Investigating the pulse short electric arc milling of Ti6Al4V alloy

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Abstract
In this study, the machining characteristics of pulse short arc milling (SEAM) Ti6Al4V alloy were studied. In this regard, the influence of SEAM parameters on the material removal rate (MRR), relative electrode wear ratio (REWR), and surface integrity of Ti6Al4V is studied. A wide variety of processing parameters, including different voltages, frequencies, duty cycles, flushing pressures, electrode rotation speeds, and electrode feed rates, are considered in the investigation. Scanning electron microscope (SEM), energy dispersive spectrograph (EDS), and micro-hardness analysis are applied to analyze results. Moreover, a multi-channel data acquisition system is used to measure gap voltage and gap current. Obtained results cover the variation of MRR, REWR, surface roughness (Ra), average resolidified layer thickness, and average heat-affected zone thickness with different processing parameters. Furthermore, the electrode surface morphology and chemical composition of the negative growth of REWR are studied. Based on the obtained results, the microstructure of the resolidified layer and heat-affected zone of the workpiece cross-section is confirmed. This study provides a basis for the high-quality pulse SEAM technology of difficult-to-machine (DTM) materials to enter the semi-finishing field.

Keywords
Pulse SEAM · Ti6Al4V alloy · Material removal rate · Relative electrode wear ratio · Surface integrity

1 Introduction
Studies show that titanium alloys have excellent physical and mechanical properties so that they are widely applied in diverse applications, including aerospace, marine, and biomedical fields. However, these alloys have some drawbacks such as significant chemical activity at high temperatures and low thermal conductivity. In conventional mechanical methods for cutting the specimens made of titanium alloy, the cutting tool is prone to contact wear and stick at high temperatures, thereby reducing the tool life [1–3]. Meanwhile, worn tools yield poor surface finish and inaccurate dimensions. Recently, electrical discharge machining (EDM) has been proposed as a noncontact processing technology to remove DTM materials such as titanium alloys [4]. However, conventional EDM has some shortcomings such as low processing efficiency and emitting environmentally harmful pollutions, which severely limit its applications [5, 6].

In order to resolve some of the abovementioned shortcomings of conventional EDM, scholars have carried out extensive researches on the processing parameters, working medium, and applied auxiliary processing technologies. Hasçalı̇k et al. [7] studied the surface integrity of Ti6Al4V processed by EDM and found that the average white layer thickness increases with the pulse current and pulse duration. Experiments were conducted, and the maximum MRR reached 77.181 mm³/min. Kong et al. [8] used air and argon as the working medium to study the characteristics of submerged EDM machining Ti6Al4V. They showed that almost no micropore and microcrack remains after processing in the argon medium. Zhang et al. [9] proposed a magnetic field-assisted EDM method and showed that the proposed method can reduce electrode wear and processing noise compared with conventional EDM. Although the abovementioned methods improved the performance of EDM processing to a certain extent, the improvement of the processing efficiency is still limited. In fact, compared with the plasma in conventional EDM, the arc plasma in arc discharges is ionized more efficiently, thereby resulting in a higher temperature and thermal density and eroding the material more efficiently [10]. This shows that the arc discharge energy is higher than the spark

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discharge energy in EDM, so the corresponding machining efficiency is high. However, the arc phenomenon is defined as harmful to the normal processing of EDM [11]. Considering the high energy density of the arc plasma, Meshcheriakov et al. [12] proposed the arc dimensional machining (ADM) method, which can achieve high MRR and low REWR. Zhao et al. [13] proposed blasting erosion arc machining (BEAM) technology based on the hydrodynamic arc breaking mechanism. Chen et al. [14] studied the BEAM processing performance in Ti6Al4V and found that the maximum MRR reaches 16,800 mm³/min. Kou et al. [15] proposed a high-speed electric arc milling method that works with DC power. Experimental results show that this method can increase the MRR of Ti6Al4V and reduce REWR. Furthermore, Zhang et al. [16] studied the effect of flushing on the performance of EDM and electric arc machining (EAM) and found that flushing in the EAM can reduce REWR and surface roughness, while it has no obvious impact on the EDM. This indicates that flushing pressure plays an important role in reducing REWR and surface roughness in EAM.

