SEAM-ECM Jet Milling TC4 Titanium Alloy Using Gas-Liquid Mixed Medium

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Abstract

A novel combined machining approach combining short electric arc machining and electrochemical machining (SEAM-ECM) is proposed in this study. It aims to improve the surface integrity of TC4 titanium alloy by adding compressed air and electrolyte into the SEAM. This approach can change the material removal mechanism of the conventional SEAM and improve the gap flow field distribution and discharge state using the dual fluid properties of electrolyte and air mixed medium. The effects of gas addition on the state of the gap flow field and the electrical conductivity of the mixed medium are illustrated by flow field simulation. The effects of the presence or absence of air and the electrical conductivity of the solution on the machining performance are compared by experiments. The results show that the recast layer is weakened by using electrolyte and air mixed medium in SEAM-ECM compared to SEAM alone. The addition of high-speed air reduces defects such as melt drops, particles, holes. It performs with higher precision and finishes than ECM alone, the overall surface integrity has been significantly improved.

1. Introduction

TC4 titanium alloy is widely used in aerospace, marine chemical industry, and medical application because of its high specific strength, corrosion resistance, and anti high temperature performance[1]. However, due to the inherent properties of this material such as poor thermal conductivity and low modulus of elasticity, conventional machining cannot meet the machining requirements of titanium alloys[2], which can easily lead to tool wear and incipient fault during the production process[3].

Among the current unconventional machining processes, short electric arc machining (SEAM) is a non-contact electrical discharge machining technology with an environmentally friendly mixture of air and tap water, releasing heat energy to melt the material by creating an intermittent arc between the workpiece and the tool electrode[4]. The machining process is free of cutting force and low tool wear, so it can be applied to machining TC4 titanium alloy. However, SEAM is a transformation technology of conventional electrical discharge machining(EDM)and still has many EDM characteristics. For example, when the discharge gap is reached between the electrode and the workpiece, the interpolar medium is broken down and ionized, after which a plasma discharge channel is generated with a temperature of up to 8000°C, causing the material to melt and vaporize[5]. The medium compresses the plasma discharge channel to produce extremely high pressure, when the pulse is turned off, the discharge is terminated and the plasma channel breaks down to produce a huge pressure difference to throw out the molten material. So that the surface of the workpiece after EDM consists of multiple discharge pits stacked with a poor surface finish[6]. When the medium flows through the gap causing the molten material to sharply cool and crumple to form particles, the remaining molten material is deposited on the workpiece surface to form recast layer[7–9]. The rapid heating and cooling lead to the brittle structure of the recast layer[10], and the uneven temperature gradient causes residual tensile stresses in the material during deposition, which seriously affects the fatigue life of the workpiece[11]. To mitigate or eliminate the adverse effects of EDM on surface integrity, the surface formed by EDM is generally subjected to electrolytic machining

(ECM) polishing. In ECM, the material is removed based on the principle of anode dissolution and the surface is free from defects such as microcracks and recast layer[12]. In addition, there is no tool wear in ECM due to the electrochemical deposition effect of cathode[13, 14]. However, ECM is prone to stray corrosion, and machining localization is difficult to guarantee[15], while subsequent ECM is hard to conduct due to the extreme oxidation of the surface of titanium alloys during corrosion[16].

