Influence of femtosecond laser processing parameters on the surface morphology of titanium alloy

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Abstract: *Titanium alloys are essential in biomedicine due to their high specific strength and biocompatibility, with surface properties directly influencing the successful osseointegration of implants. In this study, surface texturing of an experimental titanium alloy was performed using an ultrafast femtosecond laser with varying pulse energies. Roughness and topography were analysed using optical profilometry and confocal laser scanning microscopy, while microhardness was measured by the Vickers method. The results show that a pulse energy of 2.1 µJ, with a wavelength of 1030 nm, pulse duration of 190 fs, and repetition rate of 1 MHz, constitutes the optimal laser process parameters for achieving the desired surface properties in engineering and biomedical applications.*
Keywords*: TITANIUM ALLOY, FEMTOSECOND LASER, ROUGHNESS, MICROHARDNESS*

1. Introduction

Due to their biocompatibility and excellent mechanical and corrosion properties, titanium alloys play a significant role in modern engineering and biomedical applications, particularly in the production of orthopaedic and dental implants. Additionally, surface properties are crucial for successful interaction with biological tissue and the long-term functionality of implants. The femtosecond laser offers great potential for biomedical applications because it provides high precision, flexibility, and broad applicability. Femtosecond laser ablation is notable among techniques for modifying the texture and roughness of implant surfaces to improve osseointegration. This method is increasingly used due to its precise control over surface topography, high efficiency, and low material consumption. Numerous studies confirm that specially patterned roughness can improve tensile properties and help prevent bacterial colonization [1]–[5].

This work aims to analyse the surface morphology, specifically surface roughness and microhardness, of an experimental titanium alloy to determine the femtosecond laser process parameters required to achieve favourable surface properties for biomedical applications.

2. Materials and Methods

An experimental titanium alloy with the chemical composition Ti-10Nb-10Cr was produced by melting in an electric arc furnace under an argon atmosphere in a copper mould, which was rapidly cooled with water. Casting was performed by a pressure process in a vacuum furnace to form a plate measuring 32 mm × 10 mm × 1 mm. The cast plate was metallographically prepared by grinding and polishing. For surface texturing of the samples in this work, a PHAROS-type Yb femtosecond laser (Light Conversion, Vilnius, Lithuania) was used. The optical system is shown schematically in Figure 1.

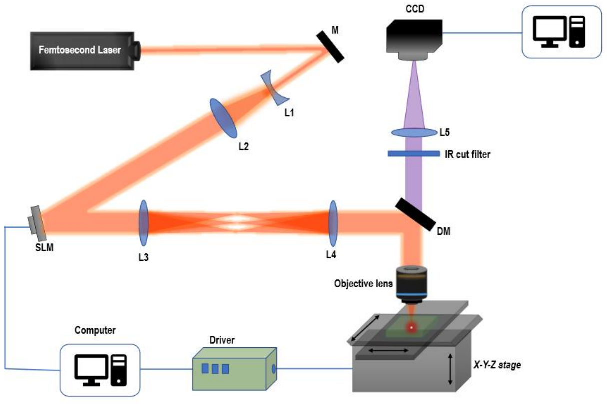

Fig. 1 *Schema of optical system.*

A femtosecond laser system emits ultrashort pulses at a central wavelength of 1030 nm with a tunable pulse repetition rate, ranging from single pulses to 1 MHz. The 190 fs pulse duration enables very high peak pulse power, allowing nonlinear interaction with the material and precise ablation with minimal thermal impact. Experiments were conducted at various pulse energies (Table 1) to investigate their effects on the morphology and topography of the titanium alloy surface. The pulse energy was the primary parameter controlling the laser-material interaction, while the pulse frequency determined the average power and heat accumulation.

