision instruments, and many other fields, with the development of MEMS and influenced by the trend of miniaturization, integration, and lightweight of MEMS products [1–3]. However, titanium alloy is a typical hard cutting material because of its viscosity, toughness, elasticity, and high chemical activity [4–6].

As an important method, electrical discharge machining (EDM) or electrochemical machining (ECM) contributes a predominant role in the tool making, automobile, and aerospace industries, since they are not in direct contact with the workpiece and are not restricted by the typical materials properties such as strength, hardness, and toughness [7–9]. Therefore, EDM and ECM can circumvent problems encountered in conventional machining methods and to be the best alternative to manufacture titanium alloy components and parts. However, EDM will cause a large number of defects such as holes, micro-cracks, and recast layers on the surface of the workpiece. Although ECM can obtain the higher surface quality without recast layer and micro cracks, it has the problems of stray corrosion and low machining efficiency.

In view of the above problems, some researchers try to combine ECM with EDM [10–12], and make full use of
the advantages of EDM and ECM to improve the processing performance and processing quality of titanium alloy. Masuzawa and Sakai [13] conducted WEDM experiments on SKD11, SKD61, SUS304, and brass workpieces, and then used the remaining part as the supporting electrode of ECM, to make NaNO₃ electrolyte flow through the micro-gap generated by WEDM. The experimental results show that the surfaces of many different kinds of metals, including tool steels, can be finished until mirror-like within a few seconds. Ramasawmy and Blunt [14] carried out an experiment in order to assess the effect of four different electrolytes in an electrochemical polishing on the surface topography of EDM. They found that the acidic medium has a better polishing effect on the surface topography of the component. In terms of environmental acceptability and safety, it would seem that a higher concentration sodium nitrate solution can also yield a good polishing rate but the current density to be used needs to be clearly identified. It can be seen that the pit structure and recast layer produced in EDM can be removed through the macro leveling effect of electrochemical anode dissolution in ECM, so as to reduce the surface roughness and improve the surface quality.

However, the above combination of EDM and ECM belongs to serial machining [15, 16], and it is necessary to change the electrode or working fluid, which makes it difficult to control the machining process and ensure the machining consistency. As a result, the efficiency and accuracy of the sequential machining of EDM and ECM is just passable.

Nguyen et al. [17] combined micro-EDM and micro-ECM as a unique hybrid machining process, and developed a simultaneous machining of EDM and ECM (SEDCM), by using low-resistivity deionized water as bi-characteristic fluid. Experimental results show that there is a conversion of material removal mechanism from mere EDM to hybrid EDM/ECM when low feed rate is applied. In addition, Zhang et al. [18] used a tube electrode and NaNO₃ salt solution with 3 mS/cm as the tool cathode and the working fluid for SEDCM. They found that the tube electrode can be used to effectively push the complex machining by-products and heat out of the narrow machining gap. The low-conductivity salt solution can be exploited as a bi-characteristic working fluid, through which the EDM and ECM processes can occur simultaneously.

The energy of material removal in SEDCM mainly comes from the pulse power supply. Affected by the energy output of the pulse power supply and the weak ionization characteristics of the working fluid, the machining mechanism, processing efficiency, and action mode of tool electrode are obviously different from the simple superposition of EDM and ECM. How to fabricate the working fluid which can be used for electrochemical dissolution without interfering the spark discharge, and how to give full play to the effect of electrochemical anode dissolution while maintaining the stability of discharge channel and discharge state, is still a problem that needs to be considered in the simultaneous machining of EDM and ECM. In addition, in order to take into account spark discharge, the conductivity of the working fluid for SEDCM must be less than that of the electrolyte of the single ECM. Consequently, it will reduce the efficiency of ECM. It is necessary to introduce high-pressure internal flushing mode, high-low-pressure composite pulse power supply, external abrasive particle assistance, and other methods to improve the electrochemical anode dissolution of SEDCM [19–21].

