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The effect of electron beam surface remelting on the wear behavior of Ti-6Al-4V by EBF³

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Abstract

Ti-6Al-4V alloy is one of the key materials in the aerospace and chemical industries. Additive manufacturing (AM), e.g., electron beam freeform fabrication (EBF³), is increasingly applied to manufacture the titanium part due to its low cost, high flexibility, high efficiency, etc. At the same time, the wear resistance and hardness of the Ti-6Al-4V alloy synthesized by AM can deteriorate during fabrication. In this paper, electron beam surface remelting (EBSR) is used to improve the wear resistance and hardness of the titanium alloy made by EBF³. The phase, microstructure, element composition, and wear track profile of layers remelted at three EBSR-beam currents were analyzed. According to the results, the synthesized alloy consists of a homogeneous α’ martensitic structure with numerous embedded nano-scale particles rather than a dual α + β lamellar structure when a rapid cooling rate is applied during EBSR. Simultaneously, the coarser prior-β grain boundary was eliminated in the process. The wear rate of the as-obtained remelted layers at the EBSR-beam currents of 0 (as-deposited), 3, 6, and 9 mA was determined as 7.7 × 10⁻¹⁰, 5.7 × 10⁻¹⁰, 7.9 × 10⁻¹⁰, and 8.9 × 10⁻¹⁰ m³/Nm, respectively. The evolution of the structure accounts for the high hardness and superior wear resistance. EBSR successfully modified the as-deposited microstructure to achieve favorable wear properties, which widens the application potential and extends service life.

1. Introduction

Ti-6Al-4V alloy is widely used in the aerospace and chemical industries due to its promising properties of high specific strength, low density, excellent corrosion resistance, and high fracture toughness [1, 2]. In recent years, additive manufacturing (AM) has become an attractive choice for titanium alloy fabrication due to its high economic benefits from near-net shape manufacturing and increased efficiency and flexibility [1-3]. Electron beam freeform fabrication (EBF³) is a promising AM technique due to its high deposition rate, suitability for large-scale component manufacture, and application in a vacuum environment [4, 5]. The thermal behavior and cooling rate of AM process are detailed studied in [6, 7]. The increasing power can decrease the cooling rate, and the trend is attributed to an increase in the heated volume, resulting in a smaller local thermal gradient and less effectiveness of the surrounding material as a heat sink. Besides, a higher power enlarges the heat-affected zone (HAZ), and its combined size with the melting pool, the temperature also increases. In this case, the rate of thermal energy extracted from the reconsolidation region is slower. In the EBF³ fabricating process, its input energy can be higher than laser-based AM process, and generally, the cooling rate is relatively lower. Under such thermal behavior, the EBF³-fabricated Ti-6Al-4V alloy shows an un-even distributed coarse lamellar, basketweave, and Widmanstätten structures [8, 9], which make EBF³-fabricated Ti-6Al-4V alloy has a lower hardness and wear-resistant, e.g., 270 HV₀.₂ than other fabrication methods 370–400 HV₀.₂ [10, 11]. The lower wear and abrasion resistance limit the further application of EBF³-fabricated Ti-6Al-4V alloy in the aeronautical manufacturing field. Therefore, a surface modification is required to enhance the hardness and wear resistance of the deposited specimens.
The surface modification techniques applied to improve the wear resistance of titanium alloys include electroplating [12], electroless plating [13], vapor deposition [14], and electron beam surface remelting (EBSR) [15]. Both electroplating and electroless plating are mature technologies. However, the bonding strength between the coating and the base metal is insufficient to suit severe wear and impact requirements. The vapor deposition equipment is complex and expensive, and the coating layer is usually only a few microns [16]. Among these technologies, EBSR acts on the substrate or the applied coating to refine the grains of the surface or increase the bonding capability of the coating. As a high-energy source, the electron beam has low reflectivity and is applied in a vacuum environment, which improves work efficiency and eliminates contamination and oxidation problems. Therefore, EBSR seems to be a superior method to other modification technologies.

