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

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Research Article

Keywords: Electrical discharge machining (EDM), electrochemical machining (ECM), hybrid machining, tool electrode material, titanium alloy

Posted Date: May 4th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1527980/v1

Abstract

In view of the difficult machining characteristics of titanium alloys and the limitations of EDM/ECM serial machining, a study of parallel machining of EDM and ECM with the aid of abrasive particles was carried out using a low conductivity $NaNO_3$ salt solution as the working medium. Firstly, the influences of the electrical conductivity of working medium, abrasive material and abrasive particle size on material removal rate, electrode loss rate, surface roughness and surface microstructure were analyzed. Then, the material removal rate, electrode loss rate and surface roughness were taken as evaluation indexes, and the multi-process objectives were transformed into a single evaluation index by orthogonal test and grey correlation analysis. The optimal combination of the main process parameters including peak current, pulse width, abrasive particle concentration and gap voltage was obtained, and the experimental verification was carried out. The results show that under the same electrical parameters and machining conditions, the comprehensive machining effect is better when the conductivity of working medium is 300 μS/cm. Compared with Cu and Al abrasives, although SiC abrasives have the lowest material removal rate, the electrode loss rate and surface roughness are the smallest; according to the analysis of multi-objective grey correlation degree, the optimal combination of process parameters for EDM and ECM parallel machining assisted by SiC abrasive particles with particle size of 50 μm is as follows: peak current 1.5 A, pulse width 15 μs, abrasive concentration 5 g/L and gap voltage 40 V. Compared with other parameter combinations, the electrode loss rate, surface roughness and surface morphology are improved obviously under this parameter combination.

1 Introduction

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

Because EDM and ECM do not directly contact with the workpiece and are not limited by the hardness and strength of the material, it is very suitable for titanium alloy and other difficult process metal materials [7−9]. However, EDM will produce a large number of holes, micro-cracks and recasting layer on the workpiece surface. Although the surface quality of ECM is high, there is no recasting layer and microcrack, but there are some problems such as stray corrosion and low machining efficiency.

To solve the above problems, researchers try to combine ECM with EDM [10−12]. The advantages of EDM and ECM were fully utilized to improve the machining performance and quality of titanium alloy. Masuzawa et al. first performed WEDM wire-cutting on SKD11, SKD61, SUS304 and brass [13], and then used the remaining part as the supporting electrode of ECM to make $NaNO_3$ electrolyte flow through the micro-gap generated by WEDM. It is found that the surface roughness of workpiece decreases from 20 μm to 2–4 μm in a relatively short time. Ramasawmy et al. used potassium nitrate, potassium nitrate-nitric acid, sodium nitrate-nitric acid and other electrolytes conduct ECM on the workpiece surface respectively after EDM [14]. The results show that the acidic electrolyte can obtain a lower surface roughness, but $NaNO_3$ neutral electrolyte can also obtain a better surface quality as long as the appropriate current density is used. It can be seen that the pits and recast layers generated by EDM discharge are removed by the macro leveling of electrochemical anodic dissolution, this could reduce surface roughness and improve surface quality. However, the combination of EDM discharge and ECM dissolution mentioned above belongs to serial processing [15–16], which often requires the replacement of electrode or working fluid, which makes it difficult to control the machining process and ensure the consistency of machining, and the machining efficiency and accuracy are not ideal.

In order to overcome the above problems in EDM and ECM serial processing, Nguyen et al. used deionized water as the working fluid to make EDM and ECM be carried out simultaneously [17], to improve surface quality and machining accuracy.It is found that the material removal mechanism changes from simple EDM to parallel EDM and ECM (Simultaneous EDM and ECM, SEDCM)at low feed rate. In addition, Zhang et al. conducted parallel EDM and ECM processing of fine group hole using low conductivity salt solution and tubular electrode [18], which confirmed that SEDCM could not only enhance surface quality, but also significantly reduce electrode loss rate.

