COMPARATIVE ANALYSIS OF SURFACE PROPERTIES OF Ti6Al4V FEMORAL STEM HIP PROSTHESES AND PLATE FOR LONG BONE FRACTURES USED IN ORTHOPEDIC SURGERY

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Femoral stem hip prostheses and plates for long bone fractures play a vital role in restoring the functionality of the patients. One of the key factors that can determine the positive result of restoring their mobility is represented by the materials used to make the medical applications. Surface topography is another essential biomaterial property significantly affecting adhesion, biocompatibility, and cell growth outcomes. The present paper aims to investigate the surface properties of two different orthopedic implants, respectively one femoral stem hip prosthesis and one plate for long bone fractures, made from the same metallic biomaterial (Ti6Al4V). Surface morphology and elemental composition, wettability, and roughness were measured comparatively, to see if any differences appear due to the lifetime in service of the different types of implants. The results showed similar surface properties for both samples, meaning that the surface properties given by the implant surface finishing are not affected by the different processing techniques of each implant substrate.

Keywords: Ti6Al4V alloy; femoral stem hip prosthesis; plate for long bone fractures; surface; roughness; wettability

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1. Introduction

Human life expectancy has increased, and its quality has improved due to advances in medical research and technology. One of the most significant developments is biomaterials. Occasionally, metallic biomaterials are used in the domains of orthopedics, cardiology, and oral surgery [1–5]. Traditional implant materials offer good fatigue, corrosion resistance, and load-bearing characteristics. Examples of these materials are titanium alloys, cobalt and chromium alloys, and stainless steel.

Hip prostheses are important medical devices that restore sick or injured hip joints, allowing patients to move freely and with less pain [6] During a hip replacement treatment, an artificial joint called a prosthesis is used to replace all or part of a damaged hip. This kind of prosthesis mimics the ball-and-socket motion of a genuine human joint thanks to the properties of the materials employed. In most situations, osteoarthritis or rheumatoid arthritis call for hip replacement. Strong plastics, usually polyethylene, ceramics, and a variety of metals, including titanium, cobalt-chromium alloys, and stainless steel, can be used to create the implant. There are two major components to the hip joint: the hip socket made up of the acetabulum, a portion of the pelvic bone, and the femoral head, the upper end of the femur, which can be replaced during surgery. The hip joint needs to be able to withstand large mechanical loads since it bears weight [7–10].

Medical devices called orthopedic plates are used to treat fractures. Orthopedic screws are frequently needed to secure these implants in a certain location, therefore they are not utilized alone. These plates assist the body's healing process and maintain the fracture's proper alignment. Specialists more frequently use these types of internal fixation devices to treat fractures. Clinicians select these implants based on the location, pattern, and severity of the fracture. There are multiple varieties of these implants. In certain situations, bone plates allow for the anatomic reduction of the bony column and, with the right implant choice and application, the neutralization of the forces acting on the fractured bone during the healing process. Bone plates also serve as a frame to which the fractured bone may be linked. Trauma plates must be able to withstand severe mechanical stress and strain to support and maintain bone structures [11–13].