In this work, a machining system suitable for SEDCM was set up, and NaNO₃ electrolyte was added to deionized water to prepare a working fluid with ultra-low conductivity for SEDCM. Three different abrasive particles of aluminum, silicon carbide, and copper were added into the NaNO₃ solution to form a mixed working fluid of SEDCM. The effects of three different particles on material removal rate, tool wear rate, and surface roughness of SEDCM were investigated. Then, SiC particle with lower tool wear rate and better surface quality was selected as the available added abrasive to improve SEDCM. Moreover, the appropriate particle size of SiC abrasive was obtained through single factor test. The quality characteristics, viz., material removal rate, tool wear rate, and surface roughness, were optimized using grey relational grade, based on the Taguchi’s design of experiments. Finally, the optimal combination of process parameters such as peak current, pulse on time, abrasive concentration, and gap voltage of SEDCM was predicted and verified by experiments.

2 Experimental procedures

2.1 Experimental procedures

The experimental setup of SEDCM is shown in Fig. 1a. The whole processing system is mainly composed of lathe bed pillar, workbench, spindle head, control system, and working fluid circulation system. The spindle head is composed of servo feeding mechanism, guiding anti-twist mechanism, and auxiliary mechanism, which is used to control the discharge gap between workpiece and tool electrode. Connected with the spindle through a clamp, the tool electrode is used as the cathode, and the workpiece is used as the anode. Meanwhile, the workpiece clamping device is adsorbed on the machine tool worktable through a strong magnet, which can be driven by X and Y axes. During the machining, the workpiece is immersed in the working fluid, which is continuously fed to the machining zone to flush away the debris. In addition, the concentration distribution of workpiece fluid needs to be relatively uniform with the help of the agitator.
As the tool electrode is continuously feeding towards the machining end face, the axial gap between the tool electrode and the workpiece is usually less than the critical distance of spark discharge, which makes the spark discharge always exist in the axial gap. The spark discharge brings instantaneous high temperature, and workpiece material is quickly melted and removed. In addition, as the working fluid, the neutral salt solution with ultra-low conductivity still has electric conductivity, so that there is a certain degree of electrochemical dissolution, while the discharge erosion occurs in the axial gap. The introduction of added abrasives has the following effects: (1) Due to the micro-explosion effect of spark discharge, the added particles in the working fluid form abrasive jets [19], which hit the workpiece electrode at high speed as shown in Fig. 1b, and improve the surface quality of electrical discharge machining in SEDCM. (2) Due to the electric field polarization of the working fluid [18], added particles impact on the anode surface, destroy the oxide layer on the workpiece surface, and strengthen the anodic dissolution and macro leveling effect of electrochemical machining in SEDCM.

### 2.2 Experimental materials

The workpiece material is commercial Ti6Al4V alloy which is widely used in industries. Its chemical compositions are as follows: V 3.5–4.8%, Al 5.5–6.8%, Fe ≤ 0.30%, O ≤ 0.20%, C ≤ 0.10%, N ≤ 0.05%, H ≤ 0.015%, and Ti allowance, respectively. WEDM machine tool is used to cut the sample into 10×10×6 mm in dimensions, and the pretreatment is as follows: Firstly, ultrasonic cleaning with anhydrous ethanol for 10 min was applied to remove the oil stain on the sample surface; secondly, the samples were polished with diamond sandpaper (400#, 600#, 1000#, 1500#, and 2000# in turn) in order to remove the metamorphic layer generated by WEDM cutting. Finally, after ultrasonic cleaning for 10 min, the sample was taken out and dried at room temperature. Solid copper rods with the diameter of 8 mm and length of 140 mm were used as the tool electrodes of SEDCM.

