

INFLUENCE OF TRAVERSE SPEED ON SURFACE TOPOGRAPHY OF Ti-6Al-4V AND Ti-6Al-7Nb ALLOYS TREATED BY ULTRASONIC PULSATING WATERJET

AKASH NAG¹, JAKUB POLOPRUDSKY², GABRIEL STOLARIK¹,
DAGMAR KLICHOVA¹, ALICE CHLUPOVA², DINARA SOBOLA²,
SERGEJ HLOCH^{3,4}

¹Faculty of Manufacturing Technologies, TUKE with a seat
in Presov, Slovak Republic

²Institute of Physics of Materials, The Czech Academy of
Sciences, Brno, Czech Republic

³Faculty of Mechanical Engineering, VSB - Technical
University of Ostrava, Ostrava, Czech Republic

⁴Institute of Geonics, Czech Academy of Sciences,
Ostrava, Czech Republic

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akash.nag@tuke.sk

This study investigates the effect of traverse speed on the surface characteristics of Ti6Al4V and Ti6Al7Nb alloys treated by ultrasonic pulsating water jet (PWJ). Surface topography, morphology, wettability, and surface free energy (SFE) were evaluated and compared with a commercial sandblasted Ti6Al7Nb femoral stem. The results showed that increasing traverse speed significantly reduced Sa and Sz for both alloys and changed the surface response from erosion to roughening and localized plastic deformation. Ti6Al7Nb generally exhibited slightly greater resistance to PWJ-induced erosion than Ti6Al4V. All PWJ-treated surfaces showed greater water wettability and higher SFE than the reference femoral stem. The polar and dispersive SFE components varied differently with traverse speed, indicating changes in the interfacial character of the treated surfaces. A traverse speed of $v = 12$ mm/s produced moderate micrometer-scale roughness together with favorable wettability and relatively high SFE, demonstrating the potential of PWJ for controlled modification of biomedical titanium surfaces.

KEYWORDS

PWJ, Titanium alloys, Surface treatment, Wettability, Surface roughness, Surface free energy

1. INTRODUCTION

Titanium and its alloys are important engineering materials with low density, high specific strength, and good corrosion resistance. These properties make it suitable for a wide range of applications, including aerospace [Peters et al., 2003], biomedical [Rack & Qazi, 2006], chemical [Gurrappa, 2003], automotive [Schauerte, 2003], and energy-related systems [Schutz & Watkins, 1998]. In aerospace, titanium alloys are used in frames, engine components, hydraulic systems, and other high-loading components [Zhao et al., 2022]. Specifically, Ti6Al4V remains the most widely used titanium alloy in this industry [Soundararajan et al., 2018]. In biomedical applications, they are prioritized for their superior mechanical properties, corrosion resistance, and biocompatibility [Niinomi, 2008]. They

are commonly used for orthopedic and dental implants, fixation devices, and joint replacements [Marin & Lanzutti, 2023].

Titanium alloys are generally classified, according to their phase constitution, as α , near- α , $\alpha+\beta$, β , and metastable- β alloys [Pushp et al., 2022]. The phase composition is controlled by alloying elements and heat treatment [Semiatiin, 2020], resulting in different combinations of strength, ductility, creep resistance, and other mechanical responses [Besisa & Yajima, 2024]. Ti6Al4V is the most commonly used alloy in this $\alpha+\beta$ group [Deng et al., 2021]. Ti6Al7Nb is another important alloy from the same group; however, it was developed specifically for biomedical applications. The mechanical properties are largely similar to those of Ti6Al4V, while Nb replaces V as the primary β -stabilizing alloying element [J. B. Wang et al., 2012]. This was done to address the issue of cytotoxicity caused by the release of vanadium ions from Ti6Al4V implants into living tissue. Therefore, Ti6Al7Nb has been proposed as an alternative and explored for orthopedic and dental applications [Bolzoni et al., 2017; Hulka et al., 2022]. Both Ti-6Al-4V and Ti-6Al-7Nb are technologically important $\alpha+\beta$ alloys, although differences in chemical compositions and phase stability may affect their microstructure and mechanical behavior.

Despite their favorable bulk properties, titanium alloys do not have optimal surface characteristics for every application. This is important because many degradation processes, such as wear, fatigue crack initiation, corrosion damage, and tissue interactions, are heavily influenced by surface and near-surface conditions. Titanium alloys, including Ti-6Al-4V, are particularly susceptible to poor tribological behavior and fretting damage [N. Wang et al., 2021]. In aerospace components, surface roughness, residual stress, localized hardening, and surface defects can affect fatigue performance. In biomedical applications, surface topography, wettability, and wear behavior can influence the interaction of the implant with the surrounding biological environment. Surface treatment is therefore used to modify the functional surface while retaining the advantageous properties of the bulk titanium alloy [Zhang et al., 2020].

Various surface treatment methods are used for titanium alloys, including chemical and electrochemical methods, thermochemical methods such as nitriding and ion implantation, laser-based treatments, and mechanical surface treatment [Zhang et al., 2020]. Among them, mechanical treatments modify the surface and near-surface regions through controlled plastic deformation without altering chemical and phase composition. Common methods include grinding and polishing, sandblasting, shot peening, and surface attrition [Kulkarni et al., 2014]. Depending on the process conditions, these techniques can modify surface roughness and morphology while producing work hardening and residual stress beneath the treated surface. Shot peening has been widely investigated for its ability to induce surface and subsurface plastic deformation, increase surface hardness, and induce compressive residual stresses, which are essential for fatigue and wear behavior [Liu et al., 2017; Xu et al., 2018]. Ball burnishing has also been studied as a means of improving the high-cycle fatigue behavior of $\alpha+\beta$ titanium alloys [Zay et al., 2011]. Ultrasonic surface rolling studies on Ti6Al4V have also shown reduced surface roughness and a simultaneous increase in surface hardness due to induced strain-hardening effects [N. Wang et al., 2021]. In addition to mechanical methods, laser-based surface texturing has also gained attention. Laser surface processing of Ti-6Al-4V has been reported to generate controlled micro- and nanoscale surface features that can tune wettability from hydrophobic to hydrophilic states, depending on the laser parameters and resulting surface morphology [Bonse et al., 2020; Vorobyev & Guo, 2013]. Femtosecond laser texturing studies have also

demonstrated that hierarchical surface structures can improve surface hardness and enhance wettability by increasing surface energy and promoting the formation of modified oxide layers through localized melting–re-solidification effects and microstructural refinement [Bizi-Bandoki et al., 2011; Cunha et al., 2013]. These investigations show that both mechanical and laser treatments modify surface topography in a controlled manner, with resulting roughness, hardness, and wettability being strongly interdependent and governed by the processing conditions and the induced surface morphology. High surface deformation or roughness can offset some advantages of compressive residual stress. This emphasizes the importance of precise control over treatment conditions.