Ti-6Al-4V alloy was originally developed for aircraft structural applications in the 1950s. While the aerospace industry still dominates the demand for Ti6Al4V, other application fields such as the marine, automotive, energy, chemical, and biomedical industries have also gained widespread acceptance over the past half-century [14]. This alloy, which has 6% aluminium and 4% vanadium, is an excellent option for medical applications because it has excellent mechanical qualities, excellent biocompatibility, and good corrosion resistance [14–16]. Generally, structural titanium alloys are classified into three categories: alpha (α) - which are heat treatable and solely comprise neutral alloying elements (like Sn) and/or alpha stabilizers (like Al, O), beta (β)-phase alloys which are metastable and contain enough beta stabilizers (like Mo, V) to retain the beta phase entirely after quenching and alpha and beta (α+β) typically contain a combination of alpha and beta stabilizers and are heat treatable to varying degrees, Usually, β alloys can be solution-treated and aged to achieve notable increases in strength. Ti6Al4V alloy is an α+β titanium alloy with high strength, low density, high fracture toughness, excellent corrosion resistance, and superior biocompatibility. Ti6Al4V has a wide application in the medical field, especially in the production of trauma plates and hip prostheses due to its exceptional qualities, which include low density, good corrosion resistance, fatigue resistance, biocompatibility, and a high strength-to-weight ratio [17]. It also has many benefits, two of which are its great tensile strength and durability. This alloy's ability to withstand high mechanical stress and strain is crucial for hip prostheses that must withstand daily use and the weight of the body. The high strength of Ti6Al4V makes it possible for the prosthesis to sustain structural integrity over extended periods, lowering the possibility of mechanical failure and lengthening the implant's lifespan. The excellent corrosion resistance is attributed to the formation of a stable oxide layer on its surface. This property ensures the longevity and reliability of medical devices, minimizing the risk of degradation and associated complications such as implant failure or the need for revision surgery. Also, Ti6Al4V is remarkably biocompatible, which means that the body can tolerate it well and doesn't react negatively to it. This characteristic facilitates a more efficient and clean healing process by preventing unfavourable reactions like infection or inflammation. The capacity of Ti6Al4V to promote osteointegration—the direct anatomical and functional bond between the implant's surface and living bone makes it a unique material for orthopedic applications. Ti6Al4V can have its surface roughened, or plasma sprayed to improve its characteristics and encourage the development of new bone. Osteointegration is a process that forms a strong link between the implant and the bone, which is essential for the stability and operation of the hip prosthesis.

Ti6Al4V is highly versatile in terms of fabrication for hip prostheses, supporting various manufacturing processes like casting, forging, and additive manufacturing [18]. This property allows the production of these medical applications in customized shapes and sizes to fit individual patient anatomies and surgical requirements. The trauma plates can be fabricated by machining and sheet metal forming, both manufacturing processes are efficient for mass production. Advances in additive manufacturing have opened new possibilities for creating complex, patient-specific implant designs that enhance fit and function. Ti6Al4V hip prostheses have proven to be incredibly reliable and perform well in clinical situations. Surface texturing and treatment techniques like electropolishing and anodization have been proposed in biomedical applications to manage surface roughness and wettability to improve the bone-implant osseointegration process.

Patients who have total hip replacement surgery frequently benefit from these implants' reduced pain and increased mobility. The qualities of the material greatly enhance patients' quality of life by promoting long-term functionality and a high success rate [19]. Ti6Al4V continues to be significant in offering hip replacement patients long-lasting, dependable, and efficient solutions that guarantee better mobility and a higher standard of living as medical technology develops.

2. Materials and Methods

We analysed two types of commercial medical devices used in orthopedic surgery: one femoral stem hip prosthesis, coded *P1* (figure 1a), and one plate for long bone fractures, coded *P2* (figure 2b). Both orthopedic implants were characterized to assess and compare their surface morphology and properties.

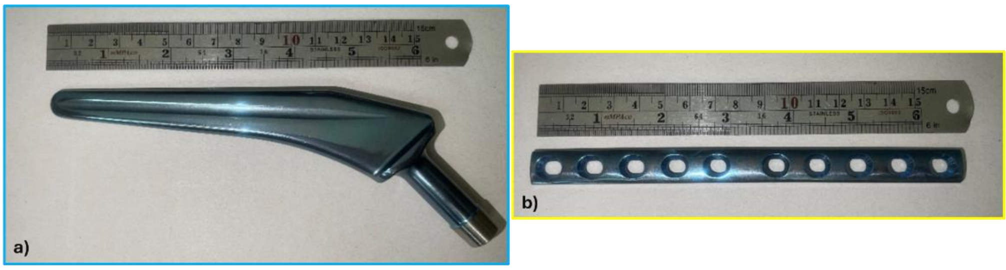

Fig. 1. Experimental orthopedic implants used in the study: a) femoral stem hip prosthesis – sample P1, b) plate for long bone fractures – sample P2.