As a type of EDM, short electric arc machining (SEAM) uses low-voltage (generally less than 60 V), wide pulse, and high current (from hundreds to thousands of amperes) pulse power. SEAM approach has been applied for machining large, high-strength, super-hard, and high-toughness alloy parts such as aero-engine casing, honeycomb sandwich, cement rolls, and coal mill rolls. Consequently, SEAM has been considered as an effective method for the efficient processing of DTM materials [17]. However, there are still some problems in SEAM, including high REWR, poor processing quality, and high surface roughness. In order to resolve these problems, several investigations have been conducted so far. Zhu et al. [18] studied the performance of SEAM under high-frequency and high-voltage pulses and achieved high MRR and low TWR. Furthermore, Chen et al. [19] studied the performance of GH4169 in SEAM under different polarities and found that the thickness of the heat-affected layer after a negative polarity machining is thinner than that after a positive polarity machining. Moreover, Liu et al. [20] studied the performance of SEAM with DC power supply in machining Ti6Al4V. They found that the maximum MRR of Ti6Al4V reaches 15,100 mm³/min, and the surface roughness S₉ reaches 699.92 μm. The surface quality of SEAM machining Ti6Al4V with DC power supply is worse than that of using pulse power supply [21].

Reviewing the literature indicates that few investigations have focused on the machining characteristics and surface integrity of pulse SEAM for Ti6Al4V alloy. Therefore, it is of significant importance to consider the influence of voltage, frequency, duty cycle, flushing pressure, electrode rotation speed, and feed rate on the MRR, REWR, and surface integrity of pulse SEAM machining Ti6Al4V. In this regard, some experiments will be carried out. It is expected to establish the foundation for the realization of the pulse SEAM Ti6Al4V process entering the semi-finishing stage.

2 Experimental details

2.1 Principle

Figure 1 shows the schematic configuration of the SEAM, where high-power pulses are generated in the power supply to provide sufficient energy. The tubular graphite electrode is installed on the spindle by an electrode clamp to achieve a high-speed rotation. When the process starts, a voltage is applied between the electrode and the workpiece. Then, the electrode starts to feed and narrows the gap between the electrode and the workpiece. Once the gap reaches a critical value, the working medium breaks down and an arc occurs. Under this circumstance, a high-temperature plasma discharge channel composed of a large number of high-speed moving charged particles forms between electrodes. Figure 2 indicates that the discharge channel acts on the surface of the workpiece and electrode and forms a gasification zone. Then, a melting zone and a heat-affected zone (HAZ) appear. The discharge channel moves on the workpiece surface through the feeding of the electrode to melt and vaporize the workpiece material. Due to the rapid flushing of the water-gas mixture between the workpiece and high-speed rotating electrode, the molten material and eroded debris discharge from the processing area. When the discharge is over, the inter-electrode returns to an electrically neutral state.

2.2 Experimental conditions

SEAM occurs under a certain proportion of tap water-air mixture with flushing pressure. Figure 3 shows the schematic configuration of the SEAM setup. The experimental conditions are detailed as follows.

1. Experimental equipment: SEAM CNC milling machine, a wire cutting machine, metallographic mosaic machine, a metallographic sample grinder (8 × 8 × 6 mm³), and a polishing machine.
2. Electrode: The electrode is a tubular graphite electrode with an external diameter of 18 mm and an internal diameter of 8 mm.
3. Workpiece: Dimensions of the Ti6Al4V workpiece are 32 × 32 × 8 mm³, and chemical composition and physical and mechanical properties are shown in Tables 1 and 2, respectively.
4. Testing equipment: Multichannel data acquisition system (DEWESoft SIRIUS), high-precision electronic scales (with a precision of 0.1 mg), digital microscope with a
super-field lens (VHX-6000), scanning electron microscopy (JSM-7610FPlus), and Vickers micro-hardness tester.

2.3 Experimental process

In order to ensure the accuracy of the SEAM in the experiment, a single-factor experiment was carried out. The experiment is repeated 3 times for each parameter. Meanwhile, the influence of different processing parameters is studied on the MRR, REWR, and surface roughness. Table 3 presents the settings of processing parameters. The surface morphology, cross-sectional morphology, chemical composition, and micro-hardness of a part of the workpiece were tested to further reveal the mechanism and performance of the pulsed SEAM Ti6Al4V. Setting of parameters is shown in Table 4. Moreover, MRR and REWR are defined as follows:

\[
MRR = \frac{M_{wi} - M_{wj}}{\rho_w} \times 10^3 \, \text{mm}^3/\text{min} \tag{1}
\]

\[
\text{REWR} = \frac{M_{ei} - M_{ej}}{M_{wi} - M_{wj}} \times 100\% \tag{2}
\]

where \(M_{wi}\) and \(M_{wj}\) are the quality of the workpiece before and after processing (g), respectively; \(M_{ei}\) and \(M_{ej}\) are the quality of the electrode before and after the processing (g), respectively; \(t\) and \(\rho_w\) denote the processing time (min) and density (g/cm\(^3\)) of the workpiece, respectively.