Waterjet-based processing provides another way of mechanical interaction with a material surface. In conventional continuous waterjet (CWJ), the momentum of the high-velocity water stream is transferred to the target [Fard et al., 2025], generating stresses that can produce surface deformation, treatment [Xie et al., 2024], peening [He et al., 2020], and material removal [Xiaochu et al., 2019] depending on the hydraulic conditions and material properties. It is also favorable for local and complex surfaces because it does not require direct physical contact with the workpiece, reducing reaction forces. To increase process effectiveness while reducing supply pressure, abrasive particles are entrained in the jet. However, for surface-treatment applications, these particles can become embedded in or contaminate the processed surface [Arola et al., 2001]. This surface contamination is more critical for components used in biomedical applications.

Recently, to increase the potential utility of the CWJ without adding abrasives, extensive research has focused on pulsating waterjet (PWJ) technology. It modifies a CWJ by forcefully transforming it into a series of water droplet clusters that subsequently impact the surface [Foldyna, 2011]. In an ultrasonic PWJ system, pressure fluctuations are generated in a pressurized acoustic chamber by an oscillating sonotrode, resulting in the formation of successive high-velocity water clusters downstream of the nozzle [Foldyna et al., 2006]. Repeated impacts induce cyclic loading and impact pressure associated with the water-hammer effect and can produce material erosion, roughening, and peening, depending on hydraulic parameters, without using abrasive particles [Kumar et al., 2025].

The potential of PWJ for surface treatment or modification has been demonstrated on several metallic materials. Previous studies have shown that repetitive impacts induce measurable surface and subsurface changes in response to input parameters such as supply pressure, standoff distance, traverse speed, nozzle type, treatment trajectory, and material properties. PWJ experiments have shown that operating pressure and jet trajectory substantially influence the surface integrity of the treated area. For titanium alloy, Poloprudský et al. [Poloprudský et al., 2021] investigated Ti6Al4V exposed to PWJ and examined changes in both the surface and subsurface regions. Increased impingement increased surface profile height due to grain tilting and slip bands, but also increased dislocation density in the subsurface, which can be further correlated with the presence of a hardened layer. Surface treatment studies focused on Titanium alloys were carried out by Stolarik et al. [Stolárik et al., 2023], who investigated Ti6Al4V surface roughening using PWJ and showed that controllable surface topography can be achieved by manipulating supply pressure, excitation frequency, and trajectory [Klichová et al., 2025]. The results also showed increased subsurface hardness near the impact surface. Another surface-roughening study by Klichova et al. [Klichova et al., 2023] on Ti6Al4V using PWJ showed that surface roughness

parameters depend largely on the surface treatment rate and decrease sharply with increasing treatment rate. Also, the surface morphology of the treated samples was comparable to that of commercially obtained femoral stems. The same group conducted another follow-up study investigating the use of PWJ on Ti6Al7Nb alloy samples [Klichová et al., 2025]. The samples were exposed to selected combinations of input parameters, and the effects on surface morphology and topography were observed. The results showed that all technological settings produced an areal roughness parameter S_a similar to that of a femoral stem, with better skewness, structural repeatability, and uniformity compared to the selected grit-blasted commercial femoral stem. Another study [Siahpour et al., 2022] investigated the effect of PWJ traverse speed on the surfaces of a wrought Ti6Al4V sample. The results showed greater roughening and erosion at lower traverse speeds than at higher traverse speeds. However, higher compressive residual stresses were observed at higher traverse speeds. Maximum compressive stresses of -626 MPa were achieved at 700 and 800 mm/s, and the stresses were distributed to depths of 250–300 μm for all peened sample conditions. The same approach was used for commercially pure titanium, and the effects of traverse speed and standoff distance on roughness and residual stresses were observed. For the optimal combination of conditions, a maximum compressive stress of about -390 MPa was measured at a depth of 450–600 μm from the affected surface, generating a roughness of $R_a = 3 \mu\text{m}$ [Siahpour et al., 2023]. Further study investigated the tribological aspect of the treated surface. The results showed a 55% increase in scratch hardness and 12% higher wear resistance compared to the untreated sample processed at a traverse speed of 900 mm/s [Siahpour et al., 2024].

These studies indicate that PWJ treatment combines features of waterjet processing and mechanical peening while avoiding the addition of abrasive media. Its ability to impose repeated localized impact loading makes it potentially useful for modifying titanium alloy surface topography and near-surface mechanical conditions. However, the final response is strongly dependent on jet parameters, material properties, and treatment strategy. This becomes more relevant when alloys with similar phase constitutions but different alloying elements are treated under the same conditions. Ti6Al4V and Ti6Al7Nb are both $\alpha+\beta$ alloys, but substitution of V by Nb changes their phase stability and microstructural response. A direct comparison under identical PWJ conditions can therefore provide insight into how alloy characteristics affect surface roughness, morphology, and wettability under repeated jet impact. Therefore, in the present study, both Ti6Al4V and Ti6Al7Nb were exposed to PWJ under the same hydraulic conditions ($p = 100 \text{ MPa}$, $d = 1 \text{ mm}$) and treatment trajectory, at varying traverse speeds ($v = 4, 12$, and 20 mm/s) to investigate their effect on surface roughness, morphology, and wettability of the resulting surfaces for both alloys. Additionally, these surface properties were compared with those of a commercially available grit-blasted femoral stem.

2. MATERIALS AND METHODS

2.1. Materials

Two $\alpha+\beta$ titanium alloys, Ti6Al4V and Ti6Al7Nb, were selected as the experimental materials for the present study. Both materials were supplied as 16 mm diameter rods in the annealed condition. Ti6Al4V is a widely used aerospace and biomedical alloy, while Ti6Al7Nb is its vanadium-free alternative for biomedical applications, where niobium replaces vanadium as the β -phase-stabilizing element due to concerns about long-term cytotoxicity from vanadium effects on ion release into the

body. The resulting distributions of niobium-rich β phase in Ti6Al7Nb and vanadium-rich β phase in Ti6Al4V are shown in Figure 1. The observed area was polished with 1 μm diamond paste and is shown in high-contrast backscattered electrons to highlight the β phase. Both materials have a β phase distributed along grain boundaries of the α phase, with larger β phase regions at grain junctions. The main difference lies in the size of the β phase, which is greater in the case of Ti6Al7Nb, while Ti6Al4V shows a finer distribution.

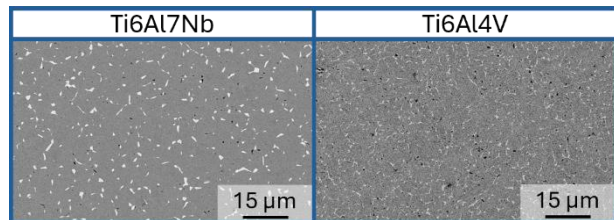


Figure 1. Microstructure of Ti6Al7Nb and Ti6Al4V.