Experimental samples were cut from each orthopedic implant. The chemical composition analysis was carried out by the optical emission spectrometry method using the LECO equipment Model: GDS 500 A. The microstructure was observed using an Olympus BX51 optical microscope (Olympus Life and Materials Science Europa GMBH, Hamburg, Germany). An FEI QUANTA INSPECT F microscope equipped with an Energy Dispersive X-ray Spectrometer Detector (EDAX) was used to obtain information about the surface morphology of the samples, respectively the elemental composition at the surface. The contact angle measurements were performed on an experimental KRÜSS DSA30 Drop Shape Analysis System, using three wetting agents (water, diiodomethane, and ethylene glycol). Contact angle values were reported as average. The surface free energy was computed using contact angle measurements through the OWRK method. The profilometry analysis was made with a Form Talysurf® I–Series PRO Range Taylor Hobson Ametek device with Metrology 4.0 Software. Based on five observations, we determine the Ra (arithmetic average deviation from the mean line) and Rq (root mean square average of the profile heights over the evaluation length) parameters.

3. Results and discussion

3.1. Elemental composition

Table 1

Elemental composition at the surface of each sample

	Composition (wt.%)					
	Al	N	O	Fe	V	Ti
P1	6.10	0.02	0.16	0.1	3.95	Balance
P2	5.90	0.02	0.16	0.1	4.00	Balance
Ti6Al4V According to ASTM F – 136	5.5 – 6.5	Max 0.05	Max 0.13	Max 0.025	3.5 – 4.5	Balance

3.3. Scanning Electron Microscopy and Energy Dispersive X-Ray Analysis

The surface of each sample was examined by Scanning Electron Microscopy and Energy Dispersive X-Ray. The microstructure Ti-6Al-4V consists of α laths with different sizes and orientations inside the prior β grains. In addition, fine rods embedded into continuous phases are observed.