In the process of SEDCM, the energy of material removal 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 medium, the processing mechanism, processing efficiency and action mechanism of the tool electrode of SEDCM are obviously different from the simple superposition of EDM and ECM. How to select and allocate the working fluid which can be used for electrochemical dissolution without hindering the discharge of EDM, and how to give full play to the effect of electrochemical anodic dissolution while maintaining the stability of discharge channel and discharge state is still a problem that needs to be considered in the current parallel EDM and ECM. In addition, in order to give consideration to EDM discharge, the conductivity of SEDCM working fluid must be less than pure ECM electrolyte, which is bound to affect the efficiency of ECM. Therefore, methods such as high-pressure internal flushing mode, high and low voltage composite pulse power supply, and auxiliary abrasive particles should be adopted to strengthen electrochemical anodic dissolution in parallel machining [19–21].

Based on this, a test device for SEDCM processing of Ti6Al4V titanium alloy was built, and $NaNO_3$ electrolyte was added to deionized water to prepare ultra-low conductivity working fluid suitable for SEDCM. Secondly, aluminum, silicon carbide, copper and other particles were used as auxiliary abrasive medium to SEDCM processing of titanium alloy. The effects of three different particles on material removal rate, electrode loss rate and surface roughness of parallel processing were analyzed. On this basis, the particles with low electrode loss rate and good surface quality were selected as the auxiliary medium of external abrasive particles, and the appropriate particle size was selected through a single factor test. Finally, with material removal rate, electrode loss rate and surface roughness as the evaluation indexes, the optimal combination of the main process parameters including peak current, pulse width, abrasive particle concentration and discharge voltage was obtained by orthogonal test and grey correlation analysis, and the experimental verification was carried out.

2 Test Method

2.1 Test apparatus

The SEDCM processing device is shown in **Fig. 1**. The whole processing system is mainly composed of lathe bed pillar, workbench, spindle head, control system and working fluid circulation system, etc. The tool electrode is connected with the cathode, the specimen to be processed is connected with the anode, and the spindle head is used to control the discharge gap between the workpiece and the tool electrode, including servo feeding mechanism, guiding anti-twist mechanism and auxiliary mechanism; the workpiece clamping device is adsorbed on the machine tool worktable which can be driven by X and Y axes through a strong magnet, and the electrode is connected to the spindle through a clamp. In addition, the concentration distribution of workpiece medium is relatively uniform by means of stirrer.

During SEDCM machining, as the tool electrode is continuously feeding towards the machining end face, the end clearance between the tool electrode and the workpiece is usually less than the limit distance of spark discharge, which makes the spark discharge always exist in the end clearance. The workpiece material is quickly removed by instantaneous high temperature melting caused by spark discharge. In addition, as the working fluid, the neutral salt solution with ultra-low conductivity still has electric conductivity, which makes the electrochemical dissolution exists to a certain extent while the discharge is removed in the end face clearance. The introduction of external particles has the following effects: Due to the micro-explosion effect of spark discharge, the external particles in the working fluid form abrasive jet, which hit the workpiece electrode at high speed and improves the machining quality of EDM. Due to the electric field polarization of ECM, the external particles impact on the anode surface, destroy the oxide layer on the workpiece surface, and strengthen the anodic dissolution and macroleveling effect of ECM.

2.2 Test materials

Using Ti6Al4V titanium alloy made by Shanghai Hangbo Alloy Group, the mass percentages of each element are: V 3.5–4.8%, Al 5.5–6.8%, Fe $\leq$ 0.30%, O $\leq$ 0.20%, C $\leq$ 0.10%, N $\leq$ 0.05%, H $\leq$ 0.015% and Ti allowance respectively. WEDM machine tool was used to cut the sample into 10×10×6 mm, and the pretreatment was as follows: Firstly, anhydrous ethanol was used for ultrasonic cleaning for 10 min to remove oil stains on the surface of the sample; secondly, the samples were polished with 400, 600, 1000, 1500 and 2000 mesh diamond sandpaper successively to remove the metamorphic layer generated by WEDM cutting. Then ultrasonic cleaning for 10min, after taking out and dry it for later use.

The tool electrode adopts solid red copper rod with diameter of 8 mm and length of 140 mm respectively. $NaNO_3$ electrolyte particles were added to deionized water with electrical resistivity of 0.1–0.8 MΩ•cm, to prepare sodium nitrate solutions with electrical conductivity of 50, 300, 600, 1000, 1500, 2500 μS/cm as the working medium of SEDCM. The salt solution can provide both dielectric strength for EDM and conductivity for electrochemical reaction of ECM.

