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Influence of the Number of Electron Beam Passes on Surface Roughness Evolution of Titanium

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A B S T R A C T

This study systematically examines the influence of the number of electron beam passes on the surface roughness of titanium samples processed at a constant beam current of 0.8 mA. The primary objective was to determine how repeated beam exposure affects the evolution of surface topography under controlled processing conditions. To achieve this, surface roughness measurements were performed after applying 2, 4, 8, and 16 beam passes, enabling a comparative analysis of progressive surface modification. The experimental results reveal a clear trend: increasing the number of electron beam passes results in a gradual and consistent increase in surface roughness. This behavior may be attributed to cumulative thermal effects, localized melting, and material redistribution occurring during repeated beam interaction with the titanium surface. Overall, the findings contribute to a better understanding of the relationship between processing parameters and surface morphology evolution. Such insights are essential for optimizing electron beam processing strategies and tailoring surface characteristics to meet the functional requirements of titanium components in advanced engineering applications.

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1. INTRODUCTION

Titanium and its alloys are widely recognized as leading materials in biomedical engineering, particularly for orthopedic applications such as hip joint replacements. Their widespread use stems from outstanding biocompatibility, excellent resistance to corrosion in physiological environments, low density, and favorable mechanical properties [1, 2]. Among these materials, the Ti-6Al-4V alloy is especially prominent in hip implant manufacturing due to its superior strength-to-weight ratio, high corrosion resistance in body fluids, and strong

potential to facilitate osseointegration [3]. Additionally, titanium possesses a lower elastic modulus compared to many other metallic biomaterials, which helps mitigate stress shielding and enables more effective load transfer to the surrounding bone tissue [4].

Despite these favorable bulk properties, the clinical performance of titanium implants is strongly influenced by their surface characteristics. Parameters such as surface chemistry, morphology, and roughness play a decisive role in governing biological interactions at the bone–implant interface [5, 6]. Among these factors, surface roughness is particularly significant, as it directly modulates cellular responses, including adhesion, proliferation, and differentiation, thereby critically affecting the extent and quality of bone tissue ingrowth [7].

Previous research has indicated that moderately rough surfaces, typically characterized by an average roughness (Ra) in the range of 1–2 μm, enhance osteoblast activity and improve bone-to-implant contact compared with either very smooth or highly roughened surfaces [8]. Surfaces that are overly smooth may encourage fibrous tissue formation instead of direct bone bonding, whereas excessively rough surfaces can promote inflammatory reactions and accelerate wear processes [9]. Furthermore, surface roughness contributes to mechanical interlocking at the implant–bone interface, which is essential for achieving primary stability and limiting micromotion during the early healing phase [10]. Inadequate primary stability may compromise osseointegration and negatively affect the long-term durability of the implant.

Considering the strong influence of surface properties on implant performance, significant research efforts have focused on developing and refining surface modification techniques. Conventional approaches—including grit blasting, acid etching, anodization, and plasma spraying—have been extensively employed to tailor titanium surface characteristics [11, 12]. More recently, electron beam processing has gained attention as an advanced surface modification technique, enabling precise control over surface morphology, microstructure, and roughness while minimizing the risk of chemical contamination [13].

A comprehensive understanding of how electron beam processing parameters, particularly the number of passes, affect surface roughness is essential for the design of implants with enhanced biological performance. In this context, the present study examines the influence of the number of electron beam passes on the surface roughness of titanium samples processed at a constant beam current of 0.8 mA. The findings aim to provide useful insights for optimizing surface modification procedures and improving the clinical performance of titanium implants used in hip joint replacement applications.

2. MATERIALS AND METHOD

2.1 Material

Commercially available titanium alloy was used for the preparation of the experimental samples. The material was machined into rectangular specimens with dimensions of 70 mm × 20 mm × 5 mm. Prior to the surface modification process, all samples underwent mechanical grinding and polishing in order to obtain a consistent and uniform initial surface condition. This procedure was carried out using silicon carbide abrasive paper with a grit size of P4000, which enabled the reduction of surface irregularities and ensured a comparable baseline roughness for all specimens [14].

