

## Investigation of the Surface Topography of Titanium Alloys Applied to Friction Components

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### ABSTRACT

The subject of this study and analysis was titanium alloy, applied among others to the friction components of orthopaedic (artificial hip joint) implants. This material was subjected to abrasive finishing using a synthetic diamond as a tool. The properties of the studied titanium alloy were characterised. The processing technology and the research methods are discussed. The surfaces, after being subjected to abrasive machining, were studied using three research instruments – an interference microscope, a scanning electron microscope, and an atomic force microscope. Advanced metrology software was used to analyse the measurement data. The aim of the research was to present the changes taking place in the forming of the surface of the studied titanium alloy, in particular those occurring in the final sequential processing. A characterisation of the machined surfaces was prepared based on parametric (surface topography – parameters and functions) and non-parametric (surface morphology – images) analysis. The significant influence of the sequence and the tool (diamond grain and micro-grain) on the surface topography shaped during the technological process is presented. Improvement in the surface quality and features was observed. Parametric analysis showed no significant differences between TA-III and TA-IV surfaces (Titanium alloy Ti-6.5Al-1.3Si-2Zr), while these differences were visualised by non-parametric analysis. Moreover, the hereditary features of the surface topography (isotropy and pits/valleys) and their influence on the potential functional properties (place/area for accumulation/retaining of the lubricant in the friction zone) of the titanium alloy were analysed.

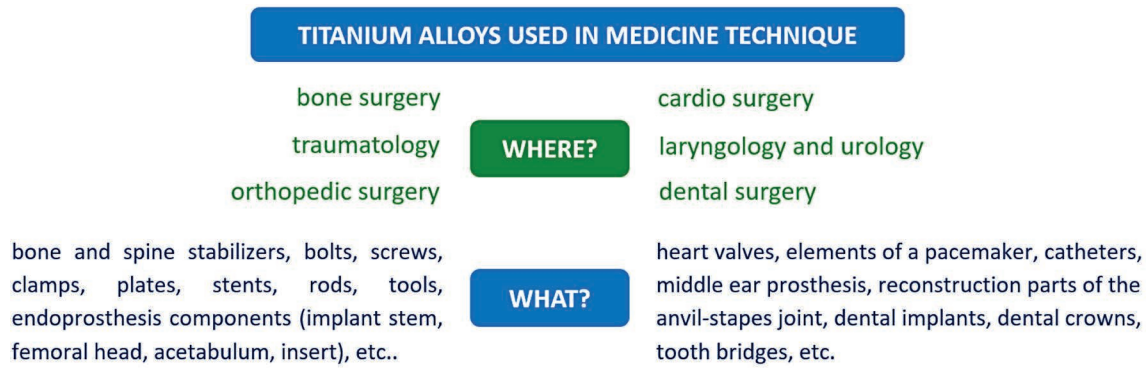
**Keywords:** orthopaedic implants, titanium alloy, surface metrology, surface topography, surface features, technological heredity, functional properties.

### INTRODUCTION

One group of metallic materials widely used in various industries are titanium alloys. Many academic works, i.a. [1, 2, 3] concerning the possibility of using titanium alloys in medical techniques (Figure 1) indicate their characteristic and unique properties, including their low density, their optimal (compared to other metallic biomaterials) biocompatibility, and their ability to connect with tissue bone (osseointegration), high corrosion resistance, high tensile strength, relatively low Young's modulus as well as low thermal expansion coefficient. These properties make titanium alloys one of the basic materials used for long-term orthopaedic implants (including

components of artificial hip or knee joints), among other things. There are also some problems with the use of titanium alloys in implantology, including [3, 4, 5]: inadequate resistance (durability) to tribological wear, which results from insufficient hardness (the possibility of loosening of artificial joints) and the need for reoperation – from the patient's point of view, this is unfavourable due to the high risk of implantation failure and postoperative complications, as well as the increase in total costs; still limited osseointegration (stabilisation of the tissue-implant connection).