For the experiments, individual samples, each 5 mm thick, were cut from the rod. To facilitate fixing and handling, the circular samples were machined from both sides to obtain flat, parallel surfaces. A resultant area of 12 x 12 mm was available for treatment for both materials. The mechanical and chemical properties of the tested materials, Ti6Al4V and Ti6Al7Nb, are given in Table 1 and Table 2.

Table 1. Mechanical properties of experimental materials

Material	Ti6Al4V	Ti6Al7Nb
Tensile strength [MPa]	957	990
Yield strength [MPa]	879	911
Elongation [%]	26	18
Reduction of area [%]	37	41

Table 2. Chemical composition of experimental materials

Material	Ti6Al4V	Ti6Al7Nb
Al [%]	6	6.41
V [%]	4	0.02
Nb [%]	-	6.75
Fe [%]	0.06	0.19
C [%]	0.02	0.01
N [%]	0.02	0.01
H [%]	0.003	0.001
O [%]	0.06	0.17
Ti [%]	Balance	Balance

2.2. Experiments

Experiments were carried out using an ultrasonic PWJ setup available at IGN CAS v.v.i, Ostrava, Czech Republic [Foldyna, 2011]. The high-pressure water required for the study is delivered by a high-pressure pump with a maximum operating pressure of 160 MPa and a flow rate of 63 l/min, and then enters the high-pressure acoustic chamber, where pressure fluctuations are induced by a vibratory sonotrode. The vibration in the sonotrode is achieved by the piezoelectric effect actuated by the ultrasonic generator. These high-pressure fluctuations propagate through the tunable acoustic chamber, where they are amplified by the internal shape of the chamber and then transform into discrete velocity fluctuations generated by discrete water clusters downstream of the nozzle exit [Říha & Foldyna, 2012]. The efficiency of the resulting jet depends on the

length of the acoustic chamber (l_c), which was set to $l_c = 22$ mm following the methodology described elsewhere [Nag et al., 2021]. Further, the optimal standoff distance (z) and stair trajectory methodology discussed in another work were followed and were determined to be $z = 116$ mm [Hloch et al., 2020]. To ensure uniform coverage across the entire experimental area, the interval between successive jet passes must be optimally set. The optimal stepover distance was determined in accordance with the methodology proposed in another study, which recommended 25% of the total groove width [Stolárik et al., 2026]. Therefore, for the present study, a stepover distance of 0.55 mm was selected. For both the experimental materials Ti6Al4V and Ti6Al7Nb, the experimental conditions were kept the same. Figure 2 shows a schematic of the experimental setup, and Table 3 lists the experimental conditions used in the study. After the experiments, all treated samples were kept immersed in the ethanol solution to prevent contact with the surrounding environment, which can affect the wettability results, as seen in a previous study [Nag et al., 2026].

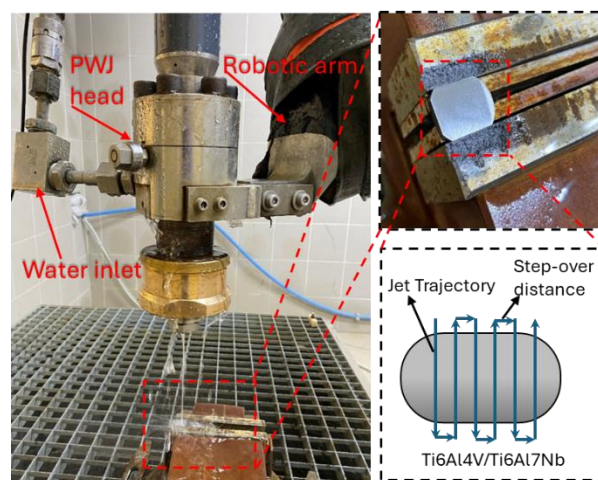


Figure 2. Schematic representation of experimental setup

Table 3. Experimental conditions used in the present study

Pressure [MPa]	100	Step over distance [mm]	0.55
Nozzle diameter [mm]	1	Traverse speed [mm/s]	4, 12, 20
Standoff distance [mm]	116	Treatment rate [mm ² /s]	2.2, 6.6, 11
Acoustic chamber length [mm]	22	Trajectory	Linear
Frequency [kHz]	20	Material	Ti6Al4V, Ti6Al7Nb

2.3. Roughness measurements

All six sample conditions were evaluated for primary surface-roughness parameters to quantify the surface topography produced by the PWJ. The samples were scanned using a digital optical microscope, Alicona Infinite Focus G5, capable of capturing 3D data. The entire dataset was further evaluated using MountainMaps Imaging Topography to obtain the required primary areal surface roughness values. The roughness data were collected from 5 randomly selected 5 x 5 mm regions to ensure statistical robustness. The primary areal roughness parameters were measured in accordance with ISO 25178-2 [ISO

25178-2:2021, 2021], using a Gaussian filter ($2.5\ \mu\text{m}$) to reduce end effects. For each investigated surface, the primary areal roughness parameters S_a , S_z , S_{sk} , and S_{ku} were measured. The average values and their standard deviations were plotted to show variability. To compare the generated surface with that of the commercial sandblasted Ti6Al7Nb femoral stem, the same measurement methodology was used. The mean value of the femoral stem was plotted as a reference line for easy comparison with the PWJ-generated surfaces.

2.4. SEM observation

The treated surface morphology was examined in detail using a scanning electron microscope (SEM). The microstructure was observed by Tescan Lyra3 XMH FEG/SEMxFIB operated at an accelerating voltage $HV = 10\text{kV}$, employing a secondary electron detector. The treated surfaces were observed using a Phenom XL from ThermoFisher Scientific with a thermionic CeB6 electron source operated at an accelerating voltage of $HV = 10\text{kV}$, employing a secondary electron detector.

2.5. Wettability measurements

Wettability measurements were carried out to identify the surface characteristics of the surfaces generated by PWJ. It was determined from the contact angle, measured using the sessile drop method with a See System E (Advex Instruments) wettability tester. A dispensing micropipette was used to deliver $3\ \mu\text{L}$ droplets of demineralized water and Diiodomethane. The contact angle was evaluated after 5, 30, and 45 s to allow droplet stabilization and assess variation over time and measurement repeatability. Measurements were conducted in a cleanroom environment with controlled temperature and humidity. The temperature was $22 \pm 1^\circ\text{C}$, and humidity was maintained at $45 \pm 5\%$ RH. Polar (demineralized water) and nonpolar (Diiodomethane) liquids were used to quantify surface energy. Furthermore, surface free energy (SFE) was evaluated using the mean contact angles obtained with both polar and nonpolar probe liquids for all the treated surfaces.

3. RESULTS AND DISCUSSION

3.1. Surface roughness analysis

The analysis of the primary areal surface roughness parameters, arithmetical mean height (S_a) and maximum height (S_z), showed that the highest level of surface irregularity was obtained at the lowest traverse speed ($v = 4\ \text{mm/s}$) (Figure 3). Increasing the traverse speed to $12\ \text{mm/s}$ and $20\ \text{mm/s}$ significantly decreased surface roughness. This trend is consistent with the physical nature of the process, as higher traverse speed reduces the number of impacts per unit area, thereby decreasing the accumulated energy and the intensity of the erosive action [Klichová et al., 2025].