Following the polishing stage, the samples were thoroughly cleaned with ethanol to eliminate possible residues such as polishing debris, oils, or other contaminants that could affect the subsequent processing. Finally, the specimens were dried using compressed air to ensure a clean and dry surface prior to further experimental treatment.

2.2 Electron Beam Surface Treatment

Surface modification of the prepared titanium samples was performed using an electron beam welding system (Probeam EBG 45-150 K14). In order to evaluate the influence of repeated electron beam exposure, each specimen was divided into four separate treatment zones. These zones were square areas measuring 10 mm × 10 mm and were processed using different numbers of electron beam passes, specifically 2, 4, 8, and 16 passes, as illustrated in Figure 1. This experimental design enabled a direct comparison of surface modifications produced under varying processing conditions on the same sample.

All surface treatments were conducted under identical operating conditions, with the beam current maintained at a constant value of 0.8 mA throughout the experiments. Keeping this parameter constant ensured that the observed variations in surface characteristics could be primarily attributed to the number of electron beam passes rather than fluctuations in beam intensity.

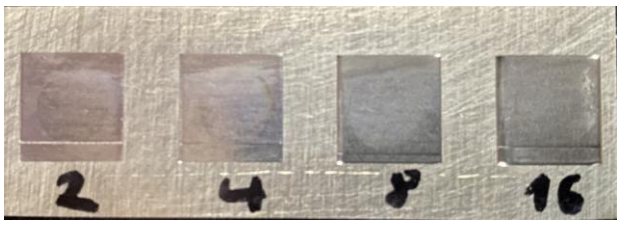


Fig. 1. Electron beam processed titanium samples: (a) sample treated with 0.8 mA; (b) sample treated with 1.0 mA.

Electron beam processing was performed at a constant beam current of 0.8 mA, while the acceleration voltage was varied within the range of 60 to 150 kV, depending on the specific processing conditions. All experiments were conducted in a high-vacuum environment to ensure beam stability, minimize electron scattering, and prevent oxidation or contamination of the titanium surface during treatment.

To achieve uniform surface modification, the electron beam was raster-scanned across the predefined treatment areas, enabling controlled and homogeneous energy distribution over the processed zones. This scanning strategy ensured consistent interaction between the beam and the material surface, thereby promoting reproducible modification of surface morphology. All processing steps were carried out at room temperature, without the application of external preheating or additional thermal assistance.

2.3 Surface Roughness Characterization

Surface roughness measurements were carried out using an INSIZE ISR C-002 profilometer, a portable contact-type device designed for accurate characterization of surface texture. The instrument utilizes a diamond-tipped stylus that travels across the sample surface, detecting vertical deviations and generating a detailed surface profile.

All measurements were performed in accordance with the ISO 4287 standard for surface texture evaluation. For each treated region, measurements were taken at three different positions in order to ensure representative results and improve measurement reliability. The evaluation length for the measurements was set to 4 mm. Based on the obtained profiles, the relevant surface roughness parameters were recorded and used for further analysis.

2.4 Experimental Plan

In the present study, titanium samples were subjected to electron beam processing in order to examine the influence of the number of electron beam passes on the resulting surface roughness. During all experiments, the beam current was kept constant at 0.8 mA to ensure consistent processing conditions and to isolate the effect of repeated beam exposure on the surface characteristics.

To investigate this parameter, each sample was divided into four separate treatment regions. These regions were processed using different numbers of electron beam passes, specifically 2, 4, 8, and 16 passes. This approach enabled a systematic evaluation of how repeated electron beam scanning affects the modification of the titanium surface. By maintaining the same beam current while varying only the number of passes, it was possible to directly assess the relationship between cumulative beam interaction and changes in surface roughness.

Such an experimental design allowed a comparative analysis of surface conditions produced under different levels of beam exposure, thereby providing a clear basis for evaluating the role of the number of passes in electron beam surface modification.

3. RESULTS AND DISCUSSION

Surface roughness measurements were carried out on titanium samples processed using a constant electron beam current of 0.8 mA, while the number of beam passes was varied in order to evaluate its influence on the resulting surface characteristics. The obtained roughness profiles provide insight into the changes in surface morphology caused by repeated electron beam exposure.

