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EFFECT OF ELECTRON BEAM PROCESSING PARAMETERS ON THE SURFACE ROUGHNESS OF TITANIUM SAMPLES: PART II

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1. Introduction

Titanium and its alloys are widely recognized as preferred materials in biomedical engineering, especially for orthopedic implants such as artificial hip joints, owing to their outstanding biocompatibility, corrosion resistance, low density, and favorable mechanical characteristics [1, 2]. Among them, the Ti-6Al-4V alloy is particularly prominent for hip implant applications because of its superior strength-to-weight ratio, high resistance to corrosion in physiological environments, and strong capacity to facilitate osseointegration [3]. In addition, titanium possesses a comparatively low elastic modulus relative to other metallic biomaterials, which helps to mitigate stress shielding and ensures more effective load transfer to the surrounding bone [4].

Although titanium offers many beneficial properties, the clinical performance of titanium implants is strongly influenced by the material's surface characteristics. Parameters such as surface roughness, chemistry, and topography are widely recognized as key determinants of biological interactions at the bone–implant interface [5, 6]. Among these, surface roughness is particularly significant, as it regulates cellular responses, impacting adhesion, proliferation, differentiation, and ultimately the integration of bone tissue [7].

A substantial body of research indicates that moderately rough surfaces (with an average roughness, Ra, of 1–2 µm) support osteoblast differentiation and improve bone-to-implant contact when compared to both smoother and excessively rough surfaces [8]. In contrast, overly smooth surfaces may promote fibrous tissue encapsulation, whereas excessively rough ones can provoke inflammatory reactions and accelerated wear [9]. Additionally, surface roughness influences the mechanical interlocking between the implant and bone, a key factor for achieving primary stability and reducing micromotion during the initial healing phase [10]. Inadequate primary stability can delay or prevent osseointegration, ultimately jeopardizing the long-term success of the implant.

Recognizing these critical implications, considerable efforts have been devoted to the development of surface modification techniques to optimize implant surface properties. Conventional approaches, including grit blasting, acid etching, anodization, and plasma spraying, have been widely employed to enhance the surface characteristics of titanium [11, 12]. In recent years, electron beam processing has emerged as a promising technique, offering precise control over surface morphology, microstructure, and roughness, while minimizing the risk of chemical contamination [13].

A comprehensive understanding of the relationship between electron beam processing parameters—particularly the number of passes—and surface roughness is fundamental to the design of implants with superior biological performance. In this context, the present study provides a systematic evaluation of the effect of pass number on the surface roughness of titanium specimens processed under a fixed beam current of 1.0 mA, offering critical insights into the refinement of surface modification strategies aimed at enhancing clinical outcomes in hip joint arthroplasty.

In summary, the experimental setup maintained a constant electron beam current of 1.0 mA while systematically varying the number of passes (2, 4, 8, and 16) to investigate its influence on the surface roughness of titanium samples.

2. Materials and Methods

Commercially available titanium alloy was selected for specimen preparation. Rectangular samples with dimensions of 70 mm × 20 mm × 5 mm were machined and subsequently subjected to mechanical grinding and polishing using P4000-grade silicon carbide abrasive paper to ensure a uniform initial surface finish [14]. Following polishing, all specimens underwent ultrasonic cleaning in ethanol and were dried with compressed air to eliminate residual surface contaminants.

Surface modification was conducted using a Probeam EBG 45-150 K14 electron beam welding system. Each specimen was subdivided into four treatment zones, each measuring 10 mm × 10 mm, and exposed to 2, 4, 8, or 16 electron beam passes, respectively (Fig. 1). The processing was performed at room temperature under high-vacuum conditions, with the beam current fixed at 1.0 mA and an acceleration voltage ranging from 60 to 150 kV. A raster-scanning approach was employed to ensure homogeneous surface modification across the designated treatment areas.

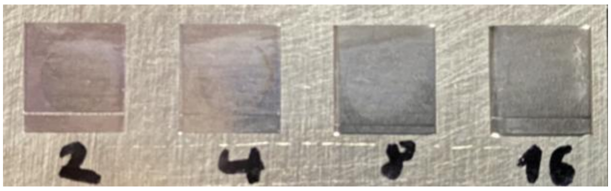

Fig. 1. Titanium specimens after electron beam processing

Surface roughness characterization was performed using an INSIZE ISR C-002 portable contact profilometer, equipped with a diamond-tipped stylus to trace the surface topography and detect vertical displacements for precise profiling. Measurements were conducted in accordance with ISO 4287 standards over a 4 mm evaluation length, with three independent measurements recorded for each treated zone to ensure representative data. The acquired roughness parameters served as the basis for a quantitative assessment of the influence of electron beam pass number on titanium surface properties.