Table 1: *Parameters of the femtosecond laser used in the experiment.*

Sample	1	2	3	4	5
Pulse energy [µJ]	0.7	1.5	2.1	2.6	3.0

The roughness of the femtosecond laser-textured surface was measured using a 3D optical profilometer, Filmetrics ProFilm 3D (KLA Corporation, Milpitas, CA, USA). This optical profilometer is a measuring system for non-contact determination of surface topography with high spatial resolution. The device is based on white light interferometry and enables precise measurement of surface irregularities, height differences, and shapes over a wide range of dimensions. The system provides a three-dimensional display of the surface in natural colours, with each pixel optimally focused throughout the entire measurement range.

Confocal laser scanning microscopy was used to characterise the surfaces of samples textured with a femtosecond laser. For this purpose, an Olympus LEXT OLS5100 confocal laser scanning microscope was used with the Olympus OLS5100 Data acquisition application and Olympus OLS5100 analysis application software packages.

The microhardness of the titanium alloy before and after texturing with a femtosecond laser was measured by the Vickers method (HV) using a Leica VHMT hardness tester (Leica Microsystems, Wetzlaru, Germany). Measurements were carried out with a force of 9.80 N (HV1), and the indenter's dwell time was 10 seconds. The microscope magnification used to measure the diagonals of the impression was 500×.

3. Results and Discussion

In Figure 2, surfaces of titanium alloy textured with a femtosecond laser are shown, photographed with a digital camera through a magnifying glass. Dark squares measuring 1 mm × 1 mm are visible.

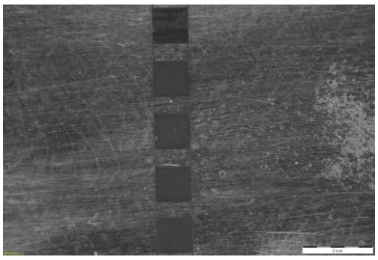

Fig. 2 *Femtosecond laser-textured titanium alloy surfaces.*

The surface roughness of the titanium alloy after texturing with a femtosecond laser at different pulse energies was measured using an optical profilometer.

First, the surface roughness of the titanium alloy that was not laser-textured was measured. Its surface roughness value is S_a = 0.18 µm, indicating a relatively smooth, unchanged surface. The topography of the surface that was not treated with the laser is shown in Figure 3.

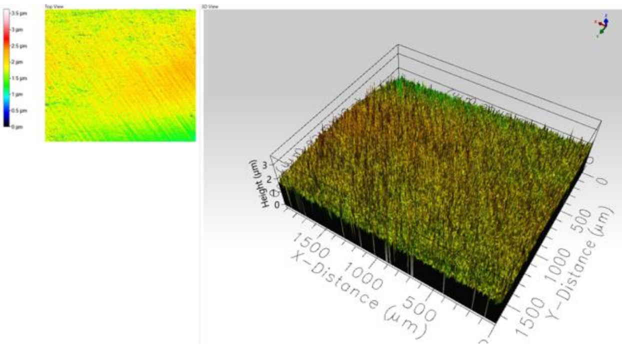

Fig. 3 *Topography of titanium alloy before fs texturing.*

Figure 3 shows the three-dimensional topography of the titanium alloy surface, obtained using a 3D optical profilometer. The measurement covers an area of approximately 1500 × 1500 µm, with the surface height distribution displayed in the nanometre range using a colourimetric scale. The results indicate a relatively smooth and homogeneous surface with small height variations. Slight irregularities, primarily resulting from previous mechanical processing such as grinding and polishing, are predominant. The low roughness value (S_a = 0.18 µm) indicates limited topographic complexity, which may be unfavourable for biological integration, as such a surface provides fewer sites for cell and protein adhesion.

Measurements of surface roughness were also carried out at five different pulse energies: 0.7 µJ, 1.5 µJ, 2.1 µJ, 2.6 µJ, and 3.0 µJ. The mean arithmetic roughness values, Sa, are shown in Table 2.

The results in Table 2 clearly show that roughness increases with higher laser pulse energy. At the lowest energy (0.7 µJ), the sample surface was relatively smooth, with a S_a value of 0.23 µm, indicating minimal material removal and slight texturing. Increasing the pulse energy to 1.5 µJ and 2.1 µJ led to a gradual rise in the S_a value to 0.32 µm and 0.37 µm, respectively, as a result of more intense material removal and the formation of deeper microstructures on the surface.