Therefore, researchers developed a combined EDM/ECM process expecting to take advantage of both EDM and ECM to provide a process method with high machining accuracy, high surface finish, and no recast layer. The process involves a shift in the type of working medium. While conventional EDM uses a kerosene medium with strong insulating properties and conventional ECM uses an electrolyte with conductive properties, the combined process uses a medium with dual properties. Minh Dang Nguyen et al[17]used deionized water as the working medium to achieve simultaneous EDM/ECM of micro holes at low feedrate, while using short voltage pulses to limit the range of ECM stray corrosion and improve the machining accuracy of micro holes. Zhang et al[18]proposed a combined process of EDM-ECM for small holes based on a low conductivity neutral salt solution, which effectively removed the residual recast layer from the hole wall by choosing a suitable electrical conductivity. Li et al[19]used a new flushing system and different working mediums (deionized water for the inner flushing and low electrical conductivity electrolyte for the external flushing) to maintain a good flushing continuity of the working medium and achieve self-adjusting small hole machining with ECM/ECDM/EDM. Han et al[20]proposed the use of a NaCl electrolyte and O₂ mixed aerosol as the working medium for EDM deep hole machining, and switching between EDM ablation machining (EDAM) and ECM mode by adjusting the electrical conductivity of the mixed aerosol, the material removal rate is greatly improved compared to the conventional EDM. The above studies mainly focus on the recast layer weakening process for drilling machining, there are fewer studies on improving the dimensional accuracy and surface finish of the workpiece at the same time. Especially for a large margin cutting process like SEAM, which generates higher temperature and heat flux density compared to EDM[21, 22], the surface properties of the machined material also change significantly, and the surface quality and integrity need to be improved urgently.

This study combines the SEAM and ECM processes by using the dual fluid properties of electrolyte and air mixed medium. On the basis of SEAM, a large amount of material is removed and the surface oxide layer is broken, then ECM dissolves the recast layer on the surface of the material and improves the surface finish of the workpiece. At the same time, the strong dielectric property of gas is used to reduce the stray corrosion of ECM. The machining performance under four different medium conditions is compared by simulation and experiment, and the influence of the medium characteristics on the dimensional accuracy, surface finish and the thickness of the recast layer on the workpiece surface by SEAM-ECM milling is investigated.

2. Fundamental Principle Of Seam-ecm Combined Machining

Fig. 1 shows the Fundamental principle of SEAM-ECM combined machining by using an electrolyte and compressed air. The machining of SEAM-ECM can be illustrated by four stages within one pulse cycle.

Stage(a), ECM generates a passivation layer. Before compressed air is passed through, ECM occurs first, as the corrosion of TC4 surface rapidly generates a metal passivation layer with very low chemical activity, it prevents ion exchange in the discharge gap, making subsequent ECM difficult.

Stage(b), SEAM removes the passivation layer and generates a recast layer. At this time, compressed air with high dielectric strength is introduced to form medium breakdown condition and generates plasma discharge channel, while compressing the discharge channel and increasing the discharge energy density to break the passivation layer on the metal surface. Due to the concentration of thermal energy in the discharge channel, a large amount of metal material melts, and part of the molten metal is recondensed on the surface to form the recast layer.

Stage(c), ECM removes the recast layer. The electrolyte contacts the recast layer on the metal surface along the discharge channel. On the one hand, the high temperature activation zone is generated due to SEAM, which catalyzes the electrolytic reaction. On the other hand, the addition of air causes forced convection between the gas and liquid phases in the gap, which enhances the electrolytic diffusion rate and dissolves the recast layer generated by SEAM.

Stage(d), Deionize and renew the electrolyte. Pulse switch out, high-speed flow of compressed air breaks through the arc and accelerates the flow of electrolyte, flushing electrolysis products and discharge debris out of the gap, reducing stray corrosion and secondary discharge.

The process is continuously cycled during SEAM-ECM, during which SEAM occurs simultaneously with ECM. Compressed air is an essential factor for SEAM, while electrical conductivity of the solution also determines the rate of ECM. Therefore, the effect of the presence or absence of air and the electrical conductivity of the solution on the machining effect is discussed.

3. Seam-ecm Combined Machining Simulation

3. 1 Simulation model and setup

The simplified physical model of SEAM-ECM is shown in Fig. 2, where compressed air and liquid medium are flushed from two inlets into the central hole of the rotating electrode and then into the end gap between the workpiece and the electrode.

The simulation process involves gas-liquid two-phase flow, using the VOF multiphase flow model, the fluid domain is filled with air before the compressed air and liquid medium is passed into it, assuming that the fluid medium is continuous, and its motion is in accordance with the mass conservation equation:

$$\frac{\partial \rho}{\partial t} + \nabla \rho v = 0 \quad (1)$$

Where ρ is the fluid density (kg/m³), v is the mixed medium flow rate (m/s).