New techniques of surface engineering offer a good chance of solving the above problems. It is also important to conduct multidirectional and comprehensive scientific research on the



**Figure 1.** Range of application the titanium alloys in medical techniques

functional properties of materials, in order to improve the wear resistance of components (parts) made of titanium alloys and co-acting parts [6, 7, 8]. This type of research has been conducted by different research teams for various types of materials, and the results are widely published, i.a. in the works [9, 10, 11, 12]. An equally important aspect is the research and analysis of the surface topography formed in the technological process (machined surface) and during the operation process (worn surface). Examples include the works [13, 14, 15, 16], where the analysis of the machined surface topography is presented (grinding/turning/lapping/coatings), and [17, 18, 19, 20] where the authors describe the wear mechanism (fatigue/fretting/cavitation, erosion and sliding wear) in relation to the surface topography. At this point it should be emphasised that despite the possibility of characterising the surface topography using several dozen surface parameters (height parameters, functional parameters, spatial parameters, hybrid parameters, feature parameters, etc.) and several functions (Abbott-Firestone curve, spectrum density, texture direction and isotropy, fractal analysis, etc) [21], most authors limit themselves to a few of these which, in their opinion, most appropriately reflect the characteristics of the analysed surface or research problem. The same approach was used by the authors of this work, and the data for analysis was chosen based on previous experience.

An equally important aspect is the technological heredity related to the technological process. Technological heredity is the transfer of the ownership features of the parts from previous technological sequences (operations) to subsequent ones. The features of the parts are nothing but the properties that characterise the surface topography, expressed by means of, inter alia, surface


parameters as well as functions. The results of research on technological heredity which to date have been presented in the literature display a lack of a comprehensive, qualitative and quantitative characterisation of surface topography. In addition, these results do not sufficiently capture the functional properties of the studied materials. There are not many works on the technological heredity of parts made of hard-to-machine materials [13, 22, 23, 24], which may result from a lack of knowledge of this subject or other limitations (lack of research infrastructure).

The aim of this work was to present the changes taking place in the surface topography of the studied material, titanium alloy, occurring in the final sequential processing, based on the results of 2D (profile) and 3D (surface) analyses. Moreover, the hereditary features of the surface topography (technological heredity) and their influence on the potential functional properties of the titanium alloy parts were analysed.

**MATERIAL AND METHODS**

The subject of research and analyses was the titanium alloy Ti-6.5Al-1.3Si-2Zr (Table 1), marked as TA (titanium alloy Ti-6.5Al-1.3Si-2Zr (sample)), which, due to its properties and lack of vanadium, is used in medical techniques, especially on the friction components of orthopaedic implants (e.g. femoral head hip joint prostheses). The use of Al increases the strength and reduces the specific weight of the titanium alloy, and the addition of Si increases its creep resistance, while the addition of Zr, a non-toxic element, replaces the carcinogenic vanadium. It should be emphasised that the use of chemical elements, including Al, is not indifferent to the organism [25],