Quantitative analysis yielded S_a values of $9.75 \pm 0.24\ \mu\text{m}$, $1.00 \pm 0.01\ \mu\text{m}$, and $0.66 \pm 0.01\ \mu\text{m}$ for Ti6Al7Nb and $10.64 \pm 0.12\ \mu\text{m}$, $1.59 \pm 0.04\ \mu\text{m}$, and $0.68 \pm 0.01\ \mu\text{m}$ for Ti6Al4V at traverse speeds of $v = 4, 12$, and $20\ \text{mm/s}$, respectively. These results show that Ti6Al7Nb exhibited greater resistance to erosion under all investigated conditions than Ti6Al4V, as indicated by the lower resulting surface roughness. In relation to the mechanical properties of the materials investigated (Table 1), Ti6Al7Nb is characterized by marginally higher material strength and lower ductility. This suggests that under the specific loading conditions considered here, material strength plays a dominant role in the material's resistance to erosive wear [POLOPRUDSKY et al., 2025]. The primary surface roughness parameter S_z also followed a similar trend to S_a and decreased from $S_z = 91.70 \pm$

$1.42\ \mu\text{m}$ to $7.33 \pm 0.29\ \mu\text{m}$ for Ti6Al7Nb and from $S_z = 95.26 \pm 4.02\ \mu\text{m}$ to $7.65 \pm 0.29\ \mu\text{m}$ for Ti6Al4V as the traverse speed increased from $v = 4$ to $20\ \text{mm/s}$.

Under high-frequency dynamic loading ($f = 20\ \text{kHz}$) and lower traverse speed $v = 4\ \text{mm/s}$, immediate onset of material loss occurs. The high strain rate suppresses the conventional elastic-plastic response, thereby eliminating the incubation stage of erosion and promoting a transition to rapid material removal [Kamkar et al., 2013]. Under these conditions, erosion resistance is governed primarily by the material's strength and ductility. The lower ductility and higher strength of Ti6Al7Nb more effectively resist micro-fragmentation and the development of eroded-surface characteristics caused by impact pressure.

Comparison with the reference surface of the femoral component ($S_a = 4.65 \pm 0.05\ \mu\text{m}$) showed that, at a traverse speed of $v = 4\ \text{mm/s}$, both titanium alloys exhibited substantially higher S_a values. In contrast, at traverse speeds of $v = 12$ and $20\ \text{mm/s}$, the measured roughness values were significantly lower. This pronounced decrease results from the discrete increase in traverse speed and the associated substantial reduction in energy density per unit area. It should also be noted that the surface roughness obtained at a traverse speed of $v = 12\ \text{mm/s}$ is fully comparable with the surface requirements reported for moderately rough dental implant surfaces ($S_a < 2\ \mu\text{m}$) [De Bruyn et al., 2017; Le Guéhennec et al., 2007]. The greater variation in roughness values also demonstrated the PWJ's ability to generate the desired roughness by varying the traverse speed.

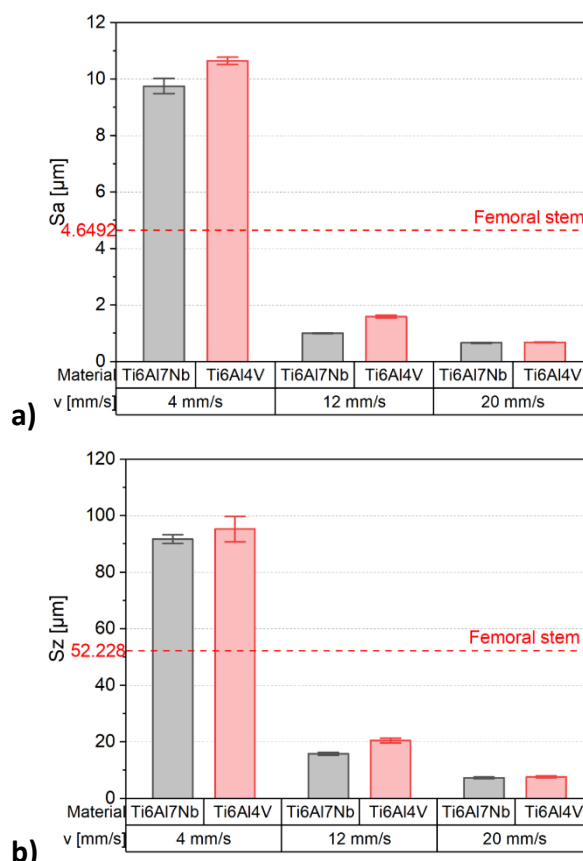


Figure 3. Influence of traverse speed on (a) S_a and (b) S_z for Ti6Al4V and Ti6Al7Nb alloys with comparison to a commercially available femoral stem.

The skewness of the primary areal height distribution (S_{sk}) provides additional information on surface morphology and the balance between peaks and valleys (Figure 4a). After PWJ treatment, negative S_{sk} values were obtained under all investigated conditions, indicating a predominance of valleys

over peaks. Such negative skewness is characteristic of surfaces subjected to liquid-droplet erosion [Siahpour et al., 2024]. The high transient pressure generated by droplet impact promotes truncation and plastic deformation of surface features, while the liquid flowing into existing microcavities contributes to their further deepening. This mechanism may also be associated with preferential removal of the mechanically less resistant β phase of the titanium matrix, which can act as a local site for accelerated erosion and development of deeper surface features [Siahpour et al., 2022].

In contrast to the PWJ-treated surfaces, the reference femoral stem exhibited Ssk values closest to zero, corresponding to a more symmetrical height distribution. The negatively skewed surfaces produced by PWJ contain a larger proportion of valleys and microcavities, which may provide favorable conditions for lubricant retention, coating adhesion, or interactions relevant to osseointegration. Comparison of the two alloys showed that Ti6Al7Nb was more resistant to localized surface deepening than Ti6Al4V. This difference can be related to their mechanical properties, as the higher strength of Ti6Al7Nb provides greater resistance to the hydrodynamic impact loading generated by the water clusters.

At the lowest traverse speed ($v = 4$ mm/s), Ssk approached zero, indicating a more balanced surface topography than that obtained at $v = 12$ and 20 mm/s, where a pronounced predominance of valleys was observed. This behavior corresponds to the relatively high overall roughness of $Sa \approx 10$ μm measured at $v = 4$ mm/s. The combination of a low traverse speed and an optimal transverse step-over distance completely modified the original ground surface. The high impact density of the water clusters produced a relatively uniform treatment across the entire area, generating peaks and valleys of similar magnitude. At higher traverse speeds of $v = 12$ and 20 mm/s, the distance between successive impacts increased [CHLUPOVA et al., 2025]. This reduced impact density led to only partial surface modification. Under these conditions, preferential removal of the softer β phase could promote deeper valley formation, while the more resistant α phase remained partly intact. The resulting morphology, characterized by relatively flat peaks and pronounced valleys, is consistent with the observed shift of Ssk toward more negative values.