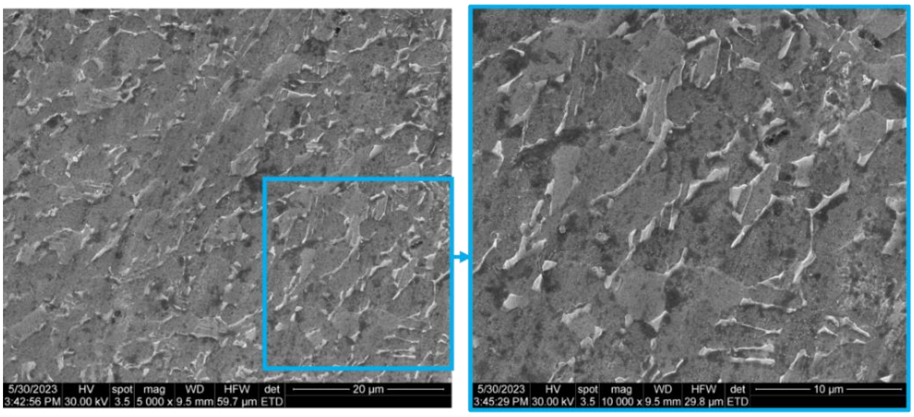

Fig. 2. SEM images of sample P1 at 500x and 1000x magnification

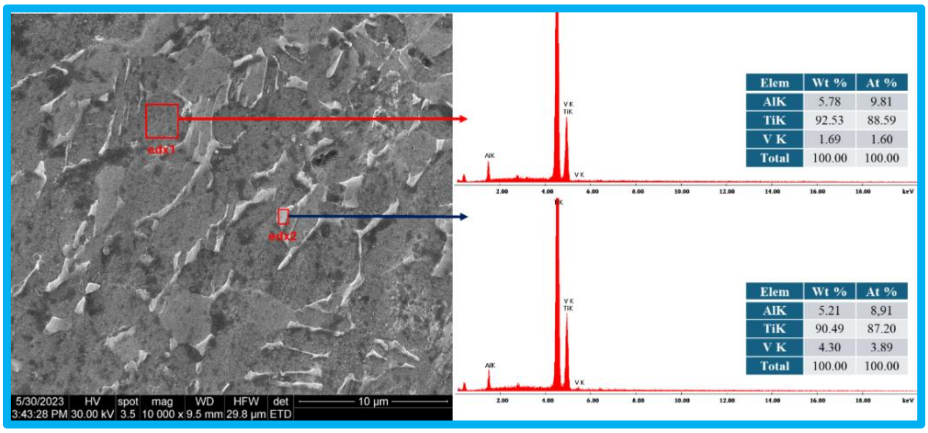

Fig. 3: SEM micrographs and EDAX diagrams of compositions sample P1

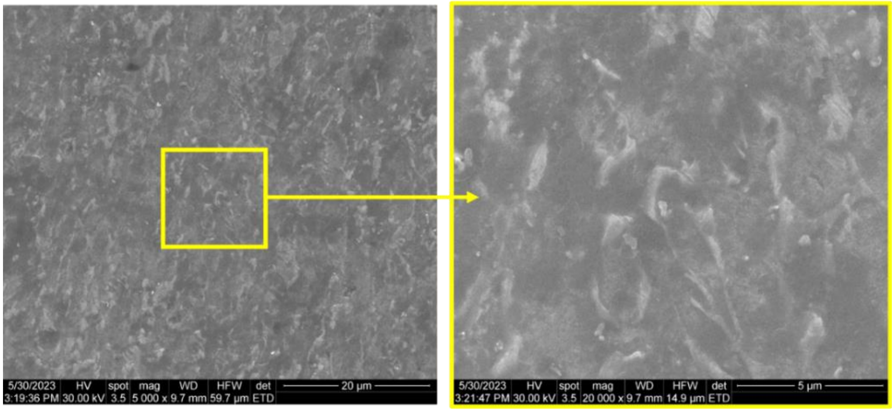

Fig. 4 SEM images of Sample 2 at 500x and 2000x magnification

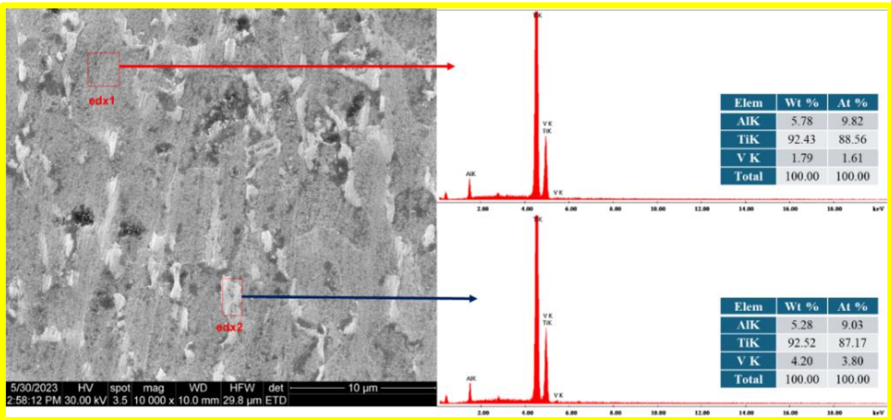

Fig. 5: SEM micrographs and EDAX diagrams of compositions sample P2

3.4. Contact Angle

The contact angle of three drops for sample P1 femoral stem hip prosthesis and sample P2 plate for long bone fractures.

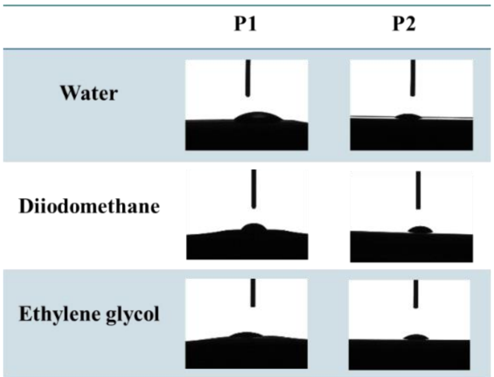

Fig. 7: Contact angle measurements of the samples

The t-test results using the measured contact angles revealed no statistically significant differences between the mean value of P1, 37.52° and the one of P2, 37.90°. The surface is hydrophilic, given the low contact angle values for water. Diiodomethane shows good surface wetting, but the surface of sample P2 appears to be less wetted, given higher contact angle values.