Also the process of motion of viscous fluid needs to follow the momentum conservation equation:

$$\rho \frac{\partial v}{\partial t} = \rho g - \nabla p + \mu \nabla^2 v \quad (2)$$

where p is the pressure (Pa), μ is the dynamic viscosity (Pa·s), and g is the acceleration of gravity (m/s²).

At the intersection of the rotational and stationary flow field, a slip grid is used to interface with the normal wall surface. The fluid flow state in the rotational domain follows a three-dimensional axisymmetric rotational flow, and the momentum equation needs to be replaced with the form of column coordinates and filled with the source term. The turbulence model uses the Realizable model commonly used for jet and two-phase flow, while the potential equation is added to the numerical model in order to solve the distribution state of the gap fluid field electrical conductivity:

$$\nabla(\sigma \nabla \varphi) + S = 0 \quad (3)$$

Where φ is the electric potential(V), σ is the fluid electrical conductivity(S/m), and S is the energy source term.

The simulation process assumes that no gas is generated at the cathode and anode, while ignoring the effect of temperature on the electrical conductivity of the medium. Table 1 lists the parameters required for the simulation.

3. 2 Simulation results and analysis

Two cross-sections of the gap flow field are intercepted as shown in Fig. 3 to analyze the simulation results, A-A is the longitudinal section and B-B is the cross-section. Fig. 3 compares the velocity clouds of the flow field with and without air and the corresponding turbulence intensity clouds, from which it can be seen that the maximum turbulence intensity of the flow field is increased by a factor of 5 when high pressure gas is added, intensifying the fluctuation intensity of the flow field. Because the mass of gas is much smaller than the mass of liquid, when the electrode rotates, the larger centripetal force drives the liquid medium to stick to the inner wall of the electrode, while the gas flowing through the electrode at high speed is still in the center of the electrode, so a larger velocity gradient is generated, which is conducive to reducing the accumulation of products to reduce the probability of secondary discharge, and also conducive to renew electrolyte, reducing the degree of stray corrosion of electrolyte.

As shown in Fig. 4, the trend of the gap flow velocity before and after adding air is the same, because the electrode rotation shows irregular fluctuation, especially at the edge of the inner hole of the electrode produces violent fluctuation, the air participation increases the overall flow velocity by more than 2-5 times, making the degree of fluctuation more violent. The fluid flow rate of the inner hole of the electrode in the cross-section is greater than the flow rate of the outer side of the electrode, and the medium flows out to the outer side of the electrode, increasing the volume of galvanic corrosion and dissolution.

Fig. 5 analyzes the change of conductivity of the mixed medium after the addition of gas. As shown in the figure, due to the presence of centripetal force the delamination of the gas-liquid two phases in the inner hole of the electrode can be clearly observed and detached at the end face of the electrode. From the cross-sectional electrical conductivity distribution cloud, it can be seen that the gas-liquid phases are well mixed at the electrode end face and the electrical conductivity is uniformly distributed, which is helpful to ensure the good dimensional accuracy of the workpiece cross-section. Fig. 5(c) shows the comparative curves of electrical conductivity before and after the addition of air. Due to the higher dielectric strength of air, the electrical conductivity of the mixed phase decreases dramatically, while increasing the turbulence intensity in the gap, so that the overall electrical conductivity shows an irregular distribution, which provides the possibility to achieve the simultaneous SEAM-ECM machining.

4. Experimental Setup

SEAM machining system is shown in Fig. 6, including control system, machine tool body, flush fluid system. The compressor delivers air to mix with the liquid medium in the water tank, mixed medium passes through the pipe in the machine tool and is flushed into the machining gap through the inner hole of the electrode. The spring-loaded chuck holds the hollow cylindrical electrode on the Z-axis and the workpiece is bolted to the dovetail guide. The power control cabinet provides pulse voltage to the anode workpiece and cathode electrode. The CNC control cabinet controls the movement of the electrode along the Z-axis and the workpiece along the X-axis and Y-axis.

The hollow cylindrical electrode material is copper, the outer circle size is $\phi 18$, the inner hole size is $\phi 6$, and the workpiece material is TC4 titanium alloy rectangular specimen, the size is $30 \times 30 \times 8$. The material properties are shown in Table 2.