3. Results and Discussion

Fig. 2 shows the surface roughness profile of the polished titanium specimen prior to electron beam processing, serving as a baseline for subsequent comparisons. The polished surface exhibits relatively low roughness, with average values of Ra ≈ 0.65 µm and Rz ≈ 4.43 µm, indicating a smooth and uniform finish suitable for surface modification studies.

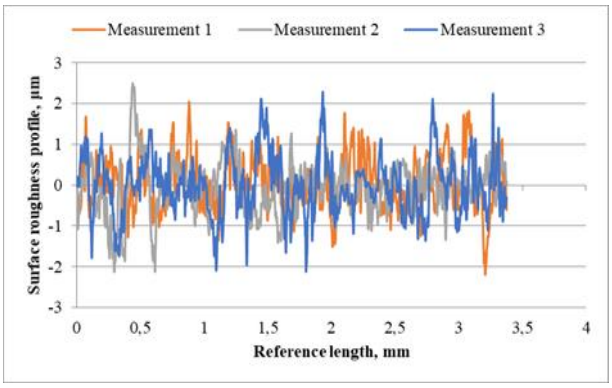

Fig. 2. Surface roughness profile of the polished titanium specimen prior to electron beam processing

Fig. 3–6 present the roughness profiles of samples subjected to 2, 4, 8, and 16 electron beam passes at a constant beam current of 1.0 mA.

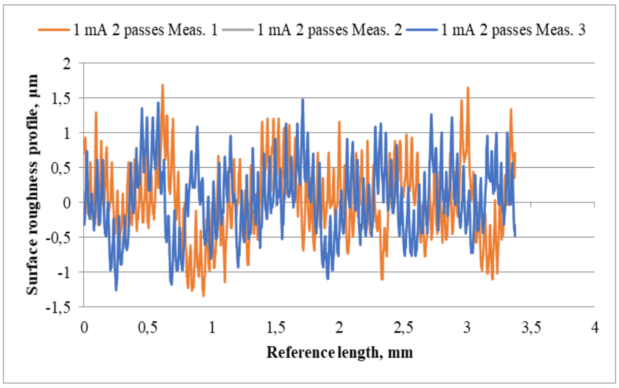

Fig. 3. Surface roughness profile of the titanium specimen after 2 electron beam passes at 1.0 mA

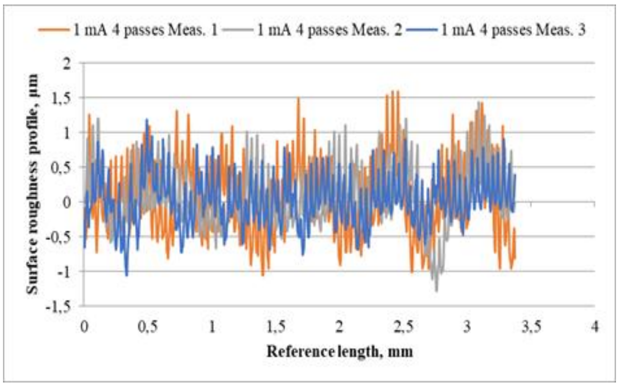

Fig. 4. Surface roughness profile of the titanium specimen after 4 electron beam passes at 1.0 mA

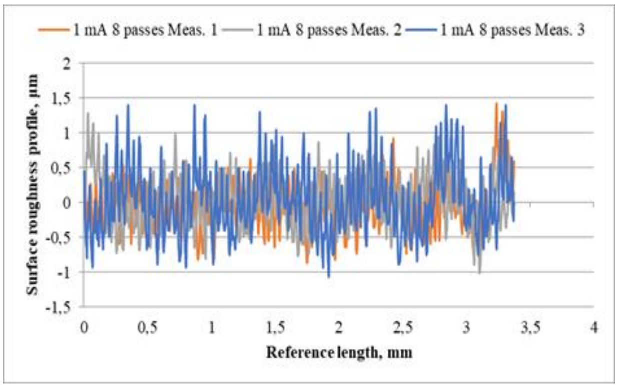

Fig. 5. Surface roughness profile of the titanium specimen after 8 electron beam passes at 1.0 mA