Table 2: *Surface roughness of titanium alloy textured with a femtosecond laser*.

E (µJ)	S_a (µm)
0.7	0.23
1.5	0.32
2.1	0.37
2.6	0.56
3.0	0.86

A more significant increase in roughness is observed at energies of 2.6 µJ and 3.0 µJ, with S_a values reaching 0.56 µm and 0.86 µm. This trend can be explained by the higher local laser energy density, which leads to more intense melting and ablation of the material, resulting in the formation of more pronounced micro-nanostructures. Such an exponential increase in roughness at higher energies indicates that the surface is transitioning from a phase of mild microtexture to one of significant microporosity.

Comparison with the untreated surface clearly shows that femtosecond laser texturing can precisely increase the roughness of titanium alloy, and its intensity can be controlled from minimal modifications to pronounced microstructures by simply adjusting the pulse energy. Such control of surface morphology is particularly relevant in applications where it is important to optimise adhesion to coatings or improve osseointegration of medical implants.

These results are consistent with the literature, which shows that increasing the pulse energy of a femtosecond laser directly affects the depth and sharpness of surface microstructures, while too low energies do not produce significant morphological changes. For applications requiring controlled roughness, such as improving adhesion to coatings or osseointegration in medical implants, it is possible to optimise the pulse energy to achieve the desired Sa value without excessive material ablation. The generally accepted roughness classification for implants is as follows: < 0.5 µm = smooth; 0.5–1.0 µm = minimally rough; 1.0–2.0 µm = moderately rough; > 2.0 µm = highly rough. According to the measured roughness values in this experiment, the surfaces are considered smooth or minimally rough. Authors state that moderately rough surfaces (approximately 1–2 µm S_a) significantly improve osseointegration and biological response compared to smooth surfaces [6], [7].

The dependence of the surface roughness of the titanium alloy on the applied pulse energies is shown graphically in Figure 4.

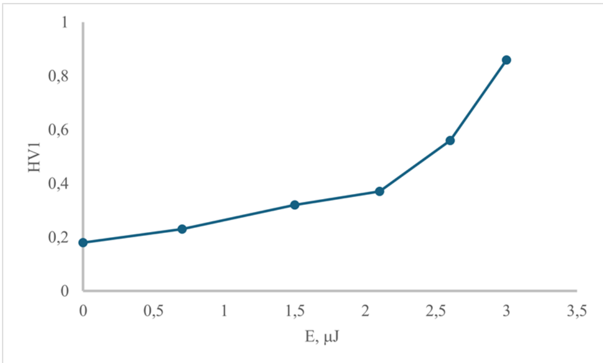

Fig.4 *Dependence of surface roughness of textured titanium alloy on femtosecond laser pulse energy.*

Experimental data confirm that the roughness of the titanium alloy surface increases as the pulse energy of the femtosecond laser increases, with the largest increase observed between 2.6 µJ and 3.0 µJ. These results indicate that the surface morphology and functional properties of titanium surfaces can be controlled by precisely adjusting the laser parameters.

A three-dimensional representation of the morphology of fs-textured surfaces obtained by a 3D profilometer is shown in Figure 5. Figure 5a shows the three-dimensional topography of the surface of a titanium alloy textured with a fs laser at a pulse energy of 0.7 µJ. The topography analysis indicates that the laser treatment modified the surface morphology compared to the initial state. The resulting surface exhibits a pronounced microrelief structure with noticeable elevations and depressions, visible in both 2D and 3D views. The height differences on the surface reach several micrometres, indicating effective interaction of the laser beam with the material at the selected pulse energy. The inhomogeneous colour distribution (green–yellow–red) reflects local variations in ablation depth and redistribution of molten material. The texture appears to spread relatively evenly over the entire analysed area, without large macroscopic defects such as cracks or areas of excessive thermal damage.