NaNO₃ particles were added to deionized water with an electrical resistivity of 0.1–0.8 MΩ·cm, in order to prepare mixed solutions with electrical conductivity of 50, 300, 600, 1000, 1500, and 2500 μS/cm, respectively. Although the ions’ amount in such low resistivity zone is rather small, it still induces the slight conductivity of the working fluid. On the other hand, the voltage applied in this work is up to several tens of volts and helps to increase the current density in the working fluid. Consequently, as a bi-characteristic working fluid, the low-resistivity mixed solution can not only act as a weak current carrier during electrochemical reaction, but also be used for electrical discharge machining owing to its considerable dielectric strength.

Al, SiC, and Cu abrasive particles were added to the prepared NaNO₃ solution, respectively, and stirred by a magnetic stirrer, as the mixed working fluid of SEDCM. Some of the important thermophysical properties of three different particles are shown in Table 1.

### 2.3 Measurement and characterization

The response variables are the material removal rate (MRR), the tool electrode wear rate (TWR), and the surface roughness, characterized by the amplitude parameter of arithmetic mean deviation (Ra). MRR is expressed as material wear away from the Ti6Al4V alloy workpiece per unit time. TWR

#### Table 1 Thermophysical properties of added particles

| Properties | Al  | SiC | Cu  |
|------------|-----|-----|-----|
| Density (g/cm³) | 2.70 | 3.21 | 8.96 |
| Specific heat (cal/g·°C) | 0.215 | 0.180 | 0.092 |
| Heat conductivity (W/m·K) | 237 | 83.6 | 386.4 |
| Resistivity (μΩ·cm) | 2.83 | 1×10⁶ | 1.75 |
| melting point (°C) | 660 | 2700 | 1083 |

Fig. 1 SEDCM experimental setup (a), and schematic diagram of SEDCM assisted by added particles (b)
may be expressed as material wear away from the tool electrode per unit time. Initial and final weights of workpiece part and tool electrode were measured by an electronic weighing scale (JY3002, Yifen Scientific Instrument Co., Ltd, Shanghai). The measurements were repeated three times. In this work, MRR and TWR can be calculated by Eqs. (1) and (2), respectively.

\[
MRR = \frac{M_a - M_b}{t}
\]

(1)

where \(M_a\) and \(M_b\) are the mass (mg) of titanium alloy specimens before and after SEDCM, respectively, and \(t\) is the machining time(s) of SEDCM.

\[
TWR = \frac{m_a - m_b}{t}
\]

(2)

where \(m_a\) and \(m_b\) are the mass (mg) of the tool electrode before and after SEDCM, respectively.

Surface roughness \(Ra\) was measured with a portable measuring instrument of surface roughness (TR200, Time Yuanfeng Technology Co., Ltd, Beijing). Every part was measured at five different locations distributed along the workpiece surface machined by SEDCM. In addition, the surface morphology and recast layer morphology can be observed with the help of images of scanning electron microscope (Apreo SEM, FEI, USA).

3 Results and discussion

3.1 Effect of electrical conductivity of working fluid

As a bi-characteristic working fluid of SEDCM, the mixed \(\text{NaNO}_3\) solution not only provides the dielectric strength for sparks, but also the sufficient conductivity for electrochemical reaction. It is necessary to find out the proper conductivity of the working fluid. A group of experiments were carried out in respect of SEDCM in working fluids with different electrical conductivity (50, 300, 600, 1000, 1500, 2500 \(\mu\)S/cm), and experimental conditions can be found in Table 2. The input process parameters in all the experiments, such as peak current, pulse on time, pulse off time, and gap voltage, were set at 3 A, 30 \(\mu\)s, 25 \(\mu\)s, and 40 V, respectively.

Figure 2 shows the MRR, TWR, and \(Ra\) of SEDCM generated in the working fluids with different electrical conductivity under the experimental conditions shown in Table 2. It can be found that the MRR increases with the increase of the electrical conductivity from 50 to 300 \(\mu\)S/cm. When the electrical conductivity of the working fluid is 300 \(\mu\)S/cm, the MRR reaches to 0.26 mg/s. Afterwards, it follows a decreasing trend, as shown in Fig. 2a. According to Nguyen’s report [17], electrical conductivity is directly related to the electrochemical reaction. Increased electrical conductivity causes evolution of more electrochemical anodic dissolution. However, anodic dissolution is weaker than spark erosion for MRR of SEDCM. Furthermore, higher electrical conductivity will weaken the form of discharge sparks, which cannot remove large amount of material from the workpiece.