EBSR is a well-established technology to enhance coating adhesion to the substrate and improves surface properties (corrosion or wear resistance). As a high-energy surface modification process, EBSR provides a new method for bulk heat treatment [17]. The remelted layer (heat treatment layer) is limited to a thin thickness due to the generation of a homogenous α′ martensitic surface layer, which provides a more stable passive film. Rastkar and Shokri [18] modified Ti-45Al–2Nb–2Mo–1B by EBSR, studied the rapid heating and solidification, and analyzed the formed composite coating layer containing B2 and α2 phases. Under the fast cooling rate of the EBSR, a harder and finer B2 phase replaced the dendritic structure. Velde et al [21] investigated the solidification and alloying process of EBSR theoretically and experimentally and proposed theoretical models. However, the influence of EBSR and its parameter on the surface microstructure and properties of titanium alloy manufactured by AM has not been fully understood. Remelting is the effect of multiple factors and complex heat input on the solidification process. Thus, the process factors such as electron beam current, scanning rate, layer thickness, and scanning strategy also play important roles. There is little coverage of the effect of the EBSR process on the molten pool geometri. The substrate metal is not heated up to the critical temperatures (no transformation), so the process has little effect on the size and thermal history of the bulk metal [19]. In recent years, interest in electron beam surface modification has increased. Walker et al [20] applied pulsed electron beam surface treatment on Ti-6Al-4V alloy. They found an enhancement in corrosion resistance due to the formation of a homogenous α′ martensitic surface layer, which provides a more stable passive film.

The temperature field and cooling rate in the process of EBSR have significant effects on its microstructure and mechanical properties. Several researchers used numerical modeling methods to assist in revealing the microstructure transformation and properties changes of alloy surface melting. Balichakra and Bontha et al [22, 23] deeply investigated deposition and laser surface melting of γ-TiAl alloy using both experiment and simulation approaches. Deposited γ-TiAl samples showed a fine lamellar structure comprised of γ and α2 phases, and 1.3%–2.1% microporosity was found. After LMS processing, α2-Ti3Al phase almost disappeared, and hardness improved due to phase transformation and higher cooling rates. Wang et al [24] combined processing parameters with dendrite spacing and developed a numerical model to predict the solidification microstructure of titanium aluminum intermetallic alloy by laser surface remelting. The nonequilibrium solidification of LAM was considered, and a geometry factor was introduced to improve prediction accuracy.

This study firstly aims to deepen the understanding of the influence of electron beam remelting parameters and integrate remelting with titanium alloy AM technology. In this paper, the EBF3-fabricated Ti-6Al-4V bulk alloy was surface-treated by electron beam remelting. Three representative electron beam currents (line energy density) from low to high were selected to carry out the remelting experiment. A simulation of transient molten pool in the process was also conducted to analyze the temperature field of the workpiece during EBSR. And the relationship between the beam current and the macro-morphologies, microstructure, phase composition, and wear behavior was investigated by changing the magnitude of the beam current.

2. Experiment

Ti-6Al-4V alloy workpiece with 150 × 70 × 100 mm was fabricated using the EBF3 technique. The workpiece was deposited under a vacuum of 10−3 Pa, using a power of 4 kW, a wire feeding rate of 3500 mm min−1, and a traverse speed of 650 mm min−1. Specimens of 15 × 15 × 4 mm were cut from the EBF3-fabricated product and then subjected to EBSR in single-track and multi-track patterns. The details of the remelting experiments are shown in figure 1. EBSR experiments were conducted in the EBF3 chamber under a vacuum of 10−3 Pa, with an acceleration voltage of 60 kV and a scanning speed of 300 mm min−1. Three different beam currents (3 mA, 6 mA, and 9 mA) were chosen to provide various energy inputs. The linear energy (E0) in the EBSR process can be calculated as E0 = UI/v [25], where U, I, and v denote the acceleration voltage, beam current, and scanning speed, respectively. The specific parameters and the corresponding linear energy inputs are listed in table 1. The overlapping rate between two tracks is 50%, the length is 15 mm, and each track was remelted along one direction.

The macrostructure was investigated by a stereomicroscope with an SZN71 zoom stereomicroscope. The microstructure was characterized by optical microscopy (OM) with a ZEISS optical microscope, by scanning
electron microscopy (SEM) with a TESCAN LYRA3 focused ion beam scanning electron microscope, and by energy-dispersive x-ray spectroscopy (EDS) with a spectrometer from Bruker. Before observing the microstructure, the specimens were polished and etched with Kroll’s reagent (4 ml HF, 6 ml HNO3, and 90 ml H2O) for 30 s. The phases of the samples with and without remelting were determined by x-ray diffraction (XRD) measurement with 2θ ranging from 30° to 80° using a D8 Advance x-ray diffractometer from Bruker with Cu Kα radiation and a scanning rate of 10° min⁻¹ at 40 kV. Hardness measurements were conducted on the remelted surface of the samples using a Vickers microhardness tester (HX-1000TM) with a load of 200 g and a dwell time of 10 s. The obtained results are the average of three readings for each indentation.