3 Experimental results and discussions

3.1 Effect of voltage on the machining performance

Figure 4 shows the influences of voltage on MRR, REWR, and Ra. It is observed that as the voltage increases, MRR and Ra increase while REWR first decreases and then increases. For the voltage of 30 V, the corresponding maximum MRR and Ra reach 32 mm\(^3\)/min and 44.98 \(\mu\)m, respectively. This is because when the voltage increases from 15 to 30 V, the output energy of the pulsed power supply increases, which increases the energy of the plasma discharge channel between electrodes, thereby increasing the critical discharge gap between electrodes [18]. Consequently, the molten material can simply discharge by the flushing liquid, thereby increasing the MRR. Due to the increase of the energy between electrodes and the discharge gap, the large volume of molten material easily removes from electrodes. These large volumes of molten material inevitably form larger pits after peeling off the workpiece surface. Moreover, the diameter of these pits increases as the discharge channel energy increases, thereby increasing Ra. On the other hand, when the voltage reduces to
25 V, the minimum REWR is 2%. This is because when the voltage is lower than 25 V, the inter-electrode gap becomes smaller, which seriously affects the discharge of the inter-electrode erosion material, resulting in a great increase in the short-circuit rate, and thus will increase the REWR of the graphite electrode. Meanwhile, when the voltage exceeds 25 V, the discharge gap and the energy of the discharge channel increase. Consequently, the molten material randomly hits the workpiece and the hits with an electrode, so the REWR increases.

### 3.2 Effect of the frequency on the machining performance

Figure 5 shows the influences of the frequency on MRR, REWR, and Ra. It is observed that as the frequency increases from 600 to 3400 Hz, MRR, Ra, and REWR decrease. This is because when the frequency increases, the duration of a single pulse decreases, and the energy in the discharge channel gradually tend to be discrete, which will lead to the formation of small and shallow discharge pits on the workpiece surface [22], thereby reducing the Ra and MRR. Moreover, as the continuous discharge time of each pulse between the electrodes reduces, discharge points between electrodes gradually uniform, thereby reducing the corner loss of the electrode, so the REWR gradually decreases.

### 3.3 Effect of the duty cycle on the machining performance

Figure 6 shows the influences of the duty cycle on MRR, REWR, and Ra. It is observed that as the duty cycle increases, MRR and Ra increase, while REWR first increases and then decreases. This is because when the duty cycle increases from 30 to 60%, the pulse width in a single arc discharge cycle increases, thereby increasing the arc discharge energy. Consequently, large and deep discharge pits appear on the workpiece surface, and the MRR and Ra increase. When the duty cycle is less than 40%, the REWR increases slowly. This is attributed to the narrow pulse width in a single discharge cycle when the duty cycle is less than 40%. Accordingly, the arc discharge energy decreases, which increases the electrode wearing. When the duty cycle exceeds 40%, the REWR decreases sharply because the pulse width output energy in a single arc discharge cycle is sufficient to melt workpiece material. Therefore, the collision probability between the electrode and workpiece material reduces during the pulse interval.

### 3.4 Effect of the flushing pressure on the machining performance

Figure 7 shows the impact of flushing pressure on machining performance. It indicates that as the flushing pressure increases, MRR first increases and then decreases, while REWR and Ra first decrease and then increase. This is because the heat dissipation in the SEAM is poor, which mainly originates from the small discharge gap and high viscosity of Ti6Al4V. Therefore, when the flushing pressure is less than 0.3 MPa, the inter-electrode melt cannot be discharged in time by the flushing, which
will cause short circuits and secondary discharges. Then, the incidence greatly increases, which decreases the MRR and increases the REWR. When the flushing pressure exceeds 0.3 MPa, excessive flushing pressure seriously affects the formation of the discharge channel. In order to further illustrate the influence of flushing pressure on the discharge state, a section consisting of inter-electrode discharge waveforms at 0.3 and 0.4 MPa is collected. Figure 7(c) shows that there are gap current waveforms in each pulse and the current average value is high. Consequently, the discharge channel energy is high, and the discharge process is stable. Moreover, Fig. 7(d) shows that there is no gap current waveform in some pulses for low-average currents. This is because when the flushing pressure is too high, the steady-state discharge channel is destroyed so that the non-steady-state discharge phenomenon increases, resulting in insufficient energy for the inter-electrode arc plasma to melt material. Consequently, MRR decreases, while REWR and Ra increase. However, Fig. 7(b) shows that when the flushing pressure reaches 0.5 MPa, the tubular graphite electrode cracks. It is concluded that in order to ensure stable processing, the flushing pressure should not be too large.