Effect of electrical conductivity of the working fluid on tool wear rate is illustrated in Fig. 2b. With increasing electrical conductivity, TWR is decreased. Especially, when electrical conductivity rises from 50 to 300 \(\mu\)S/cm, TWR decreases the fastest, by 61.25%. According to Zhang et al.’s report [18], discharge energy of SEDCM is related to electrical resistivity of the bi-characteristic working fluid. The discharge energy liberated during SEDCM not only melts and evaporates but also the tool electrode. Increase in electrical conductivity decreases discharge energy. Hence, tool wear rate is decreased.

In relation to Fig. 2c, the rising trend of \(Ra\) can be noticed when the electrical conductivity increases from 50 to 1500 \(\mu\)S/cm. Beyond 1500 \(\mu\)S/cm electrical conductivity, slight decline in roughness value is observed, due to the enhancement of electrochemical anodic dissolution. The higher electrical conductivity, the worse the stability of spark discharge, and the lower pressure between the gap, leading to less molten material removed from the workpiece surface. Consequently, more debris are remained at higher electrical conductivity. This results show that 1500 \(\mu\)S/cm electrical conductivity offers the worst surface finish.

3.2 Effect of added abrasive material

In order to improve SEDCM performance on titanium alloys, three different abrasive materials, including of \(\text{SiC}, \text{Al}, \text{and Cu}\), were added into above \(\text{NaNO}_3\) solution with the electrical conductivity of 300 \(\mu\)S/cm, respectively. Figures 3 and 4 show the MRR, TWR, \(Ra\), and surface morphologies of SEDCM generated in the bi-characteristic working fluids with different added abrasive materials, while peak current, pulse on time, pulse off time, and gap voltage are 6 A, 30 \(\mu\)s, 25 \(\mu\)s, and 40 V, respectively.

Figure 3a shows the effects of the abrasive materials on the MRR. It can be seen that Cu produces the greatest

| Table 2 | Experimental conditions and parameters of SEDCM |
|-----------------|-----------------|
| Parameters | Values |
| Peak current \(I_p\) (A) | 3 |
| Pulse on time \(T_{on}\) (\(\mu\)s) | 30 |
| Gap voltage \(U_g\) (V) | 40 |
| Pulse off time \(T_{off}\) (\(\mu\)s) | 25 |
| Machining polarity | + |
| Working fluid conductivity (\(\mu\)S/cm) | 50, 300, 600, 1000, 1500, 2500 |
MRR, and SiC the lowest. According to Tzeng and Chen’s reports [22], the spark gap for Cu is smaller than that for Al and SiC. There existed a slightly higher electrical power density and gas explosion pressure, which results in a stronger particle impact. On the other hand, the electrical conductivity of SiC is less than for both Al and Cu. A large number of SiC particles in the spark gap still tend to cause arcing instead of sparking [23]. Thus, SiC abrasive has the least improvement on material removal rate of SEDCM.

Figure 3b shows the effect of three particle materials on the TWR. It can be found that Cu has the largest TWR, followed by Al, and with SiC being the lowest. The reasons about SiC have been explained in the previous discussion. This trend is similar as the MRR results. As shown in Table 1, the density of Cu particle is higher than other two particles, which causes this particle to deposit at the bottom of the tank [24]. Although its spark gap is not improved, the reduced electrical resistivity of the working fluid enhances the ionization and spark frequency between the tool and workpiece. The increased spark frequency appears to make more discharge energy be transferred to the tool electrode, which brings out a higher TWR.