Dry sliding friction tests were performed on an MFT-5000 ball-on-flat tribometer from Rtec using ASTM G133 standard test method in a linear reciprocating motion. The specimens were polished to a mirror-like surface and cleaned in ethanol in an ultrasonic bath for 10 min before the wear test. A coupled GCr15 (62 HRC) ball with a diameter of 6.35 mm was used. Experimental parameters were kept constant at a normal load of 10 N, sliding speed of 4 mm s⁻¹ (1 Hz), stroke length of 2 mm, and 20 min. During the sliding experiments, the device continuously gave the friction coefficient. Ambient temperature and relative humidity were controlled at 25 ± 3 °C and 50 ± 5% RH, respectively. The wear volume after friction tests of each sample was estimated using a 3D non-contact optical US series profilometry from Rtec. Besides, wear scars were observed by SEM, and the wear debris was analyzed by EDS. The volume losses obtained by profilometry were converted into wear rate (Ws) via the following equation:

\[ W_s = \frac{V}{P \cdot S} \]  

where \( V \) is the wear volume in m³, \( P \) is the load in N, and \( S \) is the stroke length in m [26].

3. Results and discussion

3.1. Molten pool size

The macro-morphologies of the cross-section of a single-track molten pool for different beam currents used in the EBSR process are shown in figure 2. The cross-section morphology of all samples can be divided into three areas according to the different microstructural features, namely the remelted zone (RZ), the heat-affected zone...
It can be observed that the RZ was separated from the HAZ by a fusion line, showing different solidification states. The dimensional analyses were carried out on a single track to investigate the macrostructure further. The geometric data of the molten pool are listed in Table 2. The depth and width of the track increase with increasing beam current (power). As the power increases, the remelted layer absorbs more heat energy, the cooling rate of the molten pool decreases, and the temperature and fluidity of the molten pool increase. Under gravity, the remelted alloy spreads to both sides and ends, increasing the molten pool’s width and depth. At the same time, the photographs in figures 1(c)–(e) indicate that the remelted layer created with lower power exhibits a better surface quality.

In addition, a simulation model of the transient molten pool in the electron beam surface remelting process is built. The thermophysical properties of Ti6Al4V alloy, such as density, conductivity, and specific heat were inputs to the model as a function of temperature. And the relevant thermophysical properties used in the simulation are shown in Table 3. In the EBSR process, the dimensions of the substrate were 15 mm (length) × 15 mm (width) × 4 mm (thickness). In the mesh model, an element size of 0.3 mm (length) × 0.3 mm (width) × 0.5 mm (thickness) was used, as shown in Figure 3.

| Sample            | Width (mm) | Depth (mm) |
|-------------------|------------|------------|
| As-deposited      | 0          | 0          |
| EBSR-3 mA         | 2.17       | 0.75       |
| EBSR-6 mA         | 3.31       | 1.21       |
| EBSR-9 mA         | 3.96       | 1.54       |

### Table 3. Thermophysical properties.

| Temperature °C | Density kg m⁻³ | Specific heat J kg⁻¹ K | Conductivity W m⁻¹ K |
|----------------|----------------|------------------------|----------------------|
| 20             | 4430           | 611                    | 6.08                 |
| 100            |                | 623.81                 | 7.42                 |
| 200            |                | 652.95                 | 8.71                 |
| 300            |                | 673.94                 | 9.81                 |
| 400            |                | 690.86                 | 10.32                |
| 500            |                | 702.77                 | 11.79                |
| 600            |                | 712.17                 | 12.89                |
| 700            |                | —                      | 13.99                |
| 800            |                | —                      | 14.98                |
| 900            |                | —                      | 16.19                |
| 1000           |                | —                      | 17.21                |