On this basis, silicon carbide, aluminum and copper particles as shown in **Table 1** are added to the prepared ultra-low conductivity working solution respectively, and the external abrasive particles are evenly distributed in the neutral salt solution with the help of magnetic stirrer to form the mixed working solution.

Table.1 Material properties of applied particles

Properties	Al	SiC	Cu
Density (g/cm^3)	2.70	3.21	8.96
Hardness (HB)	95		40
Heat conductivity (W/m•K)	237	83.6	386.4
Resistivity (μΩ•cm)	2.83	1×10^9	1.75
melting point (℃)	660	2700	1083

2.3 Test characterization

The material removal rate MRR uses the ratio of the difference in weight of the specimen before and after processing to the processing time, i.e.

$$MRR = \frac{M_b - M_a}{t}$$

1

Where, M_b and M_a are the mass (mg) of titanium alloy specimens before and after EDM and ECM parallel processing respectively, and t is the time (s) of SEDCM processing.

The electrode loss rate is the main parameter to measure the degree of electrode loss in the machining process. The ratio of the mass difference between the tool electrode before and after SEDCM processing and the processing time, i.e

$$TWR = \frac{m_b - m_a}{t}$$

2

Where, m_a and m_b are the mass (mg) of the tool electrode before and after SEDCM processing.

The mass of tool electrode and workpiece electrode before and after machining is measured by JY3002 electronic balance produced by Shanghai Puchun Metrology Instrument Co., LTD. The conductivity of working fluid was measured and characterized by A DDS-11A conductivity meter produced by Shanghai Leici Company. The Surface roughness Ra was measured by TR200 handheld roughness measuring instrument. In order to reduce the test error, the surface of each specimen was measured 5 times and its arithmetic mean value was taken as the final surface roughness value. In addition, the surface morphology and recast layer morphology of titanium alloy after SEDCM processing were observed by Apreo S field emission environment scanning electron microscope produced by FEI Company of the United States.

3 Results And Discussion

3.1 Influence of working fluid conductivity

As the working liquid of SEDCM, ultra-low conductivity salt solution needs to ensure that it has certain insulation, which can provide certain dielectric strength for spark discharge, and certain conductivity, which can ensure the electrochemical dissolution reaction. Therefore, it is necessary to choose the conductivity of working fluid reasonably.

Table.2 Parameters and conditions of SEDCM

Parameters	Value
Peak current I_p(A)	3
The pulse width T_{on}(μs)	30
Open circuit voltage U_g(V)	40
Pulse interval T_{off}(μs)	25
Machining polarity	+
Working fluid conductivity (μS/cm)	50, 300, 600, 1000, 1500, 2500

According to the preliminary basic test, as shown in **Table 2**, the peak current, pulse width, open circuit voltage, pulse interval were fixed at 3 A, 30 μs, 25 μs and 40 V respectively. The content of electrolyte $NaNO_3$ was changed, and the copper electrode material was analyzed. During SEDCM processing, material removal rate, electrode loss rate and surface roughness are affected by the working fluid conductivity, as shown in **Fig. 2**.

It can be seen from **Fig. 2a** that in the range of 50–300 μS/cm, the material removal rate increases gradually with the increase of conductivity. When the conductivity is in the range of 300 ~ 2500 μS/cm, the material removal rate decreases gradually. This is because: in SEDCM processing, most of the workpiece material removal is generated by spark discharge, while the material removal caused by electrochemical anodic dissolution is relatively weak, mainly used for the dissolution and removal of recast layer. When the conductivity is 300 μS/cm, EDM plays the dominant role, the spark discharge is relatively stable, and the material removal rate reaches the highest value. When the electrical conductivity of working fluid is too high, although the dissolution and removal effect of ECM is strengthened, the machining process is prone to arc or short circuit. Violent spark discharge will produce more bubbles, which seriously affects the machining stability of EDM, thus reducing the machining accuracy and material removal speed. Therefore, salt solution with high conductivity does not have a positive effect on material removal rate.