This interpretation is also supported by the areal kurtosis parameter (Sku), which describes the sharpness of the surface-height distribution and its sensitivity to extreme peaks and valleys (Figure 4b). At the lowest traverse speed ($v = 4$ mm/s), Sku was approximately 3, corresponding to a near-Gaussian, or mesokurtic, height distribution. This value is consistent with a relatively uniform modification of the entire surface, in which valley formation and deformation, or truncation of the surface peaks, occurred to a comparable extent. Increasing the traverse speed to $v = 12$ and 20 mm/s resulted in an evident increase in Sku above 3, indicating a transition toward a leptokurtic height distribution characterized by more pronounced extreme peaks and valleys.

The increase in Sku is consistent with the proposed phase-selective erosion mechanism. At higher traverse speeds, the lower accumulated impact energy and greater spacing between individual impacts may promote preferential removal of the mechanically less resistant β phase [Siahpour et al., 2022]. Removal of this phase can generate deeper local depressions in the otherwise deformed original surface. No statistically significant difference in Sku was observed between Ti6Al7Nb and Ti6Al4V. This may indicate that, at an applied pressure of $p = 100$ MPa, the hydrodynamic loading is sufficiently intense to produce extensive degradation of the β -phase regions in both

alloys, reducing the influence of whether Nb or V is present as the β -stabilizing element. Under these conditions, the high impact energy may therefore diminish differences in the sharpness of the surface-height distribution between the two materials.

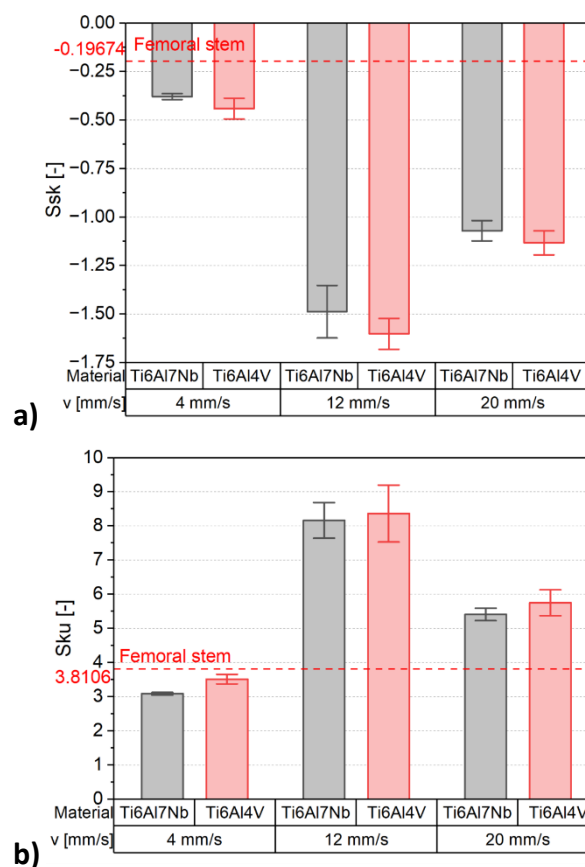


Figure 4. Influence of traverse speed on (a) Ssk and (b) Sku for Ti6Al4V and Ti6Al7Nb alloys with comparison to a commercially available femoral stem.

The magnitude of the Sa , Sz , Ssk , and Sku roughness parameters produced by the PWJ with variation in traverse speed for titanium alloys is important, particularly for biomedical applications. These parameters not only describe the magnitude of peaks and valleys but also their distribution, which affects the functional behavior of the implant surface. At the lowest traverse speed of $v = 4$ mm/s, both Ti6Al4V and Ti6Al7Nb exhibited the highest Sa and Sz values, together with Ssk values close to zero and Sku values around 3. This combination indicates extensive, relatively homogeneous modification of the original surface, driven by the high density of droplet impacts and the resulting accumulation of impact energy [Klichová et al., 2025; Siahpour et al., 2022]. Although this treatment produces a well-developed surface characteristic, the resulting Sa values of approximately 10 μm are substantially higher than those generally associated with moderately rough implant surfaces [Lim et al., 2009]. Increasing the traverse speed to 12 and 20 mm/s markedly reduced Sa and Sz because fewer water cluster impacts were delivered per unit area. At the same time, Ssk became more negative, and Sku increased above 3, showing that the lower overall roughness was accompanied by a less uniform height distribution due to a greater contribution from localized valleys and sharp asperities. From a biomedical perspective, this distinction is important because a reduction in Sa alone does not necessarily indicate a more favorable surface. The combination of roughness amplitude, valley-dominated topography, and presence of pronounced local features must also be considered in relation to cell attachment, osseointegration, coating

adhesion, and the possibility of local stress concentration or wear [Lim et al., 2009]. Among the investigated conditions, the surfaces produced at $v = 12 \text{ mm/s}$ appear particularly relevant, as their S_a values were below $2 \mu\text{m}$ for both alloys and therefore fall within the range commonly reported for moderately rough dental implant surfaces [Shalabi et al., 2006; Wennerberg et al., 2009]. Ti6Al7Nb consistently showed slightly lower S_a values than Ti6Al4V, suggesting greater resistance to PWJ-induced erosion, whereas the similar S_{ku} response of the two alloys indicates that the general shape of the height distribution was governed mainly by the intensity and spatial density of the PWJ impacts rather than by alloy composition alone.

3.2. Surface morphology

The surfaces produced by an ultrasonic pulsating water jet were examined using SEM. A distinct difference was observed between the commercially available femoral stem prepared by sandblasting and samples prepared by ultrasonic PWJ. Embedded abrasive particles are still visible on the femoral stem surface, along with rather sharp changes in surface relief visible in the detail view and typical scratch markings (Figure 5).

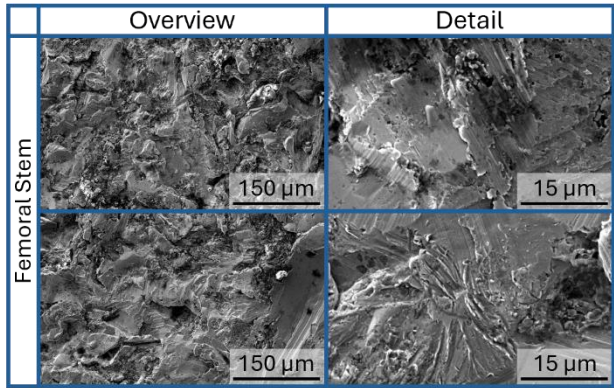


Figure 5. The surface of a commercially available femoral stem

The PWJ-treated surfaces (Figure 6) exhibit an irregular morphology created by a combination of crack formation, material removal, and plastic deformation, whereas the characteristics of the resulting surface morphology are strongly influenced by traverse speed. Ti6Al4V treated with a traverse speed of $v = 4 \text{ mm/s}$ does not show any signs of the retained original surface, and a new surface is formed by a combination of deep pits and peaks. Some areas show clear plastic deformation in the direction lateral to the impinging liquid jet axis, creating material upheaval, with one side exhibiting a relatively smooth morphology. This lateral outflow can contribute to the formation of lateral cavities that may be underestimated during optical roughness measurement or top-surface observation. The detail shows an erosion pit with equidistant markings on the pit bottom, which may indicate the cyclic nature of the damage.