In order to verify that electrolyte and air are necessary medium for SEAM-ECM combined machining, comparison experiments are carried out for deionized water(DI water), electrolyte, combination of DI water and air, and combination of electrolyte and air to ensure that other machining parameters are the same and to compare the effect of medium characteristics on machining performance, and the specific experimental parameters setup is listed in Table 3.

5. Experimental Results And Discussion

5. 1 Waveform analysis

The voltage and current waveforms of the four mediums during machining were acquired using a DEWESoft SIRIUS multi-channel data acquisition system. Fig. 7 extracts the discharge waveforms during the 6-ms time interval. Deionization is easily accomplished after Pulse switch out, which generates some spark waveforms during machining[23], and at the same time, the DI water has weak electrical conductivity, leakage current is generated during the spark breakdown delay phase, which can lead to microelectrolysis[24], and machining in DI water can be classified as SEAM, EDM-ECM combined machining. When the medium is electrolyte only, the waveforms are all electrolytic waveforms and the maximum electrolytic current is 32A. Therefore, no sparks and arcs are observed to occur during the machining process. When the medium is DI water and air, due to the strong dielectric ability of gas, it is more likely to lead to self-sustaining discharge to form arcs, but some unsteady arcs are generated due to the rotation of the electrode and the violent gas disturbance in the narrow gap. When the medium is electrolyte and air, the waveforms are distributed at intervals of arcs and electrolysis, which shows that SEAM and ECM are alternated during the machining process, but the electrolysis current and arc current are reduced compared with both pure arc machining and pure electrolysis machining, the energy acting on the workpiece surface is reduced, which is beneficial to reduce the thickness of the recast layer on the workpiece surface.

5. 2 Surface morphology and elemental analysis

Fig. 8 shows the microscopic surface morphology of the workpiece under different medium conditions. The surface of the workpiece machined with DI water shows a large number of molten droplets, particles, holes, and a thick build-up of recast layer, which is a result of the uneven re-solidification of the molten metal on the surface of the workpiece due to the poor flushing conditions. The number of molten droplets and particles on the surface of the workpiece machined with the combination of DI water and air is very small. However, due to the high pulse energy, cracks are found all along the vertical direction of the recast layer. Since the titanium alloy finish ion exchange in the electrolyte and form light flocculent material, which easily flow out of the gap, the surface products accumulation phenomenon of using electrolyte machining and combined electrolyte and air machining is greatly improved, the surface defects such as molten droplets, particles and holes basically do not exist on the surface. Because ECM is performed, no defects such as obvious recast layers and microcracks are observed on the workpiece surface. However, there are still some flocculent electrolytic products deposit on the surface of the workpiece, which indicates that there is still room for improvement in the effect of the flushing.

According to the energy dispersive spectroscopy (EDS)analysis of the surface. The carbon content of the solidification processed using electrolyte and air increased significantly, due to the electrolysis of CO_2 in air at high temperature to produce CO, CO continues to decompose into free C adsorb on the surface of the titanium alloy and diffuses to the base material to generate TiC[25], which achieve the carburization effect. The oxygen content under this machining condition is also slightly elevated compared to DI water and air machining, because oxygen is also an intermediate product of the electrolysis reaction. In addition, chlorine is detected on the surfaces machined with electrolyte and air, indicating the migration of solution elements to the workpiece in addition to ambient gases.

X-ray diffraction analysis of the four workpiece surface micro-areas marked by the red area in Fig. 8 and the workpiece substrate is carried out as shown in Fig. 9. Titanium alloy forms dense oxide films TiO_2 and TiO on the surface at room temperature, and a small amount of Ti elemental exists on the surface. After machining the spectrum is shifted, indicating the generation of residual stresses, the DI water machining surface defects are serious and have obvious residual stresses. When air is added to the medium, Ti_2O_3 is produced due to peroxidation, in addition the intermediate product of the titanium alloy in the halide electrolyte is the corresponding halide TiCl_4 [26], but it is highly hydrolyzed, so only chlorine is detected on the surface and not TiCl_4 . The surface machined with electrolyte and air underwent both SEAM and ECM, which produces more intermediate products compared to other machining conditions. Table 4 shows the chemical equations for the generation of each phase.