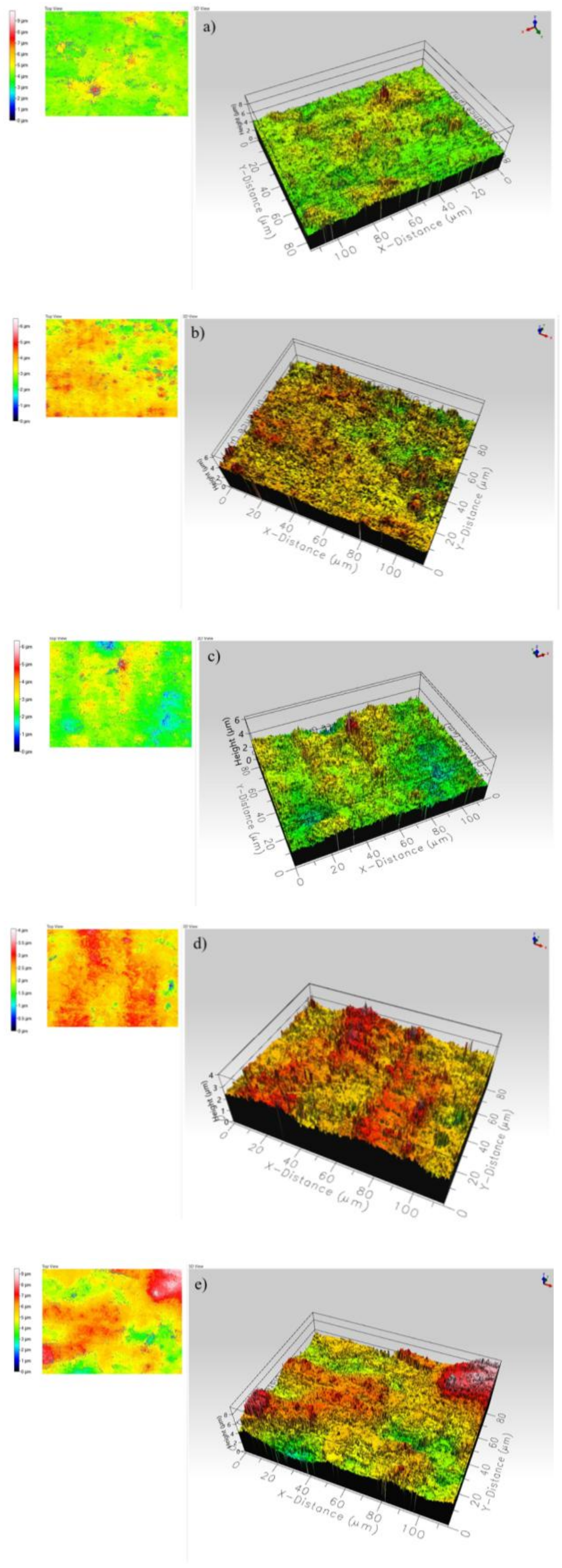

Fig.5 *Titanium alloy surfaces textured with various pulse energies: a) 0.7 µJ; b) 1.5 µJ; c) 2.1 µJ; d) 2.6 µJ; e) 3.0 µJ.*

At a pulse energy of 1.5 µJ, the microrelief structure develops further compared to lower energies (Figure 5b). 2D and 3D analyses show more pronounced and clearly defined elevations and depressions, as well as greater height differences, indicating a more intense interaction between the laser radiation and the material and more effective ablation. The more contrasting colour distribution in the 3D view confirms greater local variations in depth, with no signs of uncontrolled thermal damage. The surface remains homogeneous, without cracks or major defects, confirming the stability and repeatability of the processing. Increased roughness (S_a = 0.32 µm) indicates a transition towards a more pronounced microstructured surface, suitable for improved adhesion and proliferation of osteoblastic cells, while maintaining mechanical stability.