3.5 Effect of the electrode rotation speed on the machining performance

Figure 8 shows the influences of electrode rotation speed on MRR, REWR, and Ra. It is observed that as the electrode rotation speed increases, MRR first increases and then decreases, which is consistent with the variation of MRR in previously published results [23]. However, REWR and Ra first decrease and then increase as the electrode rotation speed increases. This is because when the electrode rotation speed is less than 1200 rpm and the input energy between electrodes and flushing pressure are constant, generated centrifugal force by the rotation of electrode cannot promptly throw the melt between electrodes, thereby solidifying the melt and covering workpiece surface, which affects the MRR. Meanwhile, when the electrode rotation speed exceeds 1200 rpm, discharge channels are generated first among the many micro-spikes. These discharge channels, which originate from the non-flat surface of the workpiece and electrode, are easily stretched and twisted or even broken. Accordingly, the cross-section of discharge channels reduces so that the MRR and Ra decrease when the rotating speed of the electrode is too high. The proper electrode rotation speed leads to uniform electrode wear and the long service life of the electrode [24]. When the electrode rotation speed is set to 1800 and 2400 rpm, REWR and Ra reach the minimum values of 2% and 18.99 μm, respectively. It is worth noting that excessive electrode rotation speed leads to a twisted discharge channel and causes mechanical contact between the workpiece and electrode, so that it may be one of the reasons for the increase in REWR and Ra.

3.6 Effect of the electrode feed rate on the machining performance

Figure 9(a) shows the influences of electrode feed rate on MRR, REWR, and Ra. It is observed that as the electrode feed rate increases, MRR and Ra increase, while REWR increases first, then decreases, and finally increases. When the electrode feed rate exceeds 30 mm/min, a short circuit occurs during the feed stage, resulting in the process failure. It is found that the critical electrode feed rate is 30 mm/min, and the MRR reaches a maximum value of 556 mm³/min. On the other hand, when the electrode feed rate is less than 30 mm/min, the energy provided by the inter-electrode discharge channel can effectively melt workpiece material and can ensure the synchronization of the energy and feed rate, thereby increasing the MRR and Ra. When the electrode feed speed is too high, the synchronization between discharge energy and electrode feed speed is poor, which will greatly increase the probability of electrode contact with the workpiece. Consequently, the possibility of short circuits and collision increases, thereby increasing the REWR. When the electrode feed rate is less than 6 mm/min, the movement speed of the inter-electrode discharge channel on the surface of the workpiece is slow.

| Table 2 Physical and mechanical properties of Ti6Al4V |
|-----------------------------------------------|
| Micro-hardness | Melting point | Tensile strength | Thermal conductivity | Elongation | Density  |
| 320~350 HV | 1604~1660°C | 862~1200 MPa | 7.1~7.3 W/m k | 15% | 4510 kg/m³ |

| Table 3 Parameters of SEAM |
|---------------------------|
| Parameter (unit) | Value |
| Polarity of workpiece | Positive (+) |
| Voltage (V) | 15, 20, 21.5, 23.5, 25, 26.5, 28.5, 30 |
| Frequency (Hz) | 600, 1000, 2300, 3400 |
| Duty cycle (%) | 30, 40, 50, 60 |
| Flushing pressure (MPa) | 0.2, 0.25, 0.3, 0.35, 0.4, 0.5 |
| Electrode rotation speed (rpm) | 600, 1200, 1800, 2400, 3000 |
| Electrode feed rate (mm/min) | 2, 4, 5, 6, 7, 8, 9, 10, 20, 30 |
| Milling depth (mm) | 2 |
| Milling width (mm) | 10 |
Therefore, cations in the discharge channel obtain greater kinetic energy and impact the electrode, thereby increasing the REWR. It is found that when the electrode feed rate reaches 6 mm/min, REWR approaches ~4%. Figure 9(b) indicates that when the electrode feed rate is set to 6 mm/min, the edge loss of the electrode is lower than that of 5, 7, and 8 mm/min. In order to further investigate the negative growth of REWR, it will be discussed in detail in Section 4.1.

4 Surface integrity analysis

In order to study the influence of the frequency, duty cycle, flushing pressure, voltage, and electrode rotation speed on the surface morphology and cross-sectional resolidified layer (RSL), heat-affected zone (HAZ), micro-hardness and chemical composition of Ti6Al4V, and other parameters are kept constant in the SEAM process. Table 4 shows that six levels named E1–E6 are considered for five parameters.