5. 3 Cross-sectional morphology and thickness of recast layer (sediment layer)

Fig. 10 shows the microscopic morphology of the workpiece cross-section under different medium conditions, can be seen that the workpiece cross-section machined with DI water alone has a thicker recast layer, and the migration of carbon and oxygen extends into the recast layer to produce larger residual stresses to increase cracks[27]. Due to poor flushing conditions, heat cannot be dissipated in time, excessive heat extension to the base material leads to a similarly large thickness of the heat-affected zone. Although the pulse energy of the combined DI water and air machining is higher, the recast layer thickness is weakened by the addition of high pressure air which improves the flushing conditions and makes it easier for the products to pass out the gap. Obviously, the cooling performance is significantly improved with the addition of air, the thickness of the heat-affected zone is significantly reduced. Comparing the cross-section machined with electrolyte and the combination of electrolyte and air, the difference is not significant. The thickness of the sediment layer is low because of the small mass of the electrolytic products and the easy to pass of the gap, and the low thermal conductivity of the titanium alloy, the heat generated by ECM is not enough to conduct to the base material, so there is basically no heat-affected zone. Although more heat is generated by using a combination of electrolyte and air, the cooling properties of the mixed medium compensate for this machining defect, and there is no significant heat-affected zone in the workpiece cross-section.

Intercepted 10 locations of the workpiece recast layer(deposited layer)cross-section according to Fig. 10, measured the thickness of the recast layer there, and plot Fig. 11. The average recast layer thickness for machining with DI water alone is $54.9\mu\text{m}$, while the recast layer thickness for machining with a combination of air and electrolyte is reduced by 72.7% relative to DI water, and increased by only 5.97% relative to machining with electrolyte alone, significantly improving the machining quality of SEAM.

Fig. 12 selected cross-section recast layer(sediment layer), heat-affected zone and base material for microhardness analysis, as shown in the figure, because TiO_2 and TiC can form a continuous solid solution, the hardness of recast layer(sediment layer)is much higher than that of heat-affected zone and base material, the hardness of heat-affected zone and base material are basically the same, which

means that TiC has not penetrated recast layer(sediment layer), and the heat-affected zone material has not undergone obvious phase change.

5. 4 Cross-sectional dimensional accuracy

Due to the symmetry of dimensional errors caused by electrode rotation, half of the shape of the same position in the middle of the intercepted milling slot is made symmetrical, as shown in Fig. 13. The specified dimension of the milled slot is 2 mm, and the machining with DI water is too low energy to reach the specified depth of cut, while the machining with a combination of DI water and air causes the phenomenon of overcutting due to the concentration of energy. In order to evaluate in detail the influence of the medium characteristics on the dimensional accuracy, the milling depth error is evaluated according to the absolute value of the difference between the actual milling depth H and the standard milling depth, and the shape error of the milling slot is evaluated according to the milling slot tilt angle θ , as shown in Fig. 14.

Fig. 15 shows both the milling groove depth error and tilt angle θ under different medium conditions. Combining with Fig. 7, it can be seen that pulse energy and milling groove depth are positively correlated, therefore, the milling groove depth is increased for both air addition machining, and ECM will also produce overcutting because of the existence of exceeding corrosion. Combining with Fig 5, it can be seen that the gas addition makes the liquid medium diffuse toward the electrode edge, so that the electrolyte can directly contact the side of the milling groove and ECM occurs at the corner of the milling groove. Therefore, the combined machining using air and electrolysis has a significant improvement in cross-sectional shape accuracy compared with other forms of machining. SEAM-ECM reduces θ by 55.56% compared to pure arc machining and by 68% compared to pure electrolytic machining.

In order to comprehensively evaluate the dimensional accuracy of the milled slot, the milling depth error and tilt angle are Min-Max normalized according to equation(4):

$$x' = \frac{x - \text{Min}}{\text{Max} - \text{Min}} \quad (4)$$

where Min, Max are the minimum and maximum values of the samples respectively.