**Table 1.** Characteristics of the studied material

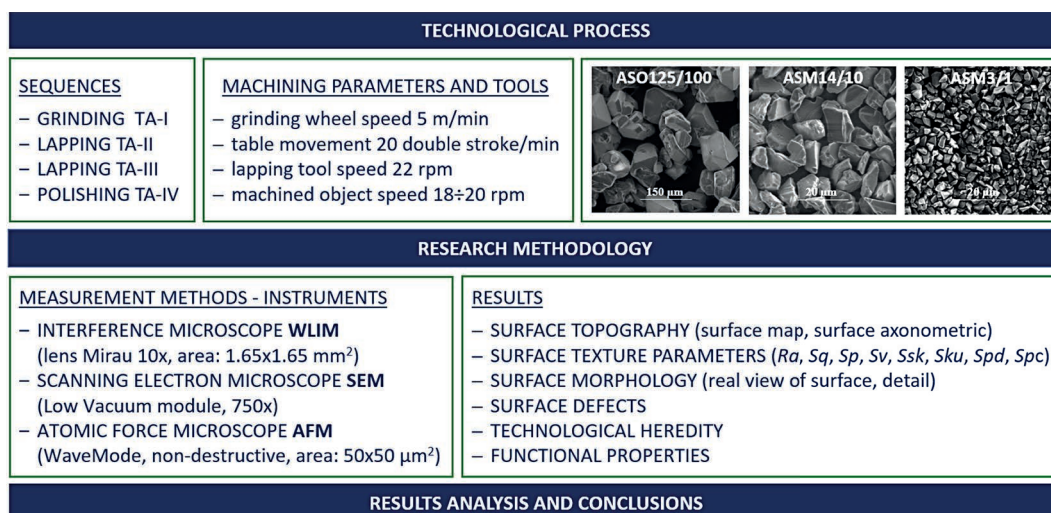
Sample (TA)	Chemical composition (wt %)				
	 37 × 17 × 7 mm <sup>3</sup>	Ti	Al	Si	Zr
Base		<6.5%	<1.3%	<2.0%	<2.2%
Properties [26]					
Density [g·cm <sup>3</sup> ]				4.43	
Tensile strength [MPa]				900	
Young's modulus [GPa]				114	

therefore additives should be carefully used in appropriate amounts. The technological process (final sequential processing) included: grinding, TA-I (giving it shape and dimensions; synthetic diamond grain ASO125/100), initial lapping, TA-II (removal of the surface damaged by grinding; synthetic diamond micro-grain ASM28/20 and ASM14/10), finishing lapping, TA-III (delivering the appropriate quality of the studied surface; synthetic diamond micro-grain ASM3/1, 30 minutes), and polishing, TA-IV (reduction of surface roughness; diamond micro-grain ASM1/0, 16 hours). After each sequence of the final technological process, the machined surface topography was examined (studies of the machined surface were conducted in ten areas on each of the three samples) using three different research instruments – a white light interference microscope WLIM (Talysurf CCI, Taylor Hobson Ltd.), a scanning electron microscope SEM (Quanta 3D FEG SEM, FEI Co.), and an atomic force microscope AFM (Q-Scope™ 250, Quesant Instrument Co). The research methodology with measurement detail is presented in Figure 2. Based on the