Figure 3c shows the effect of three particle materials on the Ra. In contrast to SEDCM with none added abrasive, three different abrasive materials can all improve surface roughness of the workpiece produced by SEDCM in the working fluid mixed with SiC, Al, and Cu particles, respectively. Due to the addition of abrasive particles, the discharge gap is enlarged. The widened discharge gap increases the spark heat area reducing the discharge density [25]. This facilitates the formation of uniformly distributed, wide, and shallow craters, as shown in Fig. 4. Therefore, surface quality is improved.

From Fig. 3c, it can be also found that SiC has the lowest Ra, followed by Al, and with Cu being the largest. Owing to high resistivity and thermal conductivity of SiC particle, breakdown voltage of discharge channel reduces, and heat dissipation rate is higher. Consequently, the discharge energy density will be inferior that produces small and shallow craters, leading to a comparatively smooth surface finish.

### 3.3 Effect of abrasive particle size

During a normal single electrical discharge of SEDCM assisted by added particles, the material removal mechanism for the addition of SiC particles is the combined effect of mechanical thrust driven by the gas explosion mainly from the working fluid evaporation and the impact by the suspended particles. It was found that the density, electrical resistivity, thermal conductivity, and size of SiC particles [23] were the important characteristics governing the machining efficiency in the SEDCM process.
A group of experiments were carried out in respect of SEDCM assisted by the SiC particle with different sizes (1, 5, 20, 50, 100 μm); some part experimental conditions can be found in Table 2. The input process parameters in all the experiments, such as peak current, pulse on time, pulse off time, and gap voltage, were set at 6 A, 30 μs, 25 μs, and 40 V, respectively. The effect of the particle size on the MRR, TWR, Ra, and surface morphologies is shown in Figs. 5 and 6.

It can be found that the proper addition of 5 μm particles helps to enhance the machining efficiency by further stabilizing the electrical discharge. The improvement in process stability results from a reasonably large gap size that reduces the arcing frequency through lower debris concentration. Figure 5a also shows a downward trend of MRR with the increase of particle size from 5 to 50 μm. This can be attributed to both a lower breakdown voltage and a higher possibility of abnormal discharge [24].

Figure 5b shows the effect of particle size on the tool wear rate. It can be seen that the particle size of 5 μm generates the greatest TWR. A higher or lower size of added particles reduces the TWR. This trend is similar as

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![Graphs and images showing MRR, TWR, Ra, and surface morphologies for different particle materials in SEDCM.](image-url)
the MRR results in Fig. 5a. Increasing particle size from 5 to 50 μm, the TWR becomes smaller, due to the combination of low electrical density, fewer particles striking, and less energy transferred to the tool electrode. However, the sinking particles will cover with the workpiece surface, when the gravity of SiC particle (100 μm) is greater than the suspension force of the working fluid. This phenomenon results in smaller spark gap and higher discharge energy density. Hence, the particle size of 100 μm causes an increased TWR.

Figure 5c shows the effect of particle size on the surface roughness. It can be found that the particle size of 50 μm (Fig. 6d) leads to a best improvement in the surface roughness, followed by 20 μm (Fig. 6c), 1 μm (Fig. 6a), and 5 μm (Fig. 6b), whereas particle size of 100 μm generates the highest Ra (Fig. 6e). The larger the particle size, the less the quantity of particles existing between the spark gap, the lower the impact frequency of added abrasives, and the more the debris near the discharge channel. On the contrary, in case of SEDCM assisted by added abrasive, SiC particles may be engaged in “polishing action” with the machined surface [19, 26], due to their higher density and hardness. As a result, the surface roughness of 50 μm particle size appears significantly lesser compared with other particle sizes, as shown in Fig. 6.
Parameter optimization

4.1 Experimental design

In order to further improve the machining characteristics of SEDCM, in this section, SiC abrasives with particles size of 50 μm were used added into the working fluid with electrical conductivity of 300 μS/cm conductivity. The L₉ (3³) orthogonal experiment table was used to design the experiment based on the Taguchi design method [27]. Process parameters such as peak current, pulse on time, particle concentration, and gap voltage were considered as the control factors. Meanwhile, the MRR, TWR, and Ra were selected as the response characteristics. The factor and levels of the orthogonal experiment are shown in Table 3. All experiments were conducted using plan of experiments as shown in Table 4, and corresponding response characteristics are also given in Table 4.