Since both the milling groove depth error and the tilt angle are consistent with the lookout small characteristic, the dimensional accuracy is evaluated by taking the average of the two. Table 5 shows the dimensionless numbers of the combined calculation, and it can be seen that the dimensional accuracy of the milled groove machined with the combination of electrolyte and air is optimal.

5. 5 Surface roughness

The center area of the milling groove is selected for observation and measurement, and the 3D shape of the surface is shown in Fig. 16. When the medium is DI water, the flow velocity of the gap flow field is low, and the particles easy to accumulate on the workpiece surface, so many bumps can be seen on the

workpiece surface, and therefore the surface roughness is as high as 63.49 μ m. The surface roughness of ECM alone decreased by 20.28% compared to SEAM using DI water. The analysis concluded that the surface roughness is lower because the ECM machining products are light flocculent, while ECM is smoother compared to SEAM and the products are easier to clear the gap, but the surface finish after machining is still unsatisfactory due to the poor flushing conditions and the presence of stray corrosion in ECM. The surface roughness of the combined DI water and air machining is the highest. Although the addition of gas reduces the accumulation of particles, the higher pulse energy acts on the surface of the workpiece, producing large and deep craters. When combined electrolyte and air machining is used, the surface finish is significantly improved. On the one hand, there are no particles buildup, and on the other hand, no deep craters are produced due to the dispersion of SEAM energy by ECM, and ECM polishing is also performed, which increase the surface roughness by 41.61% relative to pure arc machining and 24.14% relative to pure electrolytic machining.

5. 6 Comprehensive surface integrity evaluation

Fig. 17 describes the comprehensive surface integrity evaluation of the recast layer thickness, surface roughness, and dimensional accuracy of the workpiece cross-section after machining in different mediums. Three indicators satisfy the lookout small characteristic, from the figure, it can be seen that the machining using the combination of DI water and air is the least satisfactory, and the high pulse energy leads to deep pits and thick recast layer, which can indicate that the pulse energy has a certain negative correlation with the surface integrity. And electrolytic machining may lead to a lower surface finish due to stray corrosion problems. In terms of the overall capability, machining with a combination of electrolyte and air has a more balanced performance compared to other mediums.

6. Conclusions

In this paper, the introduction of compressed air and electrolyte in SEAM is proposed, and the basic principle of combined machining(SEAM-ECM) with compressed air and electrolyte is elucidated. The interstitial flow field state after the addition of air is simulated, and the effect of air on the flow field distribution state and material conductivity distribution is illustrated. The machining performance under different medium states is experimentally compared, mainly including discharge state, surface morphology and elemental analysis, cross-sectional morphology and defects, milling groove dimensional accuracy, surface roughness, and finally, the comprehensive surface integrity with different mediums is evaluated. The main conclusions are summarized as follows:

(1)The simulation results show that compressed air causes drastic disturbance to the flow field and increases the fluid flow velocity, and the rotation of the electrode causes the liquid medium to move toward the edge of the electrode, so that the gas-liquid two-phase flow shows an obvious stratification phenomenon, which is beneficial to the medium flowing outside the gap to accelerate the discharge of etching products and renew of the electrolyte. In addition, the addition of air reduces the electrical

conductivity in the gap, which makes the mixed medium with dual fluid properties and provides the possibility for SEAM-ECM.

(2) Experimentation found that the arc waveform and electrolytic waveform are distributed interphase in the waveform of combined machining. Elemental analysis results show that the machining surface generated additional TiC and Ti_2O_3 due to air peroxidation. The distribution of recast layer and heat-affected zone is observed by cross-section, and it is concluded that the product generated by adding electrolyte is easier to clear from the gap than the particles generated by arc machining.

(3) The addition of air not only improves the flow characteristics of the fluid, but also improves the cooling performance of the medium. Relative to other medium machining, the dimensional accuracy of the workpiece machined by the combination of air and electrolyte is significantly improved, and the surface roughness is increased by 41.61% relative to pure arc machining and 24.14% relative to pure electrolytic machining.

Declarations

Not applicable

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Conflicts of interest

The authors declare that they have no conflict of interest.