(HAZ), and the substrate. The dimensional analyses were carried out on a single track to investigate the macrostructure further. The geometric data of the molten pool are listed in Table 2. The depth and width of the track increase with increasing beam current (power). As the power increases, the remelted layer absorbs more heat energy, the cooling rate of the molten pool decreases, and the temperature and fluidity of the molten pool increase. Under gravity, the remelted alloy spreads to both sides and ends, increasing the molten pool’s width and depth. At the same time, the photographs in figures 1(c)–(e) indicate that the remelted layer created with lower power exhibits a better surface quality.
The Gaussian surface heat source term for the electron beam used in the heat transfer and fluid flow model is expressed by equation (2) [27],

$$ q(r) = \frac{2\eta Q}{r_0^2} \cdot \exp \left( -\frac{2r^2}{r_0^2} \right) $$

where $r_0$ is the effective beam radius (m) at which the energy density decays to $1/e^2$ at the center of the beam spot, $Q$ is the beam power (W), $r$ is the actual spot radius, and $\eta$ is the energy efficiency, which was assumed to be 90%. In addition, the boundary conditions for this simulation are tabulated in table 4.

Comparison results of the actual remelting layer and temperature field under different beam currents, as well as the molten pool temperature variation at a point on the center line, are shown in figure 4. The simulation results are in good agreement with the experimental results and the cooling speed calculated according to the

### Table 4. Simulation boundary conditions.

| Parameters                              | Value          |
|-----------------------------------------|----------------|
| Ambient and initial temperature (°C)    | 25             |
| Absolute zero temperature (°C)          | −273.15        |
| Stefan-Boltzmann constant               | 5.67E-08       |
| Liquidus temperature of Ti6Al4V (°C)    | 1660           |

Figure 3. Mesh model.

Figure 4. Comparison between simulation and experiment results of different beam current samples: (a) current of 3 mA, (b) current of 6 mA (c) current of 9 mA, and (d) temperature variation at a point on the center line.
temperature curve is respectively $1.03 \times 10^5 \degree C \text{ s}^{-1}$, $7.94 \times 10^4 \degree C \text{ s}^{-1}$, and $4.61 \times 10^4 \degree C \text{ s}^{-1}$, the cooling rate trend is consistent with that in section 3.2.

3.2. Phase composition and microstructure characterization

The XRD patterns of As-deposited, EBSR-6 mA, and EBSR-9 mA samples contain a mixture of $\alpha$-Ti phase and $\beta$-Ti phase, indicating that, when the beam current is large, the remelted sample has the same phase composition as the substrate, as shown in figure 5. In contrast, all peaks in the XRD pattern for the EBSR-3 mA sample originate from $\alpha'$-Ti phase, which is consistent with the results in figure 6. In particular, Boyer [28] and Palanivel [29] have confirmed the presence of $\alpha'$-Ti phase in Ti-6Al-4V by XRD. Additionally, the peaks characteristic of

![Figure 5. XRD patterns of untreated and EBSR-treated Ti-6Al-4V alloys.](image)

![Figure 6. Optical images of the samples: (a) As-deposited, (b) EBSR-3 mA, (c) EBSR-6 mA, and (d) EBSR-9 mA.](image)
the α-Ti phase exhibit a higher intensity in the As-deposited and EBSR-9 mA samples than in the other samples. It indicates that α-Ti phase lamella grew coarser under the thermal accumulation effect [30].

Surface microstructures of the EBF3-fabricated Ti-6Al-4V alloy with and without remelting (multi-tracks) are shown in figure 6 (OM) and figure 7 (SEM). For the EBF3-fabricated substrate (see figure 6(a)), different structures can be identified along or within the prior β-grain boundaries, and these prior β-grain boundaries are distributed with a continuous grain boundary α(αGB). Within the prior β-grains, α + β basket-weave and coarse colony-α lamella structures, which belong to the same variant of the Burgers relationship, were found. The complex thermal cycles of EBF3 lead to structural inhomogeneity [6]. Detailed SEM studies (see figures 5(b) and 6(a)) revealed that lamellar α-phase and β-phase appear alternately.

