SEAM-ECM jet milling TC4 titanium alloy using gas–liquid mixed medium

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Received: 22 August 2021 / Accepted: 10 December 2021 / Published online: 23 January 2022 © The Author(s), under exclusive licence to Springer-Verlag London Ltd., part of Springer Nature 2021

Abstract
This paper proposes a novel combined machining approach. The approach is focused on combining short electric arc machining and electrochemical machining (SEAM-ECM). 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. Flow field simulation demonstrates the effects of gas addition on the state of the gap flow field and the electrical conductivity of the mixed medium. The experiments compare the effects of the presence or absence of air and the electrical conductivity of the solution on the machining performance. The results show that SEAM-ECM with electrolyte and air reduces the relative electrode wear rate (REWR) while maintaining a good material removal rate (MRR). In addition, SEAM-ECM utilizes the electrolytic effect to weaken the recast layer compared to SEAM with deionized water and air. The addition of high-speed air reduces defects such as melt drops, particles, and holes. It performs with higher precision and finish than ECM alone, and the overall surface integrity is significantly improved.

Keywords SEAM-ECM · Dual fluid properties · Flow field simulation · Surface integrity

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]. Especially in the aviation industry in recent years, the proportion of TC4 titanium alloy used has increased from 5 to more than 14% [2]. 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 TC4 titanium alloy and often results in machining hardening and cause tool wear and early failure during the production process [3, 4]; this presents a challenge for the promotion of the application and development of titanium alloy.

Among the current unconventional machining processes, SEAM is a noncontact 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 [5]. 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 [6]. 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 [7]. 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 a recast layer [8–10]. The rapid heating and cooling lead to the brittle structure of the recast layer [11], and the uneven temperature gradient causes residual tensile stresses in the material during deposition, which seriously affects the fatigue life of the workpiece [12]. To mitigate or eliminate the adverse effects of EDM on surface integrity, the surface formed by EDM is generally subjected to 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 [13]. In addition, there is no tool wear in ECM due to the electrochemical deposition effect of cathode [14, 15]. However, ECM is prone to stray corrosion, and machining localization is difficult to guarantee [16], while subsequent ECM is hard to conduct due to the tendency of the titanium alloy surface to generate an insoluble passivation layer during the corrosion process [17].

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. Nguyen et al. [18] used deionized water as the working medium to achieve simultaneous EDM/ECM of micro-holes at low feed rate while using short voltage pulses to limit the range of ECM stray corrosion and improve the machining accuracy of micro-holes. Zhang et al. [19] 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. [20] 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. [21] 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 [22, 23], 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 passivation 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 good flushing effect and strong dielectric properties of high-speed gas are used to reduce the stray corrosion of ECM. The velocity distribution, phase distribution, and conductivity distribution of the gas–liquid two-phase mixed medium are predicted by simulations. The machining performance under four different medium conditions is compared by experiment. The effects of medium characteristics on the MRR, REWR, dimensional accuracy error (DAE), surface roughness (SR), and workpiece surface recast layer thickness (RLT) of SEAM-ECM milling are investigated.

2 Fundamental principle of SEAM-ECM combined machining

Figure 1 shows the fundamental principle of SEAM-ECM combined machining by using an electrolyte and compressed air. Figure 1b shows the partial waveform of SEAM-ECM combined machining, and Fig. 1c, d shows the partial waveform enlargement. In Fig. 1b, it can be observed that ECM and SEAM occur alternately and that the ECM time exceeds the SEAM time. However, an interesting phenomenon is found in Fig. 1c, d. In the waveform enlargement, it is found that leakage currents exist during the short breakdown delay of each discharge, and the magnitude of the leakage current is inversely related to the magnitude of the discharge current, which indicates that SEAM and ECM also occur simultaneously. In addition, during the switch-off period of the pulse, there is a polarization voltage, the current flows through the double electric layer at the interface between the solution and the metal, causing the electrode potential to deviate from the equilibrium potential [24]. Therefore, it is known that ECM is involved in the whole process of SEAM-ECM combined machining.