Increased traverse speed ($v = 12 \text{ mm/s}$) leads to less pronounced roughening, where the surface appears more planar overall, with cracks and upheaved material disturbing the plane. Occasionally, larger isolated erosion pits can be observed; these can be linked to initiation sites that act as stress concentrators and may have a locally shortened incubation period. The detail also shows one of the occasionally appearing small areas of the original surface.

Further increase of traverse speed to $v = 20 \text{ mm/s}$ mostly shows a plastically deformed original surface. Plastic deformation leads to a number of depressed or upheaved areas without material removal. The surface can be more associated with peening morphology rather than roughening. However, the formation of

cracks is still strongly apparent and can be mostly associated with the original grind marks, which act as stress concentrators.

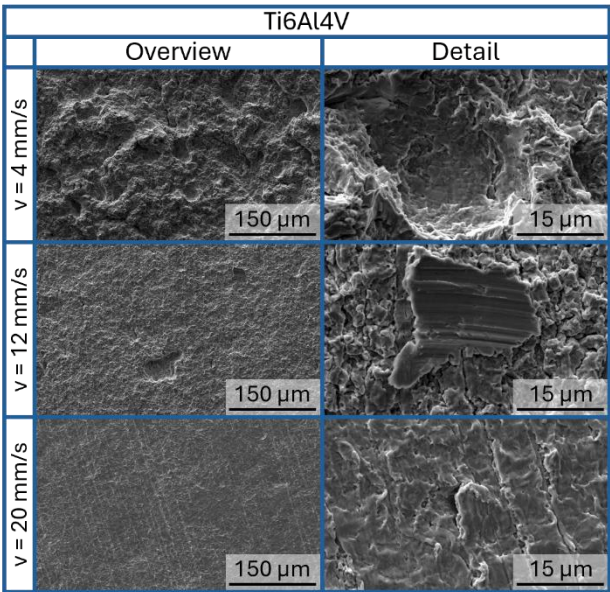


Figure 6. Surface of Ti6Al4V treated by ultrasonic pulsating water jet moving at varying traverse speed

The Ti6Al7Nb treated morphology shows similar trends to Ti6Al4V in relation to traverse speed (Figure 7). However, flat remnants of the original surface are observed already at a traverse speed of $v = 4 \text{ mm/s}$. This points to the material's higher erosion resistance, which must be evaluated prior to surface modification using PWJ. Typical lateral cavities with accompanying upheaved material are also visible in the case of Ti6Al7Nb. The traverse speed of $v = 12 \text{ mm/s}$ shows a combination of a highly deformed original surface with long cracks following the original grind marks and areas formed by material removal. The detail shows the interface between these two regions, where the morphology of the top-left area suggests lateral flow acting below the original surface. The traverse speed of $v = 20 \text{ mm/s}$ shows a mostly deformed original surface with cracks predominantly following original grind marks. As shown in detail, pits initiated at these grind marks were also observed on the treated surface.

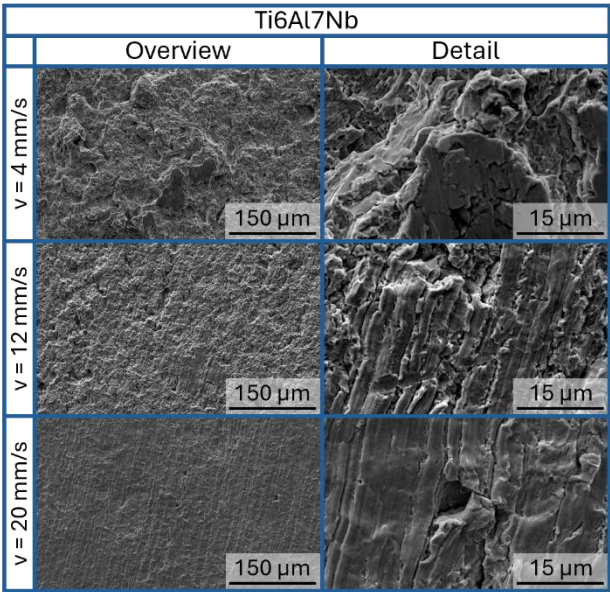


Figure 7. Surface of Ti6Al7Nb treated by ultrasonic pulsating water jet moving at varying traverse speed

3.3. Surface wettability

Figure 8 shows contact-angle measurement results using demineralized water and diiodomethane. For demineralized water (**Figure 8a**), Ti6Al7Nb showed a clear increase in contact angle with traverse speed, from approximately $10.9 \pm 2.88^\circ$ at $v = 4$ mm/s to $20.44 \pm 2.57^\circ$ at $v = 12$ mm/s and $40.04 \pm 3.38^\circ$ at $v = 20$ mm/s. The response of Ti6Al4V was less pronounced with respect to traverse speed. The contact angle remained close to $32.49 \pm 2.61^\circ$ at $v = 4$ and $31.8 \pm 1.13^\circ$ at $v = 12$ mm/s and increased to approximately $40.79 \pm 2.05^\circ$ at $v = 20$ mm/s. Thus, all treated surfaces remained wettable by water, but it decreased with increasing traverse speed. In contrast, the commercially available femoral stem exhibited a water contact angle of approximately 92.48° , considerably higher than those of all PWJ-treated surfaces. The reference surface was therefore poorly wetted by water and lay slightly above the conventional 90° boundary between hydrophilic and hydrophobic behavior.

The variation in the contact angle can be related to the roughness results discussed above. The inverse relationship between surface roughness parameters (S_a and S_z) and contact angle is particularly clear for Ti6Al7Nb. A similar response has been reported for textured Ti6Al4V, where reduced surface roughness was accompanied by an increase in water contact angle and was interpreted in terms of Wenzel-type wetting of an intrinsically wettable titanium surface [Conradi et al., 2020]. However, in the present study, the behavior of Ti6Al4V shows that surface roughness alone does not describe the wetting response. Despite the substantial decrease in S_a for $v = 4$ compared to $v = 12$ mm/s, the water contact angle changed slightly. Moreover, highly skewed and Kurtic surfaces generated at higher traverse speeds ($v = 12$ and 20 mm/s) alter the distribution and geometry of surface features and can affect liquid penetration and contact-line pinning. They may therefore modify the apparent contact angle independently of the mean roughness value.