The OM and SEM result in figures 5(b) and 6(b) indicate that the EBSR process at low beam current (3 mA) resulted in a dramatic change in the As-deposited microstructure. Acicular α′ martensitic structure completely occupies most of the remelted zone. OM images in figure 6(b) do not reveal any clear internal features, which is one of the characteristics of martensite in titanium alloy [31]. The cooling rate during the remelting and resolidification is very high and can reach $10^5 \, ^\circ\text{C} \, \text{s}^{-1}$, β structures transformed into martensitic structures [32]. And based on the temperature simulation in section 3.1, the cooling rate under the current of 3 mA is $1.03 \times 10^5 \, ^\circ\text{C} \, \text{s}^{-1}$. In this case, β structures transformed and disappeared at low beam current (see figures 5(b) and 6(b)). The EBF3-fabricated Ti-6Al-4V substrate was rapidly heated to a liquid state by the high-energy electron beam and cooled immediately. The cooling rate is too high to promote the equilibrium transformation of β to α phase. Instead, the β phase (body-centered cubic, BCC) transformed into α′ phase (hexagonal close-packed, HCP) directly at temperatures higher than the β transit temperature. Palanivel et al also demonstrated that the α′ phase is a non-equilibrium martensitic structure obtained by an extremely high cooling rate [29]. The microstructures of EBSR-6 mA and EBSR-9 mA samples are presented in figures 6(c) and (d). Unlike the EBSR-3 mA sample with a lower beam current, β→α transformation replaced β→α′ transformation. It formed a basketweave microstructure at the increased currents with larger energy inputs resulting in an increased temperature of the molten pools and a decreased cooling rate. Thus, the transformation type changes from martensitic transition to nucleation and diffusional transition of β→α, which leads to the basket weave structure [31].

Consistent with figure 6(b), the characteristics of the martensitic structure are also apparent in figure 7(b), showing small α′ laths randomly distributed in the remelted layer. As shown in figure 7(c) and (d), the remelted structure becomes coarser with larger beam currents, similar to the as-deposited sample. Interestingly, a multitude of nano-dispersoids is distributed in all remelted samples. The nano-sized particles were assumed to
be the Ti$_3$Al phase or β phase. However, the Ti$_3$Al phase can be ruled out in this experiment since Ti$_3$Al will precipitate if the peak temperature of the heat treatment remains below their solvus of 550°C and the local concentration of Al exceeds 25%. Furthermore, the nano-scale dispersoids have been confirmed as the β phase in other studies, and it was pointed out that the process is promoted by high energy input and fast cooling rate. Because of the high cooling rate, some β phase will have insufficient time to evolve into the lamella structure, which leads to the precipitation of nano-dispersoids.

3.3. Wear behavior
The evolution of the friction coefficient versus sliding time, wear track profiles, and the specific wear rates ($W_s$) of the tested samples are illustrated in figure 8. As shown in figure 8(a), EBSR processes have little effect on the friction coefficient. However, it is apparent that the EBSR-3 mA process decreases the depth and width of the wear track (see figures 7(b) and (c)), which reduces the specific wear rate, demonstrating superior friction behavior under such conditions.

The 3D profiles of the wear tracks are displayed in figure 9. As evident from figure 8(b), the EBSR-3 mA sample shows the narrowest and shallowest wear track of the tested samples, demonstrating the least wear loss.
and the best wear resistance. While the EBSR-9 mA sample exhibits low wear resistance, the as-deposited sample and EBSR-6 mA sample reveal a similar wear resistance. Referring to figure 8(c), the lowest specific wear rate (5.7 × 10⁻¹⁰ m³/Nm) was obtained for the EBSR-3 mA sample as expected, followed by the as-deposited sample (7.7 × 10⁻¹⁰ m³/Nm), EBSR-6 mA sample (7.9 × 10⁻¹⁰ m³/Nm), and EBSR-9 mA sample (8.9 × 10⁻¹⁰ m³/Nm).

The morphologies of the worn sample surfaces after tribology tests were investigated to compare the wear resistance and analyze the wear mechanism. The SEM micrographs and EDS analysis results of the worn surface morphologies are shown in figure 10. All samples contain abrasive particles and grooves parallel to the sliding direction, which is evidence of abrasive wear [35]. The apexes of the friction pair materials are in physical contact during the friction process, causing the surface material to detach and remain in the worn zones, serving as abrasive particles in the three-body wear process. Different degrees of plastic deformation and peeling caused by the load during the friction process was observed in the wear tracks of all samples, confirming abrasive wear [36]. The existence of deep grooves and severe plastically deformed pits diminish the wear resistance. The EBSR-3 mA sample exhibits shallower grooves and less plastic deformation, indicating superior wear resistance and a relatively low wear rate.

The wear mechanism was studied through the EDS analysis of the wear debris. As evident from the results displayed in figure 10, the Fe element from friction pairs is present in all samples, which indicates that material transfer of the friction pair has occurred and presents evidence of adhesive wear. During sliding, the adhesive nodes produced by the adhesion are sheared and broken. The sheared material falls into wear debris or transfers to another surface, sometimes resulting in ‘cold welding points’ [37]. The adhesive wear seems to occur in all Ti-6Al-4V samples due to titanium alloys’ low d-bond character, which results in adhesive bonding with the counterface material [35].