Observing the electrolysis waveform, we can see that the waveform fluctuates in the small current range. According to Weinmann et al. [25], titanium alloys tend to form a passivation layer on the surface that is difficult to dissolve. The passivation property increases with the titanium content, even in halide electrolytes. The structure of the passivation layer on the surface of titanium alloy is modeled by Wang et al. [26]. They consider that the passivation layer on the surface of titanium alloy is loose
and porous, so the fluctuation of the electrolytic waveform indicates that this may be caused by the electrolysis occurring in the porous structure of the passivation layer by uneven pitting. Shen et al. [27] introduce air into wet EDM to take advantage of its higher dielectric strength to reduce the machining gap and thus increase the discharge energy. This also applies in SEAM-ECM combined machining, where the addition of air increases the discharge energy. From Fig. 1b, c, it can be seen that the polarization voltage has a decreasing trend after the occurrence of a small current discharge. This is probably due to the smaller discharge energy cannot completely break the passivation layer, causing the electrolyte to come into contact with the new passivation layer. After the occurrence of high current arc discharge, the polarization voltage has a rising trend. This is probably due to the removal of the passivation layer; the electrolyte comes into direct contact with the metal substrate. The addition of air also improves the flushing efficiency of electrolysis products and particles, further improving the combined machining. SEAM-ECM combined machining using electrolyte and air provides a viable method for TC4 titanium alloy that is prone to passivation layers. Therefore, the influence of air and solution conductivity on the machining effect is discussed.

3 SEAM-ECM combined machining simulation

Considering the extremely small size of the discharge gap, it is difficult to make an intuitive description of the gap flow field by experiment. Also considering the complexity of the flow field after adding gas, it is difficult to provide an accurate mathematical model to explain it. Finite element simulation provides a validated method. By building a simplified model, the velocity, phase position, and the corresponding material conductivity of the gas–liquid two-phase mixture can be simulated. This reveals the effect of the added gas on the interpolar flow field.

3.1 Simulation model and setup

The simplified physical model of SEAM-ECM is shown in Fig. 2. Air compressor generates compressed air to the upper inlet of the gas–liquid mixing pipe; water pump conveys liquid medium to the lower inlet. The gas inlet flow rate is measured by a gas float flowmeter; the liquid inlet flow rate is measured by volumetric method. The two mediums converge through the mixing pipe and flush into the machine flow channel, subsequent flushing from the inner hole of the electrode into the machining gap. Both inlets are set to mass flow inlet and the outlet is set to outflow.

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 following the mass conservation equation:

\[
\frac{\partial \rho}{\partial t} + \nabla \rho v = 0
\]
where \( \rho \) is the fluid density (kg/m\(^3\)) and \( v \) is the mixed medium flow rate (m/s).

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

\[
\rho \frac{\partial v}{\partial t} = \rho g - \nabla p + \mu \nabla^2 v \tag{2}
\]

where \( p \) is the pressure (Pa), \( \mu \) is the dynamic viscosity (Pa·s), and \( g \) is the acceleration of gravity (m/s\(^2\)).

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 \( k-\varepsilon \) model commonly used for jet and two-phase flow, while the potential equation is added to the numerical model to solve the distribution state of the gap fluid field electrical conductivity:

\[
\nabla (\sigma \nabla \varphi) + S = 0 \tag{3}
\]

where \( \varphi \) is the electric potential (V), \( \sigma \) is the fluid electrical conductivity (S/m), and \( S \) is the energy source term.

To observe the distribution of the phase interface, the VOF model used ignores the effect of high-velocity gas on the fogging of the liquid medium; the 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

As shown in Fig. 3, two cross-sections of the flow field near the discharge gap are taken to analyze the simulation results, A-A is the longitudinal section and B-B is the cross-section. Figure 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 5 times 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

| 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        |
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.

Figure 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

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**Fig. 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, and d air-containing turbulent kinetic energy cloud

**Fig. 4** Velocity profile comparison graph: a velocity of the longitudinal section flow field and b velocity of the cross-section flow field
can be observed and detached at the end face of the electrode. Figure 5c 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, so that the overall electrical conductivity shows an irregular distribution, it indicates that a large number of discharge states with alternating SEAM and ECM may occur in the gap, which corresponds to the waveforms in the principle diagram.

4 Experimental setup

SEAM machining system is shown in Fig. 6, including the control system, the machine tool body, and the flush fluid system. The air compressor conveys air to the gas–liquid mixing inlet; the gas float flowmeter is installed in front of the inlet to regulate the gas flow. The constant power pump conveys the liquid medium to the inlet; the liquid flow is kept constant; the 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.