The large difference between the PWJ-treated alloys and the femoral stem should also be taken into account concerning their respective post-treatment histories. Following PWJ treatment, the Ti6Al4V and Ti6Al7Nb specimens were stored predominantly immersed in ethanol and were exposed to ambient conditions only for relatively short periods. In contrast, the commercially available femoral stem was stored under normal room conditions. Titanium surfaces are known to undergo time-dependent changes during ambient storage, including adsorption of hydrocarbon and carbon-oxygen contaminants, which can increase the water contact angle and reduce surface polarity [Kido et al., 2023; Minamikawa et al., 2016]. For water, the high contact angle of the femoral stem may therefore reflect the combined effects of its surface-treatment history and subsequent environmental exposure rather than sandblasting or roughness alone. Previous studies have similarly shown that sandblasting can alter both the wettability and surface free energy of titanium surfaces [Gil et al., 2021; Rodriguez-González et al., 2023]. The presence of embedded abrasive particles on the commercial stem is also visible in the SEM observations reported in the preceding section.

A different trend was obtained with diiodomethane (**Figure 8b**). For Ti6Al7Nb, the contact angle decreased from approximately $55.12 \pm 0.31^\circ$ at $v = 4$ mm/s to $42.59 \pm 0.6^\circ$ at $v = 12$ mm/s and $40.37 \pm 0.82^\circ$ at $v = 20$ mm/s. Ti6Al4V showed an inconsistent response, with values of approximately $35.05 \pm 3.39^\circ$, $23.99 \pm 0.79^\circ$, and $36.02 \pm 2.04^\circ$ at $v = 4$, 12 , and 20 mm/s, respectively. The femoral stem exhibited a diiodomethane contact angle of approximately 48.23° . In contrast to its very high level of water contact angle, this value falls within the range measured for the

PWJ-treated alloys. The opposite trends observed with water and diiodomethane, especially for Ti6Al7Nb, indicate that changes in wettability of the PWJ-treated surfaces cannot be solely attributed to increasing traverse speed. Demineralized water is a polar liquid, whereas diiodomethane is commonly used as a nonpolar probe of dispersive surface interactions in contact-angle analysis [Kozbial et al., 2014]. Their different responses therefore reflect the combined influence of surface morphology and the physicochemical state of the titanium surface.

The large difference in the contact angle values for the femoral stem between its response to water and diiodomethane indicates relatively weak polar interactions, while substantial dispersive interactions remain at the surface. Ambient exposure may contribute to this behavior because adsorption of hydrocarbon-containing species can reduce the polar character and water wettability of titanium surfaces without eliminating non-polar dispersive interactions [Kido et al., 2023]. However, the femoral stem results showed that the same Ti6Al7Nb material can show substantial differences in the balance of polar and dispersive interactions when the surface treatment and post-treatment handling change while the alloy composition remains the same. However, without direct surface-chemical analysis, the relative contributions of environmental aging, the native oxide layer, residual abrasive particles, and other aspects of the commercial treatment history cannot be separated.

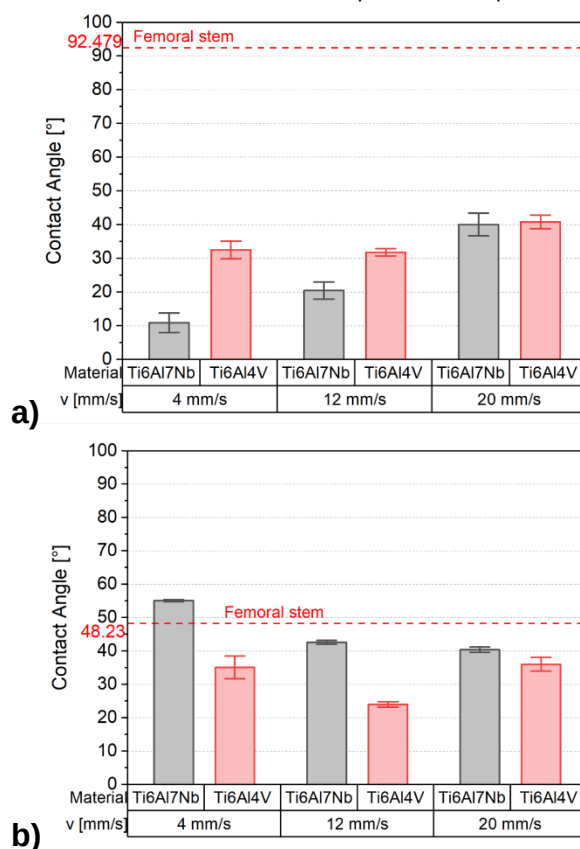


Figure 8. Variation of contact angle of the surface topography of the Ti6Al4V and Ti6Al7Nb treated surfaces using PWJ using two wetting liquids (a) demineralized water and (b) Diiodomethane.

Measurements with these two liquids therefore allow the total surface free energy (SFE) to be resolved into polar and dispersive contributions using the Owens-Wendt approach [Owens & Wendt, 1969]. **Figure 9** presents the calculated SFE and its polar and dispersive components. Ti6Al7Nb showed a decrease in the polar component with increasing traverse speed, from 41.47 mN/m at $v = 4$ mm/s to 33.96 mN/m at $v = 12$ mm/s and 23.96

mN/m at $v = 20$ mm/s. The corresponding values for Ti6Al4V were 26.61, 24.7, and 22.48 mN/m. The higher polar component of Ti6Al7Nb at $v = 4$ mm/s is consistent with the lower measured water contact angle. As traverse speed increased, the reduction in the polar component was accompanied by poorer water spreading, especially for Ti6Al7Nb.

The dispersive component followed a different trend. For Ti6Al7Nb, it increased from approximately 31.38 mN/m at $v = 4$ mm/s to about 38.28 and 39.42 mN/m at $v = 12$ and 20 mm/s, respectively. Ti6Al4V exhibited a larger dispersive contribution under all three traverse speeds, with values of approximately 42, 46.5, and 41.55 mN/m, respectively. Consequently, the decrease in the polar contribution with increasing traverse speed was partly offset by the dispersive component. The total SFE therefore varied over a narrower range than either component separately. Ti6Al7Nb reached approximately 72.85, 72.25, and 63.38 mN/m at $v = 4, 12$, and 20 mm/s, respectively, while Ti6Al4V exhibited values of approximately 68.62, 71.21, and 64.03 mN/m.