By increasing the pulse energy to 2.1 µJ, the microrelief becomes more pronounced, with greater surface roughness (Figure 5c). The 3D topography reveals a more complex morphology with micro- and sub-micrometre features and larger height differences compared to lower energies. A more uneven distribution of colours indicates more pronounced local variations in ablation intensity, probably due to nonlinear interactions of the femtosecond pulses with the material. Despite this, the absence of macroscopic defects and heat-affected zones confirms that the process remains predominantly ablative, without significant melting of the surrounding material.

At an energy of 2.6 µJ, there is a sudden increase in roughness and more pronounced morphological changes (Figure 5d). The 3D topography reveals deep depressions and sharp ridges, indicating strong ablation and a larger volume of material removed per pulse. Marked contrasts in the colour distribution suggest locally intensive ablation and possible redeposition of material. Although macroscopic defects are mostly absent, signs of weaker process control are evident. Increased roughness (S_a = 0.56 µm) can be functionally beneficial, but in biomedical applications it may cause stress concentrations, greater corrosion propensity, and an unfavourable biological response.

The highest applied energy, 3.0 µJ, resulted in an extremely rough and strongly modified topography (Figure 5e). Two-dimensional and three-dimensional images reveal deep crater structures, irregular shapes, and large height differences, indicating the dominance of strong ablation and non-linear processes. The highly inhomogeneous colour distribution suggests significant differences in ablation depth and possible melting and resolidification of the material. Such morphology can impair mechanical stability and promote the retention of impurities or bacteria. Although high roughness (S_a = 0.86 µm) increases the specific surface area, it is considered less favourable in biomedical applications due to potentially adverse long-term biological and corrosion behaviour.

Figure 6 shows the topography of the surface of a titanium alloy previously textured by a femtosecond laser, obtained using a confocal laser scanning microscope at a magnification of 500×. The image is presented as a height map, where different colours represent relative differences in surface height. Blue and green areas correspond to lower regions of the surface, while yellow and red tones indicate raised structures. A pronounced heterogeneity of the relief is visible, with clearly observed depressions and elevations, which is characteristic of laser processing on ultrashort time scales. The texture displays oriented irregularities that can be associated with the laser beam path and local energy distribution during femtosecond ablation. The presence of fine microstructures indicates dominant nonlinear laser–material interactions, with a minimal heat-affected zone, which is one of the key advantages of femtosecond laser texturing.

By analysing confocal images of titanium alloy surfaces processed with pulsed energy ranging from 0.7 µJ to 3.0 µJ, a clear and systematic trend in the evolution of the surface morphology of the titanium alloy is observed (Figure 6a-6e). At the lowest pulse energy tested, 0.7 µJ, the initial formation of laser-induced periodic surface structures (LIPSS) appears on the titanium alloy surface. These structures manifest as weakly expressed, predominantly vertically oriented lines covering the analysed area.

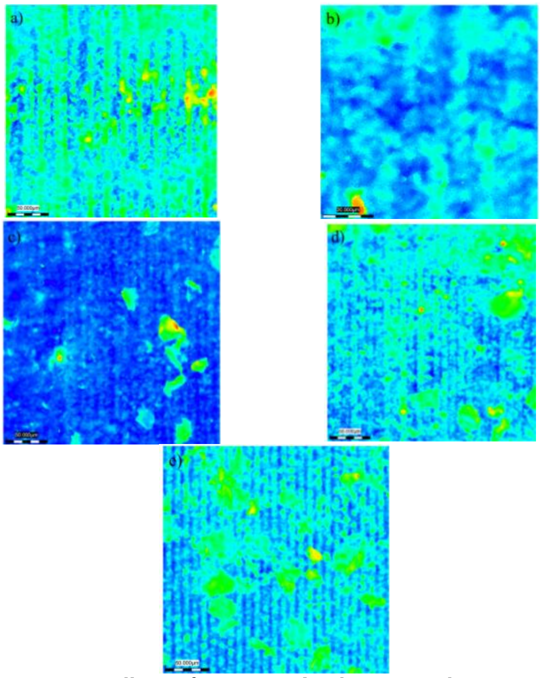

Fig. 6 *Titanium alloy surfaces textured with various pulse energies: a) 0.7 µJ; b) 1.5 µJ; c) 2.1 µJ; d) 2.6 µJ; e) 3.0 µJ.*