Fig. 2b shows the changing trend of electrode loss rate with the conductivity of working fluid. It can be seen from the figure that with the gradual increase of the conductivity of the working fluid, the loss rate of the tool electrode shows a decreasing trend, especially when it increases from 50 μS/cm to 300 μS/cm, the TWR decreases fastest, decreasing by 61.25%. The reason may be that a single pulse discharge has higher energy when electrical conductivity is low, which increases the sputtering adhesion of the workpiece material to the tool electrode. In addition, the increase of the conductivity of the working fluid leads to the change of material removal mechanism from discharge removal to electrochemical dissolution, which accelerates the transfer of workpiece debris. The tool electrode loss rate during SEDCM machining was significantly reduced by the combined effect of workpiece debris sputtering and electrochemical dissolution transfer.

The surface roughness of titanium alloy specimens processed by SEDCM in working fluids with different electrical conductivity is shown in **Fig. 2c**. As can be seen from the figure, the workpiece surface roughness increases gradually with the increase of electrical conductivity of working fluid, and decreases slightly when it exceeds 1500 μS/cm. This is because: with the increase of electrical conductivity, the spark discharge stability becomes worse, the increase of electrocorrosion products and it is difficult to throw out from the electrode gap, and then melt and solidify on the workpiece surface, the surface roughness value increases. When the conductivity exceeds 1500 μS/cm, spark discharge decreases, ECM plays the leading role, part of EDM products are electrochemically dissolved, and the surface roughness value decreases slightly.

Because the purpose of parallel EDM and ECM is to improve the processing efficiency and obtain higher surface quality, based on the above analysis, $NaNO_3$ solution with conductivity of 300 μS/cm is selected as the working liquid of SEDCM.

3.2 Effect of abrasive material

Silicon carbide, aluminum, copper and other particles with the same size were added to the neutral salt solution with conductivity of 300 μS/cm to form the mixed working solution. Fix the peak current, pulse width, pulse interval and open circuit voltage in **Table 2** at 6 A, 30 μs, 25 μs and 40 V respectively, carry out SEDCM processing on titanium alloy, and analyze the influence of external abrasive particles of different materials on material removal rate, electrode loss rate and surface roughness under the same electrical parameters and processing conditions, as shown in **Fig. 3**.

Figure 3a and 3b show the material removal rate and electrode loss rate of EDM and ECM under different abrasive materials. It can be found from the figure that the material removal rate and electrode loss rate after the addition of SiC and Al abrasive particles are lower than the processing effect of SEDCM without the addition of abrasive particles. Among them, SiC abrasive particle assisted SEDCM has the lowest material removal rate and electrode loss rate. According to **Table 1**, SiC is a semiconductor material, and its resistivity is much higher than that of Al and Cu metals, that is SiC has the worst conductivity. Due to the certain conductivity of $NaNO_3$ neutral salt solution, the addition of SiC strengthens the insulation of the mixed working solution, reduces the spark discharge frequency and electrochemical anodic dissolution in SEDCM, resulting in the decrease of material removal rate and electrode loss rate. From the perspective of inter pole energy, charged particles collide with the suspended abrasive particles between the poles and consume part of the energy in the process of running to the poles, resulting in the reduction of the energy distributed in the two poles, thus reducing the erosion of the workpiece material.

In addition, the material removal rate and electrode loss rate after the addition of Cu particles are the largest, which is higher than that of SEDCM without abrasive particles. This is because: on the one hand, Cu has good conductivity, which can aggravate the electric field distortion and is more conducive to spark discharge and electrochemical anodic oxidation reaction; on the other hand, the density of Cu is the largest and the relative molecular weight is the highest, that is, the suspension of Cu particles in the mixed working fluid is the worst. Due to the influence of particle precipitation characteristics, most Cu particles are deposited at the bottom of the dielectric fluid. Compared with SiC and Al, Cu particles have a weak effect on the increase of the gap size between the two poles, but under the micro explosion effect of spark discharge, The particle has the strongest jet erosion on the workpiece and tool electrode, that is, the material removal rate and electrode loss rate are the largest.