The femoral stem displayed a significantly different energetic state from the PWJ-treated Ti6Al7Nb surfaces. Its total SFE was approximately 36.24 mN/m, compared with 63.38–72.85 mN/m for PWJ-treated Ti6Al7Nb, while its polar component was only about 0.99 mN/m compared with 23.96–41.47 mN/m after PWJ treatment. Since the reference stem and PWJ specimens are the same alloy, these differences cannot be explained by bulk composition. They instead show that the surface state of Ti6Al7Nb can vary substantially depending on its treatment and subsequent environmental history. The very small polar contribution of the femoral stem is also consistent with its high value of water contact angle. Ambient aging may contribute to this difference, as hydrocarbon and carbon-oxygen contaminants adsorbed during storage in air can reduce the polar character and hydrophilicity of titanium surfaces [Kido et al., 2023; Minamikawa et al., 2016].

For biomedical use, roughness, wettability, and SFE results are more informative when considered together. Titanium implant surfaces interact with blood and tissue fluids immediately after implantation, followed by rapid protein adsorption that mediates subsequent cell–surface interactions. Both surface topography and physicochemical properties therefore contribute to the early stages of osseointegration [Gentleman & Gentleman, 2014; Parisi et al., 2019]. Experimental work on Ti6Al4V has also shown that combining micro/nanoscale surface structure with increased hydrophilicity can improve osteoblast response and bone integration compared with less favorable surface states [Hyzy et al., 2016].

The femoral stem provides a useful practical reference because it allows the effect of the measured surface state to be considered without changing the alloy. At the time of measurement, all PWJ-treated Ti6Al7Nb surfaces showed substantially lower water contact angles, higher total SFE, and much larger polar SFE contributions than the commercial Ti6Al7Nb femoral stem. These differences indicate stronger interaction of the PWJ-treated surfaces with polar aqueous media under the present measurement conditions. However, it should not be interpreted as evidence that PWJ-treated Ti6Al7Nb is biologically superior to the commercial stem. The stem and the PWJ specimens differed in both surface processing and post-treatment storage, and the individual contribution of each factor cannot be separated from the present measurements.

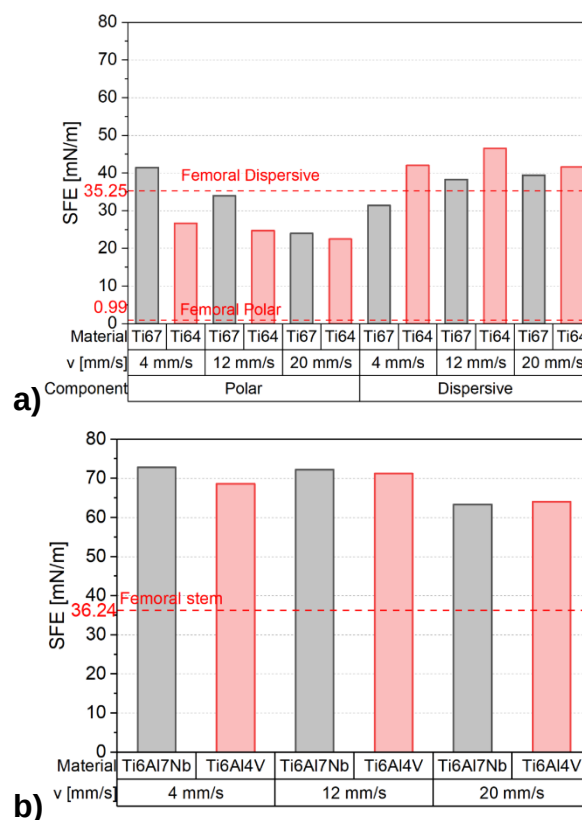


Figure 9. Dependence of (a) solid polar and dispersive component and (b) total surface free energy of the PWJ treated Ti6Al4V and Ti6Al7Nb generated by various traverse speeds.

The difference between Ti6Al7Nb and Ti6Al4V is most apparent in the polar contribution to SFE and in their water contact angles at the lower traverse speeds. At $v = 20$ mm/s, both alloys exhibited similar water contact angles and total SFE, despite retaining different polar-to-dispersive ratios. The results suggest that PWJ treatment can tune the interfacial properties of both $\alpha+\beta$ titanium alloys through changes in processing intensity, while the magnitude of the response remains alloy-dependent. Comparison between the PWJ-treated Ti6Al7Nb specimens and the Ti6Al7Nb femoral stem further demonstrates that surface treatment and subsequent environmental exposure can produce large differences in wettability and SFE even when the nominal alloy composition is held constant. A biological advantage of one alloy or PWJ condition cannot, however, be inferred directly from roughness values, contact angle, or SFE. Verification would require measurements of protein adsorption and osteoblast adhesion, proliferation, or differentiation, followed by direct assessment of bone–implant contact in an appropriate in vivo model.

4. CONCLUSIONS

The present study investigated the surface characteristics generated by ultrasonic PWJ at different traverse speeds ($v = 4, 12$ and 20 mm/s) on two $\alpha+\beta$ Titanium alloys, Ti6Al4V and Ti6Al7Nb. The main results of the study are summarized below:

- 1) The primary areal roughness parameters S_a and S_z showed an inverse trend with increasing traverse speed for both alloys owing to the lower number of impingements and energy density per unit surface area at higher traverse speeds.
- 2) Small differences in roughness levels under the same conditions were observed between the two alloys owing to the difference in the mechanical properties,

with Ti6Al7Nb showing higher resistance to PWJ-induced erosive modification compared to Ti6Al4V.

- 3) The skewness and kurtosis parameters showed a nonlinear trend with increasing traverse speed owing to the changes in the distribution of surface features generated, suggesting that PWJ creates highly skewed and leptokurtic surfaces that show potential to have better wear behavior, lubrication retention, and biological interaction.
- 4) The surface morphology showed the transition of the surface generated by increasing speed levels from material erosion to surface roughening to local plastic deformation.
- 5) All the surfaces generated by the PWJ for both the alloys showed strong wetting behavior, with Ti6Al7Nb showing better hydrophilicity as compared to Ti6Al4V under similar conditions.
- 6) The surface free energy showed that both the alloys respond differently to the probe liquids. The polar component decreased as traverse speed increased, while the dispersive component increased. These results indicate that PWJ treatment alters the balance between polar and dispersive surface interactions rather than producing a uniform increase or decrease in total surface free energy.

Overall, the results demonstrate that traverse speed is an effective parameter for controlling the topography, wettability, and surface energetic characteristics of Ti6Al4V and Ti6Al7Nb during PWJ treatment, with the two alloys showing distinct responses despite their similar $\alpha+\beta$ phase constitution.

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DECLARATION ON THE USE OF ARTIFICIAL INTELLIGENCE

During the preparation of this manuscript, the authors used AI-based tools such as Grammarly Pro version to assist with language editing and/or improving clarity and structure. The authors reviewed and edited the output and take full responsibility for the content, including the accuracy of statements, completeness of references, and originality of the work. No AI tool was used to generate or fabricate experimental data or results.

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CONTACTS:

Ing. Akash Nag, PhD
Faculty of Manufacturing Technologies, TUKE with a seat in Presov
Presov, 08001, Slovak Republic
akash.nag@tuke.sk

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