The appearance of LIPSS indicates that the applied pulse energy is slightly above the ablation threshold for the titanium alloy used, where nonlinear optical effects and surface electromagnetic interference dominate. In this regime (0.7 µJ), the morphology is relatively uniform with a small amplitude of height deviations, confirming the precision of texturing with minimal thermal influence. With an increase in pulse energy to 1.5 µJ, the periodic line structures become less well defined, and the relief becomes more diffuse. This state suggests a transitional area between dominantly optically driven LIPSS formation and thermally assisted structuring, where, along with pure ablation, local surface melting also begins to occur. At higher energy levels (≥ 2.1 µJ), there is a clear change in the processing regime, where deeper micro-channels and accumulations of deposited material (debris) are observed instead of LIPSS. Although at the highest energy of 3.0 µJ properly oriented vertical channels can still be seen in the background, the presence of large fragments created by explosive ablation disrupts the functional regularity and purity of the underlying periodic texture. Thus, as the energy increases, there is a gradual development and deepening of LIPSS structures, which at lower energies are regular and shallow, while at higher energies they become wider, deeper, and less homogeneous. In parallel, a significant increase in surface roughness is noted, clearly visible through the expansion of the colour range on the height maps of the confocal microscope. At the same time, increased pulse energy leads to a greater amount of secondary deposited material, marking the transition from the precise laser texturing regime to the coarse ablation regime. This transition is key for process optimisation, as it defines a trade-off between the regularity of the structure and the degree of thermal damage to the surface.

The HV1 microhardness measurement results for all samples are shown in Table 3. The reference sample without laser treatment (E = 0 µJ) exhibited a microhardness of 392 HV1. After femtosecond laser texturing, changes in surface hardness were observed, depending on the applied pulse energy. At a pulse energy of 0.7 µJ, microhardness decreased to 339 HV1, which can be attributed to initial softening of the surface layer due to local thermal effects and microstructural changes without significant hardening. Increasing the pulse energy to 1.5 µJ resulted in a significant rise in microhardness to 464 HV1, while the maximum value of 526 HV1 was achieved at 2.1 µJ. This increase suggests a more effective influence of femtosecond lasering, likely related to microstructure refinement, increased dislocation density, and possible formation of compressive residual stresses in the surface layer. Further increasing the pulse energy to 2.6 µJ and 3.0 µJ led to a decrease in microhardness, to 356 HV1 and 365 HV1, respectively. This trend can be attributed to excessive laser energy, which causes stronger ablation, local overheating, or partial relaxation of residual stresses, thereby reducing the surface hardening effect.

Table 3: *Microhardness of all samples of the experimental titanium alloy.*

E (µJ)	HV1
0.7	392
1.5	339
2.1	464
2.6	526
3.0	356

Overall, the results of microhardness measurements indicate an optimal range of femtosecond laser pulse energy (approximately 1.5–2.1 µJ) in which surface microhardness increases compared to the untreated sample. Outside this range, the effect of laser treatment on surface hardness is reduced, emphasising the importance of proper selection of process parameters.

4. Conclusion

In this study, the surface of an experimental titanium alloy with the chemical composition Ti-10Cr-10Nb was textured using a femtosecond laser at different pulse energies. Results clearly show that the laser pulse energy has a decisive influence on the surface topography, roughness, and microhardness of the material. The results confirm that by varying the pulse energy, the surface characteristics can be controlled in a targeted manner, but there is also a significant compromise between the topographic and mechanical properties.

Based on all the results obtained, it can be concluded that a pulse energy of 2.1 µJ at a laser beam wavelength of 1030 nm, a pulse duration of 190 fs, and a repetition rate of 1 MHz represents the optimal value of the process parameters. Such a surface simultaneously ensures mechanical stability and a microrelief suitable for biological adhesion, which is especially important in applications such as biomedical implants.

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