4.2 Optimization method

As a multi-objective optimization method, grey relational analysis is used to optimize the three performance measures, i.e., MRR, TWR, and Ra simultaneously to achieve the optimum condition. There are two criteria that correspond to the response variables, i.e., lower-the-better and higher-the-better criteria. In this work, MRR corresponds to the latter; TWR and Ra correspond to the former.

After normalizing the experimental data in Table 4, a standardized data can be established. The coefficient of grey relational analysis is determined to examine the correspondence between theoretical and actual statistics. Then, averaging the grey relational coefficients that corresponds to response measured, the overall grey relational grade is obtained. Finally, the grey relational grade of three responses is calculated and presented in Table 5.

4.3 Grey relational analysis

Furthermore, the grey relational analysis should be performed for identifying the significant factors for optimizing the process parameters. According to the grey relation theory [28], the three responses in Table 5 are then converted into a single response, named grey relational grade. The mean values of grey grades of process parameters at each level are determined as shown in Table 6. This table shows the optimum condition for higher MRR, lower TWR, and Ra. It can be found that the peak current is most significant factor followed by the particle concentration and pulse on time, while the least significant is the gap voltage. From Table 6, it can be seen that the optimal parameter combination for the machining characteristics is A₁B₁C₂D₂, which

| S. No. | A | B | C | D | MRR | TWR | Ra |
|-------|---|---|---|---|-----|-----|----|
| 1     | 1 | 1 | 1 | 1 | 0.0178 | 0.0098 | 0.817 |
| 2     | 1 | 2 | 2 | 2 | 0.0272 | 0.0080 | 2.703 |
| 3     | 1 | 3 | 3 | 3 | 0.0427 | 0.0127 | 4.001 |
| 4     | 2 | 1 | 2 | 3 | 0.0545 | 0.0100 | 3.226 |
| 5     | 2 | 2 | 3 | 1 | 0.0930 | 0.0185 | 3.863 |
| 6     | 2 | 3 | 1 | 2 | 0.0637 | 0.0123 | 4.406 |
| 7     | 3 | 1 | 3 | 2 | 0.0940 | 0.0217 | 3.934 |
| 8     | 3 | 2 | 1 | 3 | 0.0968 | 0.0202 | 3.717 |
| 9     | 3 | 3 | 2 | 1 | 0.1048 | 0.0125 | 4.138 |

| S. No. | MRR | TWR | Ra |
|--------|-----|-----|----|
| 1      | 0.8912 |     |     |
| 2      | 0.9407 |     |     |
| 3      | 0.5417 |     |     |
| 4      | 0.6453 |     |     |
| 5      | 0.3947 |     |     |
| 6      | 0.4781 |     |     |
| 7      | 0.3683 |     |     |
| 8      | 0.3904 |     |     |
| 9      | 0.4364 |     |     |

| Table 3 | Control factors and levels of the orthogonal experiment |
|---------|-------------------------------------------------------|
| Process parameters | Level 1 | Level 2 | Level 3 |
| Peak current A (A) | 1.5 | 3 | 4.5 |
| Pulse on time B (μs) | 15 | 30 | 60 |
| Concentration of SiC particle C (g/L) | 0 | 5 | 12 |
| Gap voltage D (V) | 30 | 40 | 50 |