Availability of data and material (data transparency)

Code availability (software application or custom code)

Authors' contributions (optional: please review the submission guidelines from the journal whether statements are mandatory)

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Tables

Table 1 Simulation setup and parameters

Factors	Value
Gas flow (kg/s)	0.000879
Liquid flow (kg/s)	0.125
Gas electrical conductivity (S/m)	0.0001
Liquid electrical conductivity (S/m)	72
Electrode speed (rad/s)	15
Voltage magnitude (V)	25

Table 2 Material properties

Material	Density (kg/m ³)	Melting point (C)	Thermal conductivity (W/m·K)	Resistivity (Ω·m)	Composition
TC4 titanium alloy	4430	1933	8	1.6×10^{-6}	Al=5.5-6.8% V=3.5-4.5% Fe=0.3% O=0.2% Other=0.81% Ti rest
Copper	8960	1083	386.4	1.8×10^{-8}	Cu>=99.95%

Table 3 Experimental parameters setup

Factors	Value
Medium type	DI Water, 5Wt%NaCl electrolyte, Compressed air
Voltage(V)	25
Frequency(Hz)	1000
Duty cycle(%)	55%
Electrode speed(rad/s)	15
Milling depth(mm)	2

Table 4 Chemical equation for the formation of the main phases

Phase	Chemical equation
TiO ₂	Ti→Ti ⁴⁺ +4e ⁻ Ti ⁴⁺ +2O ²⁻ →TiO ₂
Ti ₂ O ₃	Ti→Ti ³⁺ +3e ⁻ 2Ti ³⁺ +3O ²⁻ →Ti ₂ O ₃
TiO	TiO ₂ +Ti→2TiO
TiCl ₄	2Cl ⁻ -2e ⁻ =Cl ₂ TiO ₂ +2Cl ₂ →TiCl ₄ +O ₂
TiC	2CO ₂ →2CO+O ₂ 2CO→[C]+CO ₂ Ti+[C]→TiC

Table 5 Evaluation coefficients for dimensional accuracy in different medium conditions

Medium Type	DI Water	Electrolyte	Air+DI Water	Air+Electrolyte
Dimensionless number	0.3825	0.78	0.794	0.344

Figures

Figure 1

SEAM-ECM machining principle:(a) Electrolysis generates passivation layer, (b) Arc removes passivation layer and generates recast layer, (c) Electrolysis removes recast layer, (d) Arc breaks, taking away discharging products and electrolysis products.

Figure 2

Schematic diagram of the flow field model

Figure 3

Flow field velocity cloud and its turbulent kinetic energy cloud:(a) air-free flow field velocity, (b) air-containing flow field velocity cloud, (c) air-free turbulent kinetic energy cloud, (d) air-containing turbulent kinetic energy cloud.

Figure 4

Velocity profile comparison graph:(a) Velocity of longitudinal section flow field, (b) Velocity of cross-section flow field.

Figure 5

Cloud diagram of mixed phase distribution and conductivity distribution:(a) Phase volume fraction distribution cloud, (b) Electrical conductivity distribution cloud, (c) Electrical conductivity of cross-section flow field.

Figure 6

SEAM machining system

Figure 7

Voltage and current waveforms:(a) DI Water, (b) Electrolyte, (c) DI Water + air, (d) Electrolyte + air.

Figure 8

SEM image and EDS spectrum:(a) DI Water, (b) Electrolyte, (c) DI Water + air, (d) Electrolyte + air.

Figure 9

X-ray diffraction pattern of workpiece surface

Figure 10

Microscopic morphology of the workpiece cross-section:(a) DI Water, (b) Electrolyte, (c) DI Water + air, (d) Electrolyte + air.

Figure 11

Thickness of recast layer (sediment layer) of workpiece cross-section

Figure 12

Microhardness of recast layers (sediment layer) of workpiece cross-section

Figure 13

Milling groove cross-section profile

Figure 14

Schematic diagram of dimensional

Figure 15

milling groove depth error Δh and tilt angle θ

Figure 16

3D surface shape of the milling groove

Figure 17

Evaluation of comprehensive indicators