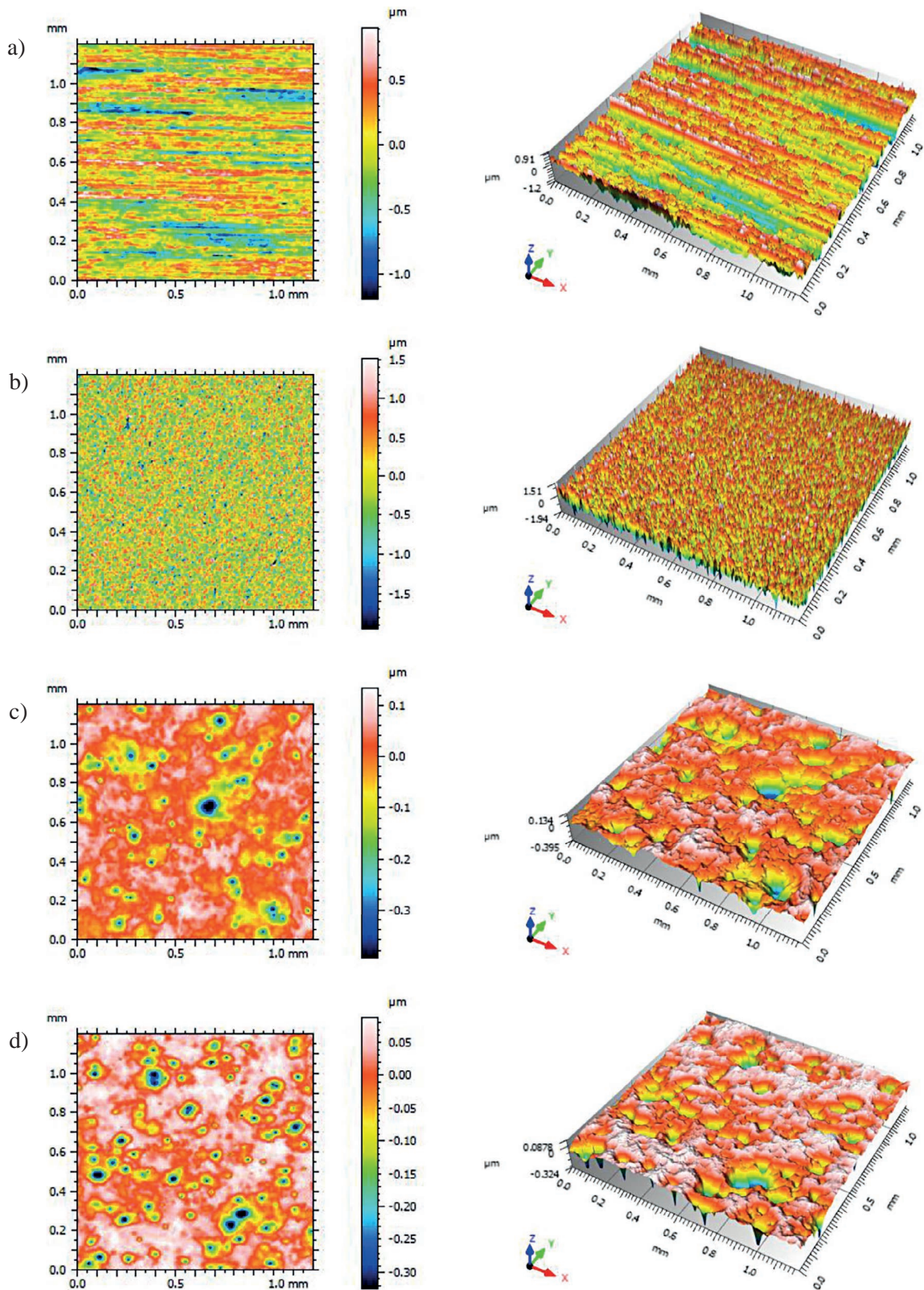
number of obtained results and their repeatability, the representative results are presented in the section titled Results and Discussion.

## RESULTS AND DISCUSSION

The research results have been collected and are presented in three figures and one table. Figure 3 shows the 2D view (surface map) and 3D view (surface axonometric) of the machined surface topography obtained after each abrasive machining sequence. The results were obtained using WLIM. The analysis was preceded, using Taly-map Platinum v.7.1 advanced metrology software (Taylor Hobson Ltd. in cooperation with Digital Surf), by removing the measurement noise (spatial filtering – median denoising filter) for removing noise and spikes (filter size 3×3) and suitable filtering for the elimination of incorrect pits and/or peaks with a threshold of 1% from the top and 99% from the bottom, which ensured obtaining a statistically relevant effect. The non-measurement points (non-contact measurement method, number



**Figure 2.** Research methodology



**Figure 3.** 2D and 3D views of the machined surface (WLIM): a) TA-I, b) TA-II, c) TA-III, d) TA-IV

of points unmeasured at the level of 0.01% per  $1024 \times 1024$  points) were filled with a smooth shape according to the neighbourhood. For analysis, areas with dimensions of  $1.20 \times 1.20 \text{ mm}^2$