4.1 Surface morphology analysis of the electrode

In the experiment, when the electrode feed rate is set to 6 mm/min, the corresponding REWR is ~4%. However, for the electrode feed rates of 5 and 7 mm/min, the corresponding REWR is 3 and 5%, respectively. In order to further study the reasons for the negative growth of REWR. Three groups of electrodes with electrode feed rates of 5, 6, and 7 mm/min were selected to observe and detect the micro-morphology and chemical composition of the graphite electrode surface by SEM and EDS, respectively.

Figure 10 shows the SEM images and EDS spectrum of the graphite electrode surface for different electrode feed rates. It is observed that pits appear on the electrode surface due to the influence of electric discharge, so that some eroded particles are attached to the electrode surface. Meanwhile, the EDS spectrum in Fig. 10(a)–(c) indicates that Ti, O, Ca, and Na appear on the electrode surface. Figure 10(a) and (b) shows the presence of Fe, Cl, and Al elements. It should be indicated that Ti, Fe, and Al are typical elements of Ti6Al4V workpieces, while O, Ca, Na, and Cl elements originate from the tap water. This is because processing under certain pressure of water and gas medium is affected by the multi-field coupling when the electrodes are discharged, and electrochemical reactions will occur to produce titanium, aluminum, oxygen, calcium, chlorine, and other ions. The abovementioned ions will form TiO2, Al2O3, CaO, and other compounds under the rapid cooling of the water-gas flushing liquid, and these oxides adhere to the surface of the electrode and workpiece to form an oxide layer similar to an oxide film [8]. The melting points of TiO2, Al2O3, and CaO are 1842°C, 2054°C, and 2572°C, respectively.

| No. | Voltage (V) | Frequency (Hz) | Duty cycle (%) | Flushing pressure (MPa) | Electrode rotation speed (rpm) | Electrode feed rate (mm/min) |
|-----|-------------|----------------|---------------|------------------------|-------------------------------|-----------------------------|
| E1  | 30          | 1000           | 40            | 0.3                    | 1800                          | 2                           |
| E2  | 30          | 600            | 40            | 0.3                    | 1800                          | 2                           |
| E3  | 30          | 1000           | 30            | 0.3                    | 1800                          | 2                           |
| E4  | 30          | 1000           | 40            | 0.5                    | 1800                          | 2                           |
| E5  | 25          | 1000           | 40            | 0.3                    | 1800                          | 2                           |
| E6  | 30          | 1000           | 40            | 0.3                    | 3000                          | 2                           |

Fig. 4 Effect of voltage on machining performance

Fig. 5 Effect of frequency on machining performance
respectively, which are all higher than the melting point of the Ti6Al4V material (1604–1660°C). Therefore, to a certain extent, it reduces the further wear of the electrode and affects the removal efficiency of workpiece material. When these oxides adhere to the surface of the electrode, the weight of the electrode increases, which reduces REWR and even compensates the electrode wear. On the other hand, for the electrode feed rate of 6 mm/min, the contents of O, Ca, and Al are 2.5 times, 8 times, and 3 times the other two feed rates, respectively. Subsequently, more oxides are produced on the electrode surface, thereby increasing the electrode weight. Accordingly, the corresponding REWR reduces to −4%.

4.2 Surface morphology analysis of the Ti6Al4V

Figure 11 shows the SEM image of the surface after pulsed SEAM Ti6Al4V under different processing parameters. Erosion holes, micro-cracks, RSL, pits, droplets, and spherical
particles are observed on the Ti6Al4V surface processed with different parameters. Erosion holes are formed due to the rapid flushing of water-gas mixed medium and high-speed rotation of electrodes. As a result, the erosion debris hits the molten pool on the surface of the workpiece at high speed. Since the molten material is rapidly cooled and solidified under the high-pressure flushing liquid between poles, the internal thermal stress of the material cannot be released in time, thereby forming micro-cracks. The RSL is formed because the molten workpiece material is rapidly solidified and attached to the surface of the workpiece under the cooling of the rapid flushing medium. Due to the different processing parameters, different features will appear on the surface of the workpiece after processing.

Comparison of Fig. 11(a) and (b) shows that the SEM images are significantly different. It is found that when the frequency is reduced from 1000 to 600 Hz, large and deep pits appear on the surface of the workpiece and the bottom is relatively smooth without RSL. Figure 11b shows that the number of micro-cracks on the surface of the workpiece is significantly reduced when the frequency is 600 Hz. When the frequency is reduced, the single arc discharge time is prolonged. Therefore, Fig. 11b shows that large and deep pits occur, which is consistent with the analysis results in the Section 3.2. Comparing Fig. 11(a) and (c) shows that when the duty cycle drops from 40 to 30%, the surface integrity of the workpiece is significantly improved, the microcracks are reduced, and almost no erosion holes are observed. Moreover, laminated droplets are observed. This is because the pulse width in a single discharge cycle is narrowed, resulting in a shorter arc discharge energy duration. Therefore, the newly melted material cannot be sufficiently cooled, and the adhesion between the droplets occurs.