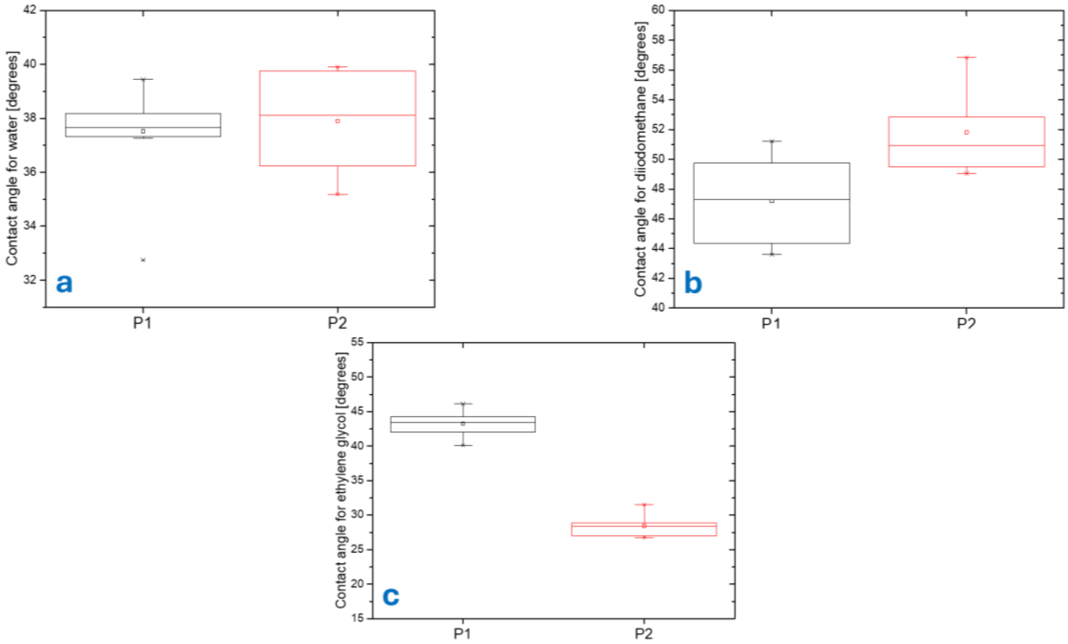

Fig. 6. Box plot showing the statistics for the measured contact angle for water (a), diiodomethane (b) and ethylene glycol (c)

The t-test results reflect that there is a statistically significant difference between mean values of P1, 47.19° and 51.82° for P2. Similar to water, ethylene glycol shows an enhanced surface wetting, sample P2 shows lower contact angle values.

Comparison of surface-free energies

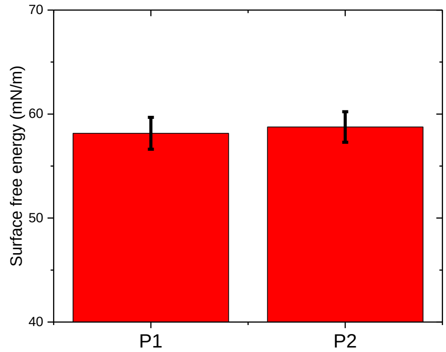

Fig. 7. Surface-free energies chart.

The surface free energies of both samples are similar. Even though the sample is P2 showing a slightly higher value, 58.78±1.47mN/m compared to 58.15±1.53mN/m for P1, from a statistical point of view, the average values can be regarded as equal.