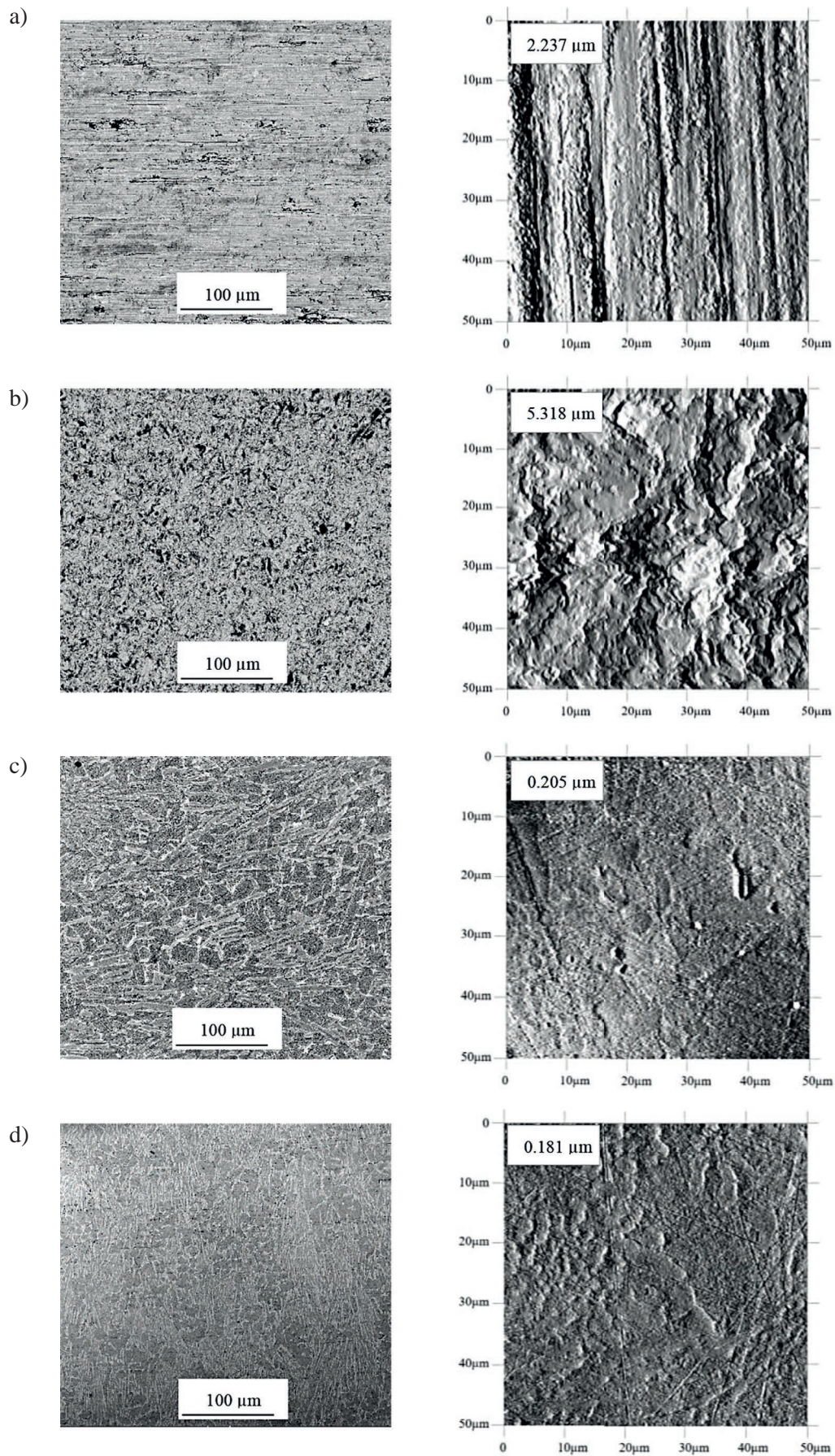
were separated. The results show the characteristics of the surface, its surface topography (mapping of the machined surface based on the measured points – 2D and 3D views with parametric