For each treated area, surface roughness measurements were performed at three different locations to ensure representative and reliable results. The corresponding surface roughness profiles are presented in Figures 2–5. Figure 2 illustrates the roughness profiles obtained for the sample treated with 2 electron beam passes (Group 1), serving as the baseline condition for comparison with samples subjected to a higher number of passes

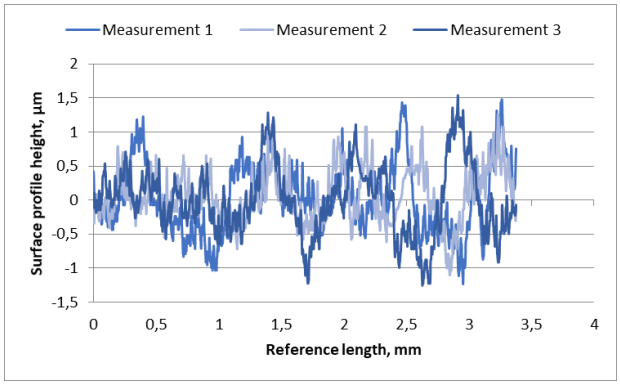


Fig. 2. Surface roughness profiles measured at three different locations (Measurement 1–3) on the titanium sample processed with 2 passes.

The surface roughness profiles for the sample processed with 4 passes are shown in Figure 3.

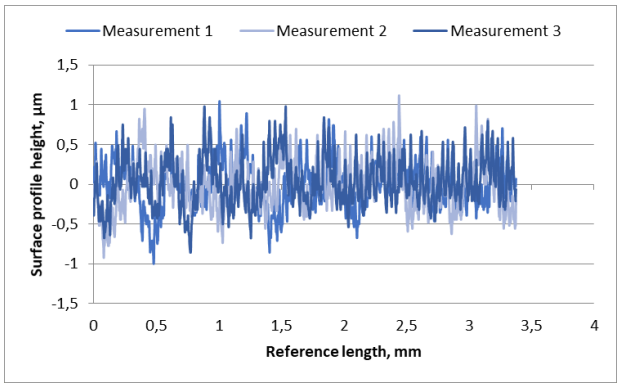


Fig. 3. Surface roughness profiles measured at three different locations (Measurement 1–3) on the titanium sample processed with 4 passes.

The surface roughness profiles corresponding to the sample processed with 8 electron beam passes are shown in Figure 4. Similar to the previous cases, the measurements were conducted at three different locations in order to ensure representative characterization of the modified surface. The obtained profiles provide insight into the changes in surface morphology resulting from the increased number of beam passes.

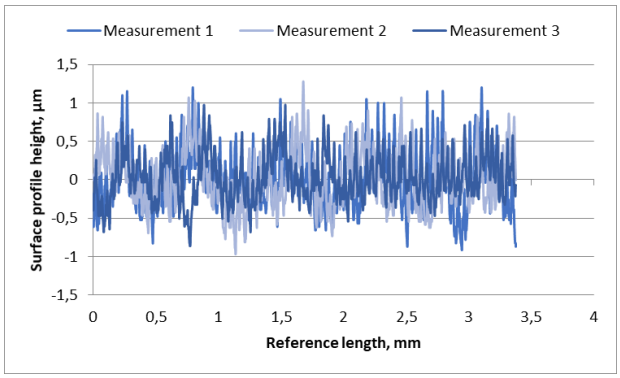


Fig. 4. Surface roughness profiles measured at three different locations (Measurement 1–3) on the titanium sample processed with 8 passes.

The surface roughness profiles corresponding to the titanium sample processed with 16 electron beam passes are presented in Figure 5. As in the previous cases, measurements were performed at three different locations within the treated area in order to obtain representative information about the modified surface. The obtained profiles illustrate the surface morphology after the highest number of beam passes applied in this study, providing insight into the cumulative effect of repeated electron beam exposure on the surface roughness of the titanium samples.