3.5. Roughness

When integrating an implant into the human body, surface roughness is an important factor that needs to be considered. Numerous investigations have documented the impact of surface topography on cellular adhesion and growth. Therefore, the goal of surface texturing treatments is to improve the tissue-implant interface. Tissue integration with implants can be significantly impacted by the topographical characteristics of the titanium alloy surfaces, which are crucial in controlling the cell response at the implant-tissue interface. The study of the surface topography was conducted using profilometry analysis.

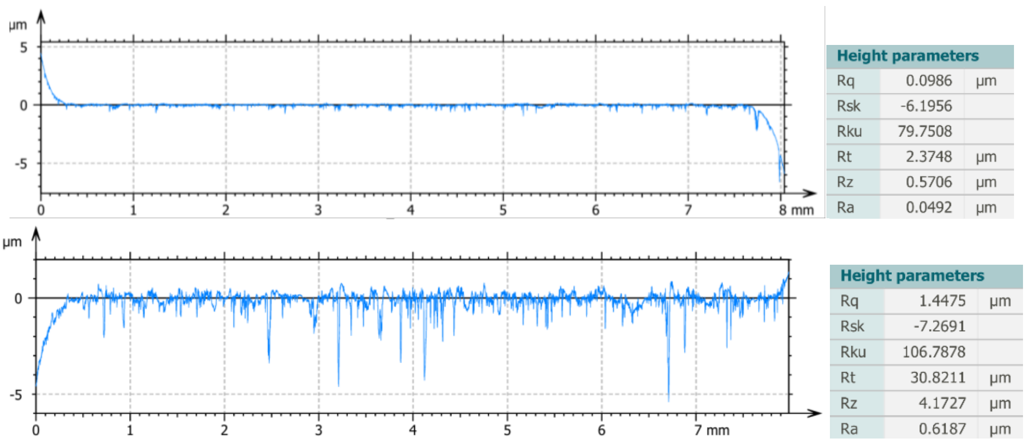

Fig. 8. Roughness profile of the investigated samples P1 and P2.

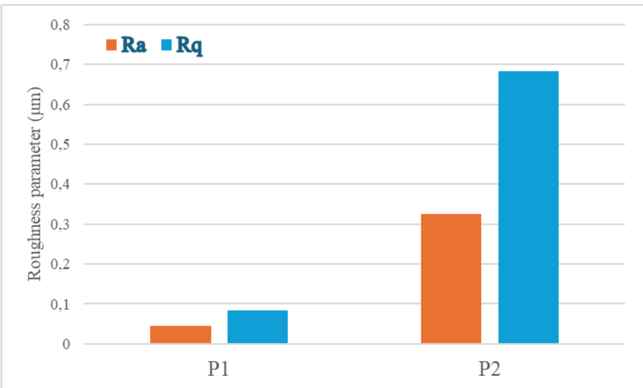

Fig. 9. Ra and Rq parameters for surface roughness of the investigated samples P1 and P2.

Our results revealed that the P1 samples had the lowest values of the Ra and Rq parameters (e.g., Ra = 0.0447 µm, Rq = 0.0841 µm). In the case of long bone fractures sample (P2) generated a higher increase in the Rq parameter (Rq = 0.6825 μm) and Ra = 0.3259 μm. The homogenous passive layer is not affected by chemical composition variation or by roughness.

4. Conclusions

The experimental results showed similar chemical composition for both orthopedic implants being realized by Ti6Al4V alloy. The microstructure evaluation revealed α laths with different sizes and orientations inside the prior β grains. Both samples showed a hydrophilic behaviour with a similar surface free energy, meaning that the homogenous passive layer is not affected by chemical composition variation or roughness.

The plate for the long bone fractures sample showed a higher value of Ra compared with the femoral stem hip prosthesis. The titanium plate for long bone fractures with a surface roughness of 0.3 μm exhibited a higher water contact angle (37.90°), whereas slightly lower water contact angles (37.52°) were observed for the femoral stem hip prosthesis substrate with a surface roughness of 0.04 μm. This result indicates that both surfaces were hydrophilic.

We can conclude that the two samples are similar, not only in chemical composition and structure but also in terms of surface properties, even though the implants are different.

R E F E R E N C E S

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