As can be seen from **Fig. 3c**, the Ra value of SEDCM surface after any particle addition is lower than the surface roughness before particle addition. On the one hand, due to the addition of abrasive particles, the discharge gap between the two poles increases and the dielectric cycle accelerates, which is conducive to spark discharge erosion and the discharge of electrochemical dissolution products, and reduce the occurrence of bad inter pole phenomena such as short circuit and arc discharge; on the other hand, the mixed working fluid produces micro explosion phenomenon and bubbles under the high temperature of spark discharge, and the abrasive particles impact the surface materials of the workpiece under the micro explosion effect and electrode polarization.

It can also be found from the figure that among the three abrasive materials, the surface roughness of SEDCM assisted by SiC is the lowest, Al at the second place, and Cu is the highest. The reason may be that the insulation strength of working fluid mixed SiC abrasive particles is the highest, which improves the unstable conductive environment of working medium. The addition of SiC particles increases the discharge gap, expands the discharge channel and reduces the breakdown voltage. Only a small part of molten metal splashes out, and the rest extends around the discharge channel to form shallow discharge pits and obtain lower surface roughness; the settlement of Cu particles will lead to the random distribution of conductive particles on the workpiece surface, deteriorate the inter electrode environment, and easily lead to the phenomenon of concentrated discharge, so as to reduce the machining quality of the workpiece surface.

3.3 Effect of abrasive particle size

The addition of abrasive particles makes the working medium of salt solution change from one phase to two phases, and the single pulse discharge channel is dispersed into multiple channels; the polarization charge generated by the particles in the electric field causes the distortion of the nearby electric field, forms a superimposed electric field and increases the discharge channel. The effects of abrasive particles with different particle sizes on electric field and discharge channel are also different. Therefore, SiC with the best surface quality and the lowest electrode loss rate of SEDCM in **Fig. 3** is used as the additional abrasive auxiliary medium to fix the electrical parameters peak current, pulse width, pulse interval and open circuit voltage at 6 A, 30 μs, 25 μs and 40 V respectively, carry out SEDCM processing on titanium alloy, and analyze the influence of SiC abrasive particles with different particle sizes on material removal rate, electrode loss rate and surface roughness under the same electrical parameters and processing conditions, as shown in **Fig. 4**.

It can be seen from **Fig. 4a and 4b** that the SiC abrasive particle material removal rate and electrode loss rate with particle size of 5 μm are the largest, while the material removal rate and electrode loss rate with particle size of 50 μm are the smallest. This is because the expansion of discharge gap is closely related to the particle size, shape and concentration in addition to the material properties of particles in the working medium; the larger the particle size is, the more energy the particles consume in the process of collision with other high-speed charged particles, the less energy allocated to the workpiece and electrode, and the lower the material removal rate and electrode loss rate; when the particle size reaches 100 μm, the gravity of the particles is much greater than the suspension force of the working fluid medium. Part of the abrasive particles cover the surface of the workpiece, and the other quickly sinks into the bottom of the working fluid, which is difficult to suspend through the mixing device, which increases the material removal rate and electrode loss rate.

As shown in **Fig. 4c**, the surface roughness value of the specimen processed by 50 μm abrasive particle assisted SEDCM is the lowest, while the surface roughness value is the highest when the particle size is 100 μm.

This is because: on the one hand, the smaller the particle size is, the more number of particles in the working medium with the same concentration, thus lead to the distortion of inter electrode field strength, and increase the discharge gap, reduce the discharge energy of a single pulse; the expansion of discharge gap makes it is easy to throw away the corrosion products of molten metal between electrodes. The single pulse discharge energy decreases and the discharge traces are large and shallow, so as to obtain the workpiece surface with less surface attachments and high surface finish, as shown in **Fig. 5c and 5d**. However, when the particle size exceeds 100 μm, due to the large size and weight of particles, it is very easy to form precipitation in the discharge gap area, resulting in new spark discharge inducer, causing discharge concentration or short circuit, destroying normal spark discharge, overlapping discharge pits and forming deep discharge corrosion pits, which makes the surface quality of SEDCM worse, as shown in **Fig. 5e**. On the other hand, under the micro explosion effect of spark discharge with the same energy, the smaller the abrasive particle size, the worse the impact erosion effect on the surface of titanium alloy specimen, the smaller removal amount of EDM recasting layer and ECM oxidation products, and the worse surface quality, as shown in **Fig. 5a and 5b**. Based on the above analysis, the particle size should be 50 μm.