To verify that electrolyte and air are the necessary mediums 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. Other machining parameters are the same and to compare the effects of medium characteristics on MRR, REWR, discharge state, RLT, DAE, and SR. The specific experimental parameters setup is listed in Table 3.

5 Experimental results and discussion

5.1 Material removal rate (MRR) and relative electrode wear rate (REWR)

The MRR is calculated according to the following equation:

\[
\text{MRR} = \frac{1000(M_{w_i} - M_{w_j})}{\rho t} \times 100\%
\]

where \( M_{w_i} \) and \( M_{w_j} \) is the mass of the workpiece before and after machining (g), \( \rho \) is the workpiece material density (g/cm\(^3\)), and \( t \) is the machining time (min).

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Fig. 5 Cloud diagram of mixed-phase distribution and conductivity distribution: a phase volume fraction distribution cloud, b electrical conductivity distribution cloud, and c electrical conductivity of cross-section flow field
The REWR is calculated according to the following equation:

\[
\text{REWR} = \frac{M_{ei} - M_{ej}}{M_{wi} - M_{wj}} \times 100\% 
\]

where \(M_{ei}\) and \(M_{ej}\) is the electrode mass before and after machining (g).

The calculation results are shown in Fig. 7. In order to ensure that the whole process of machining with electrolyte is ECM, the critical feed rate of ECM was measured. When the feed rate is 1 mm/min, the whole waveform shows that only three discharges occur and the rest are ECM waveforms. Therefore, the MRR is very low compared to other mediums with higher dielectric strength, but REWR shows negative losses, which is the machining advantage of ECM. The addition of high-velocity air improves the flushing efficiency of the products and also improves the discharge energy. Relative to liquid medium-deionized water and electrolyte, MRR improved by 32.91% and 158.15%, respectively, showing that gas is a necessary medium for efficient arc machining. The electrolyte disperses some of the discharge energy, resulting in a 10.73% reduction in MRR relative to machining with deionized water and air. In REWR, due to the presence of cathodic deposition compensation in ECM, the REWR using electrolyte and air machining is the lowest, except for the ECM. It shows that the electrolyte compensation is higher than the loss of discharge energy.

| Material          | Density (kg/m³) | Melting point (°C) | Thermal conductivity (W/m·K) | Resistivity (Ω·m) | Composition                  |
|-------------------|-----------------|--------------------|-----------------------------|------------------|-----------------------------|
| TC4 titanium alloy | 4430            | 1933               | 8                           | \(1.6 \times 10^{-6}\) | 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                      | \(1.8 \times 10^{-8}\) | Cu > = 99.95%     |

Fig. 6 SEAM machining system
5.2 Waveform analysis

The voltage and current waveforms of the four mediums during machining were acquired using a DEWEsoft SIRIUS multichannel data acquisition system. Figure 8 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 [28]. The DI water has weak electrical conductivity; leakage current is generated during the spark breakdown delay phase, which can lead to microelectrolysis [29]. When the medium is electrolyte only, the waveforms are electrolytic waveforms, and the maximum electrolytic current is 32 A. 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 waveform includes arc waveform, electrolysis waveform, and leakage current. The process is divided into SEAM-ECM synchronous, SEAM, and ECM alternate. Compared with using deionized water and air, electrolyte machining, electrolytic current, and arc current are reduced, and the energy acting on the surface of the workpiece is reduced, which helps to reduce the recast layer thickness on the surface of the workpiece.

5.3 Surface morphology and elemental analysis

Figure 9 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 buildup of the recast layer, which is a result of the uneven resolidification 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 the 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 exchanges in the electrolyte and form light flocculent material, which easily flows out of the gap, the surface product 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 deposited 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 $\text{CO}_2$ in the 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 [30], 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. 9, and the workpiece substrate is carried out as shown in Fig. 10. Titanium alloy forms dense oxide films TiO₂ 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, Ti₂O₃ is produced due to peroxidation. In addition, the intermediate product of the titanium alloy in the halide electrolyte is the corresponding halide TiCl₄ [25], but it is highly hydrolyzed, so only chlorine is detected on the surface and not TiCl₄. 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.

### 5.4 Cross-sectional morphology and recast layer thickness (RLT)

Figure 11 shows the microscopic morphology of the workpiece cross-section under different medium conditions; it 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 [31]. 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 RLT 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 ease to pass of the gap, the low thermal conductivity of the titanium alloy, and the heat generated by ECM is not enough to conduct to the base material, so there is basically no heat-affected zone.