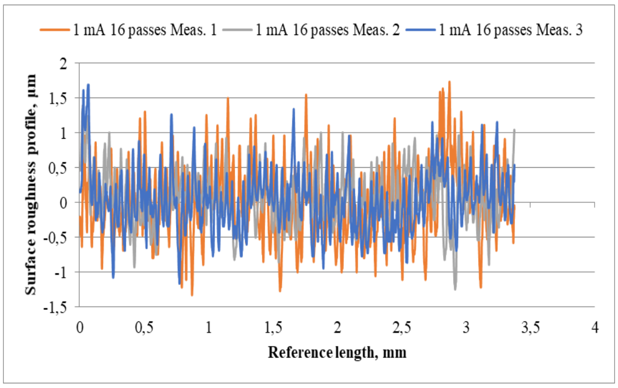

Fig. 6. Surface roughness profile of the titanium specimen after 16 electron beam passes at 1.0 mA

Quantitative analysis of the roughness parameters (Table 1) reveals a clear influence of pass number on surface topography. After two passes, both Ra and Rz decrease significantly (Ra ≈ 0.50 µm, Rz ≈ 2.83 µm), suggesting that localized melting and re-solidification during electron beam processing smoothen the initial asperities. Increasing the number of passes to four continues this trend (Ra ≈ 0.43 µm, Rz ≈ 2.54 µm), indicating progressive surface homogenization.

Table 1. Average surface roughness parameters (Ra and Rz) of titanium specimens subjected to electron beam processing with different numbers of passes at a constant beam current of 1.0 mA

Passes	Ra avg (µm)	Rz avg (µm)
0	0.655	4.429
2	0.498	2.832
4	0.431	2.535
8	0.373	2.351
16	0.432	2.848

The lowest roughness values are observed at eight passes (Ra ≈ 0.37 µm, Rz ≈ 2.35 µm), demonstrating that this processing condition achieves an optimal balance between energy input and surface reflow. However, with sixteen passes, a slight increase in both Ra and Rz is recorded (Ra ≈ 0.43 µm, Rz ≈ 2.85 µm), which may be attributed to cumulative thermal exposure, repeated remelting, and potential microstructural coarsening. This non-linear behavior highlights that increasing the number of passes beyond a certain threshold does not necessarily improve surface smoothness and may even reintroduce surface irregularities.

These findings align with literature reports indicating that surface modification via high-energy beams can initially level micro-asperities, but excessive energy input may lead to roughness recovery due to localized melting instabilities and solidification dynamics [13]. In comparison with conventional surface treatments such as grit blasting or acid etching, which can produce non-uniform surfaces and introduce chemical residues [11], electron beam processing provides precise control of surface morphology and reproducible roughness adjustment without contamination.

The measured Ra values remain below 1 µm across all samples, well within the range suitable for promoting osseointegration, as moderate roughness levels (Ra ≈ 1–2 µm) are often cited as optimal for bone–implant integration [8]. While the processed surfaces in this study are smoother than those typically achieved through mechanical or chemical texturing, the ability to finely tune surface roughness with electron beam passes demonstrates strong potential for optimizing implant surface properties.

4. Conclusions

This study systematically investigated the influence of electron beam processing parameters—specifically the number of passes—on the surface roughness of titanium specimens at a constant beam current of 1.0 mA. The findings demonstrate that the number of passes plays a critical role in controlling surface morphology, with a clear trend observed:

- ✓ Electron beam processing initially reduced both Ra and Rz values, with the lowest roughness achieved after eight passes (Ra ≈ 0.37 µm, Rz ≈ 2.35 µm).
- ✓ Increasing the number of passes beyond this point resulted in a slight roughness increase, likely due to cumulative thermal effects, repeated remelting, and microstructural coarsening.
- ✓ The process produced smooth, uniform surfaces without chemical contamination, demonstrating the high precision and controllability of electron beam surface modification.

These results indicate that electron beam processing offers a versatile and reproducible approach for tailoring implant surface characteristics, enabling fine adjustment of roughness to levels suitable for improved osseointegration and clinical performance. Future work will focus on correlating these topographical modifications with mechanical properties and biological responses to optimize surface treatments for orthopedic applications such as hip joint replacements.

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