Furthermore, the wear debris of all samples contains a certain amount of O element, suggesting that oxidation occurs on the surfaces of the tested samples, which is related to the elevated friction heat caused by the reciprocating sliding motion [38] and the high affinity of titanium for oxygen [39]. Surface plastic deformation causes the oxygen in the air to diffuse into the deformation layer, while oxidation enhances plastic deformation [26, 40]. Thus, the severe plastic deformation of as-deposited and high-current remelted specimens reflects their severe oxidation wear. In addition, some cracks are found in the wear track of the as-deposited sample and EBSR-9 mA sample (figures 9(a) and (d)), which is a typical feature of fatigue wear. The cracks appear and propagate near the weak regions, after which delamination emerges when the cracks further propagate to the edges [41].

The as-deposited sample contains some grain boundaries of columnar grains, and the shear stress is impeded by the grain boundaries, resulting in stress concentration and severe wear [42]. To further illustrate the wear...
behavior, the microhardness of the sample surfaces was tested. Ten random points were taken on the surface of each sample for testing. The microhardness variations at different points on the surface are shown in figure 11(a). And the average microhardness of as-deposited and multi-track remelted samples is illustrated in figure 11(b). The heterogeneous microstructure (low microhardness of about 274 HV0.2 and coarse lamellae), caused by the complex thermal cycling effect during the deposition, reduces the load-carrying ability and diminishes the wear resistance. The treatment process to obtain the EBSR-3 mA sample (341 HV0.2 in hardness) enhances the wear resistance of EBF3-fabricated Ti-6Al-4V. The increase in base metal hardness (about 67 HV0.2), caused by solution strengthening of the $\alpha'$ martensite and dispersion strengthening of the nano-scale particles, contributes to the improvement in wear resistance [43]. In addition, the hard uniform full $\alpha'$ martensitic structure offers a higher load-carrying ability than the ductile EBF3-fabricated titanium matrix and effects a decreased plastic deformation during long reciprocating sliding.

Meanwhile, the hardness of 290 HV0.2 and 271 HV0.2 of the EBSR-6 mA and EBSR-9 mA samples confirmed the microstructure’s influence on the material microhardness. In summary, the wear mechanism for the as-deposited sample and the EBSR-9 mA sample consists of abrasive wear, fatigue wear, adhesive wear, and severe oxidation wear. In contrast, abrasive, adhesive, and slight oxidation wear occur in the EBSR-3 mA and EBSR-6 mA samples.

4. Conclusions

This paper investigated the effect of different energy inputs in the electron beam surface remelting (EBSR) process on the microstructure, phase composition, and wear behavior of Ti-6Al-4V alloy manufactured by electron beam freeform fabrication (EBF3). A suitable EBSR process effectively improves the surface hardness and the wear resistance of this titanium alloy. The main conclusions are as follows:

- The remelting depth of the EBSR-treated Ti-6Al-4V alloy is controlled by the energy input. With increasing energy input, the remelting width and depth increase, and the microstructure refinement decrease.
- The microhardness of the EBF3-fabricated sample was increased by about 67 HV0.2 after remelting at a beam current of 3 mA. The strengthening mechanism is mainly solid solution strengthening and dispersion strengthening. The microstructure evolution and strengthening effect are sensitive to the remelting parameters.
- The EBSR process has little effect on the friction coefficient but can decrease the wear rate with appropriate conditions. The wear resistance of the samples follows the order, EBSR-3 mA > as-deposited > EBSR-6 mA > EBSR-9 mA, and the wear rate decreased from $7.7 \times 10^{-10}$ m$^3$/Nm for the as-deposited sample to $5.7 \times 10^{-10}$ m$^3$/Nm for EBSR-3 mA sample.
- For the EBSR-3 mA and EBSR-6 mA samples, the wear mechanism comprises abrasive wear, adhesion wear, and oxidation wear. Next to these modes of wear, as-deposited and EBSR-9 mA samples are conducive to fatigue wear.
• At the low current of 3 mA, as the surface modification before the end of the EBF3 process, the surface properties of the titanium alloy by EBF3 can be improved, which would shine some light on its application potential.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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