Figure 13 selected cross-section recast layer (sediment layer), heat-affected zone, and base material for microhardness analysis, as shown in the figure; because TiO₂ and TiC can form a continuous solid solution, the hardness of the recast layer (sediment layer) is much higher than that of the heat-affected zone and base material; the hardness of the heat-affected zone and base material is basically the same, which means that TiC has not penetrated the recast layer (sediment layer), and the heat-affected zone material has not undergone obvious phase changes.

### 5.5 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. 14. 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 $\theta$, as shown in Fig. 15.

Figure 16 shows both the milling groove depth error $\Delta h$ and tilt angle $\theta$ under different medium conditions. As pulse energy and milling groove depth are positively correlated, the milling groove depth is increased using air machining. ECM also produces overcutting because of the existence of exceeding corrosion. 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. So, the combined machining using air and electrolysis has a significant improvement in cross-sectional shape accuracy compared with other forms of machining. Machining with electrolyte and air reduces $\theta$ by 55.56% compared to machining with deionized water and air and by 68% compared to machining with electrolyte alone.

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 Eq. (6):

$$x' = \frac{x - \text{Min}}{\text{Max} - \text{Min}}$$  \hspace{1cm} (6)

where Min and 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.
5.6 Surface roughness (SR)

The center area of the milling groove is selected for observation and measurement, and the 3D shape of the surface is shown in Fig. 17. When the medium is DI water, the flow velocity of the gap flow field is low, and the particles are easy to accumulate on the workpiece surface, so many bumps can be seen on the workpiece surface, and therefore the SR is as high as 63.49 μm. Although the flocculation of ECM-machined products is lighter and the products can be easily flushed out of the gap, the SR machined with electrolyte only is not ideal due to the presence of uneven stray pitting. The SR 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. When machining with electrolyte and air, the SR is significantly improved. Since ECM disperses the discharge energy, no deep pits are produced, and ECM polishing is also performed. SR is improved by 41.61% relative to machining with DI water and air and by 24.14% relative to machining with electrolyte alone.

5.7 Comprehensive performance evaluation

Figure 18 describes the comprehensive evaluation of the MRR, REWR, RLT, SR, and DAE after machining in different mediums. From the figure, MRR is the highest for

| Medium type | DI water | Electrolyte | Air + DI water | Air + electrolyte |
|-------------|----------|-------------|----------------|------------------|
| Dimensionless number | 0.3825 | 0.78 | 0.794 | 0.344 |

Fig. 17 3D surface shape of the milling groove
machining with DI water and air. However, the REWR and surface integrity indicators are not satisfactory. It is suitable for the first rough machining of the workpiece. The REWR of machining with electrolyte alone is very low. But low MRR and excessive stray pitting limits machining speed and accuracy. Machining with DI water alone does not meet machining expectations in all indicators. In terms of overall capability, machining with a combination of electrolyte and air provides a more balanced performance than 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 MRR, REWR, discharge state, surface morphology and elemental analysis, cross-sectional morphology and defects, RLT, DAE, SR, and finally, the comprehensive performance with different mediums is evaluated. The main conclusions are summarized as follows:

1. The simulation results show that the addition of gas increases the flow rate of the mixed medium and improves the flushing capacity. However, it causes a significant gas–liquid two-phase stratification phenomenon, which may lead to alternating SEAM and ECM.
2. Experimentation found that the combined machining waveform includes arc waveform, electrolysis waveform, and leakage current. The process is divided into SEAM-ECM synchronous, SEAM, and ECM alternate.
3. The results of surface morphology and elemental analysis show that additional TiC and Ti$_2$O$_3$ are produced on the machined surface due to air peroxidation. The product of machining by adding electrolyte produces a light flocculent substance that can be easily removed from the gap to improve the surface finish.
4. 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 machinings, the RLT of the workpiece machined by the combination of air and electrolyte is significantly reduced.
5. After a comprehensive performance evaluation, machining with electrolyte and air provides a more comprehensive and balanced machining performance.

Funding This research was supported by the Natural Science Foundation of Autonomous Region (Grant No. 2019D01C070) and the open topic research fund (Grant No. sklms2019009).

Declarations

Conflict of interest The authors declare no competing interests.
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