Comparing Fig. 11(a) and (d) illustrates that when the flushing pressure increases from 0.3 to 0.5 MPa, larger diameter pits, smaller erosion holes, fewer microcracks, and irregular edges RSL are observed on the surface of the workpiece. Figure 11d shows that when the flushing pressure increases to 0.5 MPa, due to the high-speed flushing of inner and outer flushing fluid, the inter-electrode discharge channel is destroyed and a large explosive force is produced [15]. Therefore, the molten workpiece material does not have enough time to cool and adhere to the surface of the workpiece, which leads to larger pits, smaller erosion holes, and fewer micro-cracks.

Comparison of Fig. 11(a) and (e) indicates that when the voltage was reduced from 30 to 25 V, more erosion holes appear on the surface of the workpiece, and the distribution of RSL was more. This is because when the voltage is low, the arc energy reduces, resulting in a slower material melting speed so that the workpiece is cooled by the flushing liquid before it is completely melted. Consequently, more RSL distributions appear on the workpiece surface. Meanwhile, considering the tap water–air mixed medium scouring, air enters the molten pool on the surface of the workpiece and then the air is heated so that it expands and escapes, resulting in more erosion holes.

Comparing Fig. 11(a) and (f) indicates that when the electrode rotation speed is increased from 1800 to 3000 rpm, the surface of the workpiece has an RSL, fewer micro-cracks, and more spherical particles. When the electrode rotation speed is increased to 3000 rpm, since the high-speed rotation of the electrode enhances the discharge ability of the inter-electrode erosion, there will be fewer micro-cracks and larger pits. Moreover, the high-speed rotation of the electrode causes the inter-electrode discharge channel to be distorted, deformed, or even broken. Therefore, the high-speed rotating electrode will bring part of the molten material into the molten pool on the surface of the workpiece randomly, resulting in a large number of spherical particles, as shown in Fig. 11(f).

4.3 Cross-section analysis of the Ti6Al4V

4.3.1 Cross-sectional topography analysis

Figure 12 shows the SEM images of the cross-sectional morphology of Ti6Al4V after SEAM under different processing parameters, including partially enlarged images of the RSL and HAZ. Moreover, Fig. 13(a) shows the average resolidified layer thickness (ARSLT) and average heat-affected zone thickness (AHAZT) under different processing parameters. Figure 12 presents that the RSL, HAZ, and base material can be observed in all cross-sectional SEM images [22].
Figure 13(a) shows that when the frequency is reduced from 1000 to 600 Hz, the ARSLT increases from 41.4 to 49.6 μm. Moreover, it is found that the AHAZT is reduced from 14.1 to 5.1 μm. Figure 12(a) and (b) shows that the microstructure of the RSL changes from granular to larger snowflake-like shape, and columnar grains appear in the microstructure of the HAZ. This is because when the frequency decreases, the discharge time of a single pulse is prolonged. Therefore, the energy in a single pulse increases, and the ARSLT increases. The decrease in the AHAZT may be explained by the poor thermal conductivity of Ti6Al4V. When other parameters are constant, reducing the frequency will increase the energy of a single pulse, resulting in a snowflake-like microstructure with larger particle size. Due to the poor thermal conductivity of Ti6Al4V, the heat in the cross-section is reduced in a very short time. Therefore, grain refinement appears in the HAZ.

Figure 13(a) shows that when the duty cycle is reduced from 40 to 30%, the ARSLT decreases from 41.4 to 39.6 μm, and the AHAZT is reduced from 14.1 to 7.4 μm. Moreover, Fig. 12(a) and (c) shows that the microstructure...
of the RSL changes from larger particles to smaller particles. The microstructure of the HAZ changes from refined columnar crystals to coarse α+β phases. This is because when the duty cycle decreases, the pulse width becomes narrower. Therefore, the energy in a single pulse decreases, which will lead to a decrease in ARSLT and AHAZT. When other parameters are constant, the energy of a single pulse is reduced after the duty cycle is reduced, which leads to a smaller size of the microstructure particles of RSL when the duty cycle is 30%. When the heat transferred from the Ti6Al4V machining surface to the HAZ reduces, the degree of the grain refinement reduces too.