4 Optimization Of Test Parameters

4.1 Orthogonal test

According to the above analysis, in the $NaNO_3$ salt solution with 300 μS/cm conductivity, the 50 μm silicon carbide particles play a positive role in improving the performance of parallel EDM and ECM. The sedcm assisted by abrasive particles is not only affected by electrical parameters, but also related to abrasive particle concentration. In order to deeply study the influence of process parameters on SEDCM performance in the machining process, considering the interaction among process parameters, taking peak current, pulse width, abrasive particle concentration and gap voltage as independent variables and material removal rate, electrode loss rate and surface roughness Ra value as dependent variables, an orthogonal experimental table as shown in **Table 3** is designed, and the test results are shown in **Table 4**.

Table.3 Process parameters and level table

Process parameters	1	2	3
Peak current A(A)	1.5	3	4.5
Pulse width B(μs)	15	30	60
Abrasive particle concentration C(g/L)	0	5	12
Gap voltage D(V)	30	40	50

Table.4 Orthogonal test results

Serial number	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

4.2 Optimization method

Table.5 Grey correlation coefficient and grey correlation degree value				
Serial number	*MRR*	*TWR*	*Ra*	Grey correlation degree
1	1	0.7919	0.8818	0.8912
2	0.8222	1	1	0.9407
3	0.6360	0.5931	0.3961	0.5417
4	0.5424	0.7740	0.6194	0.6453
5	0.3665	0.3948	0.4233	0.3947
6	0.4866	0.6143	0.3333	0.4781
7	0.3628	0.3333	0.4089	0.3683
8	0.3551	0.3596	0.4565	0.3904
9	0.3333	0.6035	0.3724	0.4364

The data in **Table 4** are processed by grey correlation analysis. It is a method to describe the strength, size and order of the relationship among factors with the order of grey correlation [21–22], which could comprehensively consider MRR, TWR and Ra. So as to obtain the optimal combination of process parameters, the steps are as follows: firstly, determine the comparison sequence, dimensionless process it, and then calculate the grey correlation coefficient respectively to obtain the grey correlation degree, as shown in **Table 5**, then analyze the advantages. That is transform the optimization problem of multiple process objectives into the optimization problem of single grey correlation degree, so as to realize the optimization of multiple process objectives and obtain the optimized parameter combination scheme.

4.3 Correlation analysis

For the grey correlation coefficients of four process parameters, three different levels of peak current, pulse width, abrasive particle concentration and gap voltage in **Table 5**, and a total of 9 groups of parameter combinations, multi process objective grey correlation analysis on material removal rate MRR, electrode loss rate TWR and surface roughness Ra is carried out. The results are shown in **Table 6**.

According to the grey correlation theory, the level with high grey correlation degree is the best level for the analysis of multiple process objectives. It can be found from **Table 6** that the grey correlation order of peak current to comprehensive process index is $r_{1.5\ \mathrm{A}}> r_{3\mathrm{A}}> r_{4.5\ \mathrm{A}}$; the grey correlation order of pulse width affecting the comprehensive process index is $r_{15\ \mu\mathrm{s}}> r_{30\ \mu\mathrm{s}} > r_{60\ \mu\mathrm{s}}$; the grey correlation order of the effect of abrasive particle concentration on the comprehensive process index is: $r_{5\ \mathrm{g/L}}> r_{0\ \mathrm{g/L}}> r_{12\ \mathrm{g/L}}$; the grey correlation order of gap voltage affecting the comprehensive process index is $r_{40\ \mathrm{V}}> r_{30\ \mathrm{V}}> r_{50\ \mathrm{V}}$. Therefore, after the grey correlation analysis of multiple process objectives, the optimal combination of process parameters is: peak current, pulse width, abrasive particle concentration and gap voltage are 1.5 A, 15 μs, 5 g/L and 40 V respectively. In addition, through the range analysis in **Table 6**, it can also be found that the peak current has the greatest comprehensive impact on the material removal rate MRR, electrode loss rate TWR and surface roughness Ra, and the discharge voltage has the least impact.