| Table 4 | Experimental results of MRR, TWR, and Ra |
|---------|----------------------------------------|
| S. No. | A | B | C | D | MRR | TWR | Ra |
|        |   |   |   |   |     |     |    |
| 1      | 1 | 1 | 1 | 1 | 0.0178 | 0.0098 | 0.817 |
| 2      | 1 | 2 | 2 | 2 | 0.0272 | 0.0080 | 2.703 |
| 3      | 1 | 3 | 3 | 3 | 0.0427 | 0.0127 | 4.001 |
| 4      | 2 | 1 | 2 | 3 | 0.0545 | 0.0100 | 3.226 |
| 5      | 2 | 2 | 3 | 1 | 0.0930 | 0.0185 | 3.863 |
| 6      | 2 | 3 | 1 | 2 | 0.0637 | 0.0123 | 4.406 |
| 7      | 3 | 1 | 3 | 2 | 0.0940 | 0.0217 | 3.934 |
| 8      | 3 | 2 | 1 | 3 | 0.0968 | 0.0202 | 3.717 |
| 9      | 3 | 3 | 2 | 1 | 0.1048 | 0.0125 | 4.138 |
represents 1.5 A peak current (level 1), 15 μs pulse on time (level 1), 5 g/L particle concentration (level 2), and 40 V gap voltage (level 2).

### 4.4 Verification experiment

However, from Table 5, it can be observed that the maximum and third highest grey relational grades are for 2nd experiment (A1B2C2D2) and 4th experiment (A2B1C2D3), respectively. Furthermore, the optimal parameter combination (A1B1C2D2) is not in the orthogonal experiment shown in Table 4. It is necessary to verify the optimal parameter combination through additional experiments. The verification experiments were carried out and repeated 5 times, and the experiment results are shown in Fig. 7.

Compared with A2B1C2D3, A1B1C2D2 reduces the MRR from 3.23 to 2.58 mg/s, and the TWR from 0.01 to 0.007 μm. Meanwhile, the Ra is improved from 0.055 to 0.027 μm. The improvement rates of the MRR, TWR, and Ra are 51%, 23%, and 21%, respectively. In conclusion, it is clearly shown that the multiple response characteristics in SEDCM assisted by added abrasives are significantly improved through the integrated Taguchi-GRA (grey relational analysis) optimization method.

### 5 Conclusions

In this work, the quality criteria (MRR, TWR, and Ra) of SEDCM under NaNO₃ solution conditions with added abrasive particles were investigated experimentally. The effect of electrical conductivity of mixed working fluid, abrasive material, and abrasive size on the material removal rate, tool wear rate, and surface roughness was analyzed. In addition, the optimal combination of process parameters such as peak current, pulse on time, particle concentration, and gap voltage was obtained using the integrated Taguchi-GRA optimization method. The following conclusions can be drawn.

1. The material removal rate increases firstly and decreases subsequently with increasing the electrical conductivity of working fluids from 50 to 2500 μS/cm. A higher electrical conductivity reduces the WRR, and increases the tool wear rate and surface roughness. For the investigated range, the optimal electrical conductivity of the working fluid is 300 μS/cm under the same other process parameters and experimental conditions.

2. Of the added abrasives investigated, Cu particle produces the largest material removal rate and tool wear rate, followed by Al, with SiC particle producing the smallest. As for the surface roughness, SiC particle has the lowest, followed by Al, with Cu particle having the greatest.

3. SiC particle size of 5 μm produces the largest material removal rate and tool wear rate under the same other process parameters and experimental conditions. Furthermore, the particle size of 50 μm produces the least MRR, TWR, and Ra. The particle size of 100 μm produces the highest surface roughness.

4. The optimal parameter combination for the machining characteristics of SEDCM assisted by 50 μm SiC particles is obtained by integrating the Taguchi design and GRA method. The optimum levels for process parameters are peak current 1.5 A, pulse on time 15 μs, particle concentration 5 g/L, and gap voltage 40 V. The verification experiment results indicate that the machining characteristics, especially tool wear rate and surface roughness, are significantly improved.

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Code availability All software application is available.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication We confirm that this work is original and has not been published elsewhere, nor is currently under consideration for publication elsewhere. All the authors listed have agreed to publish the manuscript that is enclosed.

Conflict of interest The authors declare no competing interests.

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