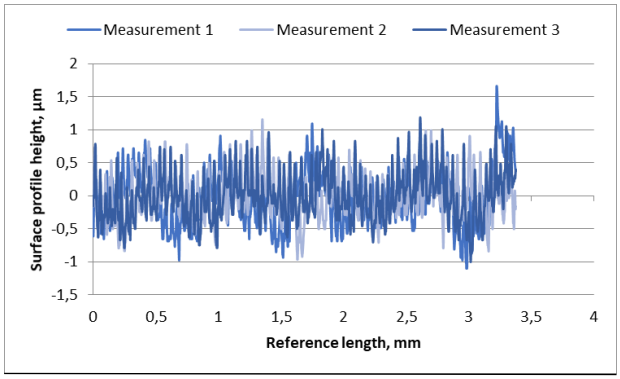


Fig. 5. Surface roughness profiles measured at three different locations (Measurement 1–3) on the titanium sample processed with 16 passes.

The calculated average surface roughness parameters (Ra and Rz) were used to evaluate the influence of the number of electron beam passes on the surface characteristics of the titanium samples. For the sample processed with 2 passes, the average roughness values were Ra = 0.468 µm and Rz = 2.631 µm. When the number of passes was increased to 4, the surface roughness decreased, with average values of Ra = 0.311 µm and Rz = 1.972 µm.

Further processing with 8 passes resulted in a slight increase in roughness, where the average values reached Ra = 0.330 μm and Rz = 2.071 μm. A similar trend was observed for the sample treated with 16 passes, where the measured average roughness values were Ra = 0.374 μm and Rz = 2.358 μm. These results indicate that variations in the number of electron beam passes lead to noticeable changes in surface roughness, reflecting the cumulative influence of repeated beam interaction with the titanium surface.

The obtained results reveal a noticeable variation in surface roughness with increasing numbers of electron beam passes. When the number of passes was increased from 2 to 4, both Ra and Rz values showed a reduction, indicating an improvement in surface smoothness. However, further increases in the number of passes to 8 and 16 resulted in a slight increase in the measured roughness parameters. This observation suggests that the relationship between the number of electron beam passes and the resulting surface roughness is not linear.

The influence of the number of electron beam passes on the surface characteristics of titanium processed at a constant beam current of 0.8 mA is therefore significant. The initial decrease in roughness observed between 2 and 4 passes can be explained by the repeated scanning of the electron beam across the surface. During this stage, the beam interaction tends to smooth the material by reducing surface asperities and promoting a more uniform surface morphology.

In contrast, when the number of passes is further increased, additional thermal effects become more pronounced. Repeated beam exposure introduces cumulative heat input into the material, which may lead to localized melting and subsequent re-solidification of the surface layer. These processes can generate fine surface irregularities, microstructural modifications, or resolidified features that contribute to a moderate increase in surface roughness.

Similar non-linear behaviour in the evolution of surface roughness during electron beam processing has been reported in previous studies [13, 14]. The observed transition from initial surface smoothing to slight roughening highlights the importance of carefully controlling the number of electron beam passes during processing. Proper parameter optimization is essential to achieve the desired surface characteristics while avoiding excessive thermal effects that could degrade the surface quality.

Overall, the results indicate that an intermediate processing condition provides the most favorable surface characteristics. In the present study, the lowest roughness values were obtained for the sample processed with 4 electron beam passes. Such a surface condition may be particularly advantageous for biomedical applications, where a controlled level of surface roughness is required to promote osseointegration while minimizing potential wear or adverse biological responses.

4. CONCLUSION

This study investigated the influence of the number of electron beam passes on the surface roughness of titanium samples processed at a constant beam current of 0.8 mA. The obtained results showed that the number of electron beam passes significantly affects the resulting surface characteristics. An initial reduction in surface roughness was observed when the number of passes increased from 2 to 4, where the lowest Ra and Rz values were recorded. However, further increases in the number of passes to 8 and 16 resulted in a moderate increase in roughness, which can be attributed to cumulative thermal effects and repeated melting–re-solidification processes occurring at the surface.

These findings emphasize the importance of carefully controlling electron beam processing parameters in order to obtain the desired surface properties. The results indicate that an intermediate number of passes can provide an optimal balance between surface smoothing and the prevention of excessive thermal influence on the material. Such surface conditions are particularly relevant for biomedical applications, where appropriate surface roughness can contribute to improved implant performance, enhanced osseointegration, and stable tribological behaviour.

Future research should focus on establishing a clearer relationship between the observed changes in surface roughness, the associated microstructural modifications, and the biological response of surrounding tissues. Such investigations would further support the optimization of electron beam surface treatments for advanced biomedical implant applications.

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