Table.6 Average correlation coefficient of multiple process objectives

Level	*A*	*B*	*C*	*D*
1	0.7912	0.6349	0.5866	0.5741
2	0.5060	0.5753	0.6741	0.5957
3	0.3984	0.4854	0.4349	0.5258
Range	0.3928	0.1495	0.2392	0.0699

4.4 Experimental verification

Through the above grey correlation analysis, the best process parameter of SiC abrasive particle assisted the sedcm processing, namely $A_1B_1C_2D_2$, is obtained. The optimized process parameters are used for the sedcm processing experiment, and the test results are compared with the processing results of group 2 parameter combination $A_1B_2C_2D_2$ and group 4 parameter combination $A_2B_1C_2D_3$ with the highest grey correlation in **Table 5**, as shown in **Fig. 6**.

Compared with $A_2B_1C_2D_3$, $A_1B_1C_2D_2$ reduces the plasma diameter in spark discharge and reduces the amount of erosion of workpiece materials due to its low pulse width. The material removal rate of $A_1B_1C_2D_2$ decreased by 51%, the electrode loss rate and surface roughness decreased by 23% and 21%, respectively. Similarly, compared with the second group of parameter combination $A_1B_2C_2D_2$, the material removal rate of $A_1B_1C_2D_2$ reduced by 1.5%, but the electrode loss rate and surface roughness Ra value are reduced by 3.8% and 4.6% respectively.

5 Conclusion

Taking Ti6Al4V titanium alloy as the machining object and the low conductivity $NaNO_3$ mixed salt solution with abrasive particles as the working medium, the parallel machining of EDM and ECM assisted by abrasive particles is carried out. The effects of working fluid conductivity, abrasive particle material and abrasive particle size on material removal rate, electrode loss rate and surface roughness are deeply analyzed. The main process parameters such as peak current, pulse width, abrasive particle concentration and gap voltage are optimized. The conclusions are as follows:

(1) In the range of 50 ~ 2500 μS/cm, with the increase of conductivity, the material removal rate increases firstly and then decreases; if the conductivity is too high, the material removal rate decreases, and the electrode loss rate and surface roughness increase significantly; under the same electrical parameters and processing conditions, the comprehensive processing effect is better when the conductivity of working medium is 300 μS/cm.

(2) Among the three abrasive materials, SiC has the lowest material removal rate and electrode loss rate, while Cu has the highest material removal rate and electrode loss rate; the surface roughness under the assistance of SiC is the lowest, Al at the second place, and Cu is the highest.

(3) Under the same electrical parameters and processing conditions, the material removal rate and electrode loss rate of SiC abrasive particles with particle size of 5 μm are the largest, the material removal rate, electrode loss rate and surface roughness value of 50 μm particle size are the smallest, and the surface roughness value of 100 μm particle size is the highest.

(4) Through multi-objective grey correlation analysis, the optimal combination of process parameters of 50 μm SiC abrasive particle assisted SEDCM is obtained, that is: peak current 1.5 A and pulse width 15 μs. Abrasive concentration 5 g/L, gap voltage 40 V; compared with the other two parameter combinations, the electrode loss rate, surface roughness and surface morphology of the optimal process parameter combination have been significantly improved.

Declarations

Acknowledgements The authors would like to acknowledge the editors and the anonymous referees for their insightful comments.

Availability of data and materials All data and materials are available.

Code availability All software application are available.

Author contribution Jianbing Meng: Conceptualization, writing original draft. Shuaike Wang: Conceptualization, writing review and editing, project administration. Qingyi Guan: Methodology. Xiaojuan Dong: Data curation. Hongmei Li: Investigation. Li Li: Supervision. Guoyong Zhao: project administration. Yugang Zhao: Supervision.

Funding This work was supported by the Natural Science Foundation of Shandong Province [ZR2021ME159], and the National Natural Science Foundation of China [No. 51875328].

Ethical approval This article does not contain any studies with human participants performed by any of the authors.

Consent to participate The work was conducted with no human test subjects.

Consent to publication The work has consent to publish.

Conflict of interest The authors declare no competing interests.