Figure 13(a) shows that when the flushing pressure increases from 0.3 to 0.5 MPa, ARSLT decreases from 41.4 to 26.0 μm, and AHAZT decreases from 14.1 to 9.3 μm. Moreover, Fig. 12(a) and (d) shows that the microstructure of RSL changes from a granular shape to a snowflake-like shape with larger gaps, while the microstructure of HAZ has fewer columnar crystals. This is because when the flushing pressure increases, the cooling effect between the machining electrodes is better, which leads to the reduction of ARSLT and AHAZT. When other parameters are constant, increasing the flushing pressure will enhance the ability of the inter-electrode to discharge particles, resulting in a larger gap.

Fig. 11 Effects of different processing parameters on the surface morphology of Ti6Al4V. (a) E1, (b) E2, (c) E3, (d) E4, (e) E5, and (f) E6
between the snowflake-like particles in the RSL microstructure when the flushing pressure is 0.5 MPa. Due to the enhancement of the cooling capacity, most of the heat is difficult to transfer to the HAZ. Therefore, the microstructure of HAZ does not change significantly.

Figure 13(a) indicates that when the voltage decreases from 30 to 25 V, the corresponding ARSLT decreases from 41.4 to 33.1 μm, and the AHAZT reduces from 14.1 to 7.2 μm. This is because when the voltage decreases, the arc energy decreases, too, thereby reducing the discharge heat transfer to
the inside of the workpiece so that ARSLT and AHAZT decrease. Moreover, Fig. 12(a) and (e) shows that the microstructure of the RSL changes from larger particles to smaller particles. This is because when the voltage decreases while other parameters remain constant, the arc energy decreases. Meanwhile, a large volume of the molten material can be removed from the processing area under the flushing of the inner and outer fluids, and only a part of small volume of molten material is cooled and solidified on the workpiece surface.

Figure 13(a) illustrates that when the electrode rotation speed increases from 1800 to 3000 rpm, the ARSLT decreases from 41.4 to 35.8 μm, while the AHAZT is reduced from 14.1 to 6.4 μm. Moreover, Fig. 12(a) and (f) shows that the microstructure of RSL changes from granular to smaller particles. This is because when the rotation speed of the electrode increases, the centrifugal force generated by the high-speed rotating electrode increases, which simplifies the discharge of the erosion material between discharge electrodes. This reduces the phenomenon of secondary discharge and short-circuit ablation; thereby, ARSLT and AHAZT are reduced. When other parameters are constant, increasing the electrode rotation speed enhances the ability of the electrode to discharge and abolish particles, resulting in an increment of the electrode rotation speed, while the particle size of the microstructure of RSL decreases.

### 4.3.2 Micro-hardness and EDS analysis

Figure 13(b) E1 and E2 show the micro-hardness of RSL, HAZ, and base material. It is observed that when the frequency is reduced from 1000 to 600 Hz, the micro-hardness of RSL increases from 464 to 525 HV, and the micro-hardness of HAZ increases from 364.5 to 482 HV. This is because as the frequency decreases, the duration and energy of a single-pulse discharge increase. Accordingly, the micro-hardness of RSL and HAZ increases, too. Studies show that because some α-Ti in the HAZ transform into β-Ti under high temperature and rapid cooling, the micro-hardness of HAZ is lower than that of RSL [25]. Figure 14(a) and (b) shows the EDS spectra of RSL, HAZ, and base material. It is observed that when the frequency reduces to 600 Hz, the content of Al in the RSL reduces from 2.10 to 0.28%, the C content in the RSL is more than 2.6 times that of 1000 Hz. This is due to the lower melting point of Al.

Comparing Fig. 13(b) E1 and E3 shows that when the duty cycle reduces from 40 to 30%, the micro-hardness of HAZ is reduced from 364.5 to 352.5 HV, the micro-hardness of RSL increases from 464 to 525HV. As the pulse width decreases, the discharge energy decreases, and the micro-hardness of the HAZ decreases. It is worth noting that the micro-hardness in the RSL increases, which may be attributed to the rapid cooling of the working medium. Figure 14(a) and (c) shows that the C content in the RSL at a duty cycle of 40% is lower than at a duty cycle of 30%. This is because when the pulse width reduces, the pulse interval increases and electrode wear increases, too, thereby increasing the C content.

Comparing Fig. 13(b) E1 and E4 shows that when the flushing pressure increases from 0.3 to 0.5 MPa, the rapid cooling between the processing electrodes and the ability to discharge ablated particles are greatly enhanced. The process is similar to quenching. Therefore, the RSL micro-hardness increases from 464 to 583 HV, and the HAZ micro-hardness increases from 364.5 to 491 HV. Combined with the changes in the content of C and O elements in RSL and HAZ, it is found that after increasing the flushing pressure, the discharge channel will be destroyed by working medium fluid. As a result, Fig. 14(a) and (d) shows that a greater explosive force is generated to accelerate the interpolar element infiltration, which will lead to an increase in the content of C and O elements in RSL at 0.5 MPa. Considering the better cooling effect of rapid flushing, the reduction of Al content significantly decreases.
Comparing Fig. 13(b) E1 and E5 shows that when the voltage is reduced from 30 to 25 V, the micro-hardness of RSL decreases from 464 to 452 HV and the micro-hardness of HAZ decreases from 364.5 to 358 HV. This is because when the voltage decreases, the arc energy decreases, the melting speed of the workpiece material decreases, and the rapid cooling effect weakens, so the microhardness of RSL and HAZ decreases. In addition, considering the reduction of the arc energy between electrodes, the oxidation rate of the workpiece material decreases, and the rapid cooling effect weakens, so the microhardness of RSL and HAZ decreases. In addition, considering the reduction of the arc energy between electrodes, the oxidation rate of the workpiece material reduces, so the content of O and Al reduces. This phenomenon is illustrated in Fig. 14(a) and (e).

Comparing Fig. 13(b) E1 and E6 shows that when the electrode rotation speed increases from 1800 to 3000 rpm, the micro-hardness of RSL increases from 464 to 562 HV and the micro-hardness of HAZ increases from 364.5 to 476.5 HV. This is because the centrifugal force generated by the rotation of the electrode increases so that the inter-electrode melt cools quickly and then it is quickly thrown away from the processing area. Meanwhile, fast cooling increases the microhardness of RSL and HAZ. When the electrode rotation speed increases to 3000 rpm, the arc between the positive and negative electrodes mechanically stretches.

Fig. 14 Cross-sectional EDS spectrum under different processing parameters: (c) E1, (d) E2, (e) E3, (f) E4, (e) E5, and (f) E6.
and destroys, thereby generating a greater explosive force and accelerating the movement of the graphite electrode erosion particles to the surface of the workpiece and the oxidation of the workpiece surface. Accordingly, the content of C and O elements in the RSL increases. This phenomenon is shown in Fig. 14(a) and (f).

5 Conclusions

In the present study, the effects of voltage, frequency, duty cycle, flushing pressure, electrode rotation speed, and electrode feed rate on pulsed SEAM Ti6Al4V are experimentally studied. Moreover, the changes in the surface and cross-sectional morphology of Ti6Al4V, the ARSLT, the AHAZT, the element composition, and the micro-hardness of the processed Ti6Al4V are investigated. The main conclusions are as follows.

1) MRR increases as the voltage, duty cycle, and electrode feed rate increase and decrease as the frequency increases. Moreover, MRR initially increases and then decreases as the flushing pressure and electrode rotation speed increase. When the electrode feed rate is 30 mm/min, MRR reaches the maximum value of 556 mm³/min. REWR initially decreases and then increases as the voltage, flushing pressure, and electrode rotation speed increase, while it decreases as the frequency increases. Moreover, it initially increases and then decreases as the duty cycle increases. The surface roughness Ra increases as the voltage, duty cycle, and electrode feed rate increase, while it decreases as the frequency increases. Moreover, Ra initially increases and then decreases as the flushing pressure and electrode rotation speed increase. When the frequency is 3400 Hz, Ra reaches the minimum value of 13.15 μm.

2) The negative growth of the REWR parameter group is detected. Moreover, it is found that O, Ca, and Cl in water and gas medium and Ti, Fe, and Al in Ti6Al4V penetrate the electrode surface. An electrochemical reaction occurs between the electrodes, and the compound produced by it adheres to the electrode surface to help compensate for the electrode wear.

3) Appropriate reduction of frequency and duty cycle can result in better surface integrity. Moreover, a reasonable reduction in the flushing pressure can effectively reduce the number of erosion holes and microcracks.

4) The ARSLT increases as the voltage, duty cycle, and flushing pressure increase, while it decreases as the frequency and electrode rotation speed increase. Moreover, AHAZT increases as the voltage, frequency, duty cycle, and flushing pressure increase, while it decreases as the electrode rotation speed increases. The micro-hardness of the RSL increases as the flushing pressure, voltage, and electrode rotation speed increase, while it decreases as the frequency and duty cycle increase. The micro-hardness of HAZ increases as the voltage, duty cycle, flushing pressure, and electrode rotation speed increase, while it decreases as the frequency increases. Moreover, it is found that the micro-hardness of RSL and HAZ increase as the carburizing amount increases, and the microstructures of RSL and HAZ are confirmed.

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Data availability Data transparency

Code availability Software application or custom code

Declarations

Conflict of interest The authors declare no competing interests.

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