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Figures

Figure 1

Abrasive grain assisted SEDCM processing device and its schematic diagram. (a) SEDCM processing device diagram (b) Schematic diagram of particle assisted SEDCM processing

Figure 2

Influence of working fluid conductivity on SEDCM material removal rate, electrode loss rate and specimen surface roughness. (a) Material removal rate (b) Tool wear rate (c) Surface roughness

Figure 3

Effects of different abrasive materials on sedcm material removal rate, electrode loss rate and specimen surface roughness. (a) Material removal rate (b) Tool wear rate (c) Surface roughness

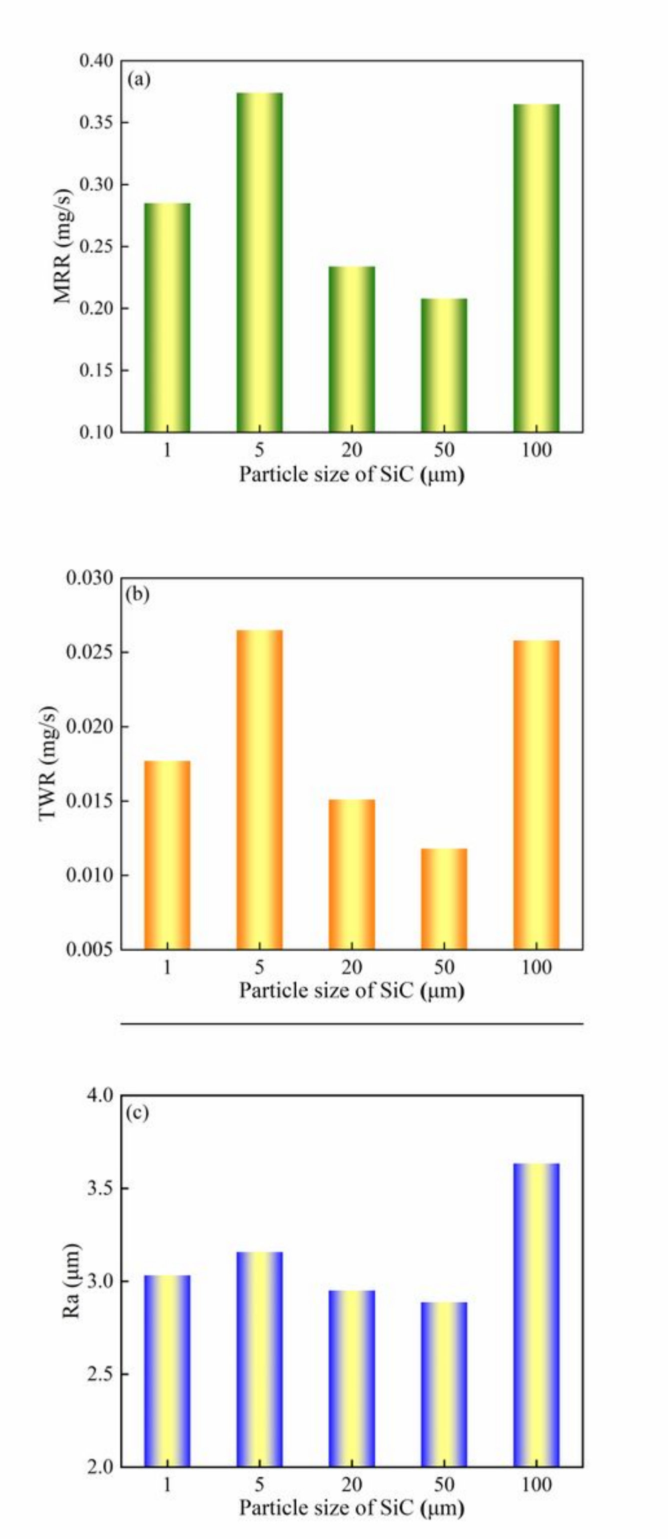

Figure 4

Effects of different abrasive particle sizes on sedcm material removal rate, electrode loss rate and specimen surface roughness (a) Material removal rate (b) Tool wear rate (c) Surface roughness

Figure 5

SEM of surface morphology of sedcm under the action of different abrasive particle sizes

Figure 6

Verification and comparison of optimization combination of process parameters