analysis) and surface features (including surface defects). Differences and gradual changes can also be seen in the surface morphology (real images of machined surfaces with non-parametric analysis) – Figure 4. The TA-I surface (Figure 3a and Figure 4a) has characteristic longitudinal traces, in accordance with the direction of the grinding wheel movement relative to the surface of the machined parts. The grinding operation (first sequence) using the ASO125/100 diamond tool provided the required shape and dimensions of the machined parts. Moreover, the traces on the TA-I surface indicate clearly its textural direction, which should be removed in subsequent sequences of technological process, thus improving the machined surface, ensuring appropriate functional properties. The grinding surface was subjected to an initial two-stage lapping using ASM28/20 and ASM14/10 diamond tools. As a result of the second sequence (TA-II) – Figure 3b and Figure 4b, a machined surface characterised by a lack of directivity and an even distribution of irregularities (peaks and pits) on the TA-II surface was obtained. Since the TA-II operation was to ensure the removal of the layer damaged in the TA-I operation, it was done at the expense of increasing the height of the peaks and the depth of the pits, which is shown in scale in Figure 3b, and the value of the distance between the lowest and highest point of the machined surface ( $5.318 \mu\text{m}$ ) in Figure 4b – AFM.

In order to improve the surface quality, non-parametric analysis, as shown in Figure 3c–3d and Figure 4c–4d, and parametric analysis, as defined by the 2D and 3D roughness parameters (Table 2), the surfaces were subjected to successive machining sequences, namely the TA-III operation (finish lapping) and TA-IV operation (polishing). Comparing the obtained surfaces to the results of the previous machining sequences, an improvement in the surface topography/morphology and surface features can be seen (including a reduction in the number and dimensions of pits). Figure 5 shows how the surface directivity (textural direction and isotropy) changed in subsequent sequences. With each operation, the surface isotropy increased from 9.02% for the TA-I surface (anisotropic surface) to 82.6% for the TA-IV surface (isotropic surface). The isotropic nature of the surface was inherited in the last machining sequences. The greater the isotropy of the surface (minimised surface directivity), the more evenly the unevenness (peaks and pits) and features are distributed over the surface, influencing the functional properties.

Table 2 presents the profile and surface texture parameters which describe the surface topography and changes taking place in the sequential machining process in a quantitative manner. Due to the fact that 2D parameters are provided in standards, including the  $Ra$  parameter, which is the arithmetical mean height of the profile (a parameter commonly used to assess surfaces), therefore this parameter was also included as part of the analysis of the machined surfaces. The value of the  $Ra$  parameter was determined for the 1024 profiles that were generated (using advanced metrology software; a function converts surface into series of profiles [27]), providing a given average value and standard deviation, which allowed for the assessment of the measured areas of the samples. The  $Ra$  parameter was from  $0.277 \mu\text{m} \pm 0.030$  for the TA-I surface, up to  $0.031 \mu\text{m} \pm 0.009$  for the TA-IV surface. The  $Ra$  parameter as an average parameter does not show sensitivity to local peaks or pits. Therefore, based on experience from previous research, an analysis of the 3D parameters (ISO 25178 [21]) describing the surface topography was performed:  $Sq$  – root mean square height,  $Sp$  – maximum peak height,  $Sv$  – maximum pit depth,  $Ssk$  – skewness,  $Sku$  – kurtosis,  $Spd$  – density of peaks, and  $Spc$  – arithmetic mean peak curvature. This allowed for the characterisation of the studied surfaces in terms of surface topography, surface features (including surface defects), and the potential functional properties of these surfaces.

Both the  $Ra$  parameter and the  $Sq$ ,  $Sp$ ,  $Sv$  parameters for the TA-II surface increased value compared to the TA-I surface. This confirms the earlier comment that such an effect (increased values of parameters) was due to the removal of the surface layer damaged by the grinding operation, which simultaneously minimised the directivity of the machined surface. After stabilisation of the surface directivity (textural direction) and isotropy (above 60%), the parameters describing the surface topography and features obtained in subsequent machining sequences decreased. There was also a noticeable reduction in the size of surface features, such as pits ( $Sv$  parameter), but a large difference was not noticed in the case of the TA-III and TA-IV surfaces. On the other hand, the number of surface features changed; this is well illustrated by 2D and 3D views of the machined surfaces (Figure 3). The  $Ssk$  and  $Sku$  parameters provide information about the shape of the surface features, such as peaks or pits. Positive  $Ssk$



**Figure 4.** Surface morphology (SEM and AFM): a) TA-I, b) TA-II, c) TA-III, d) TA-IV

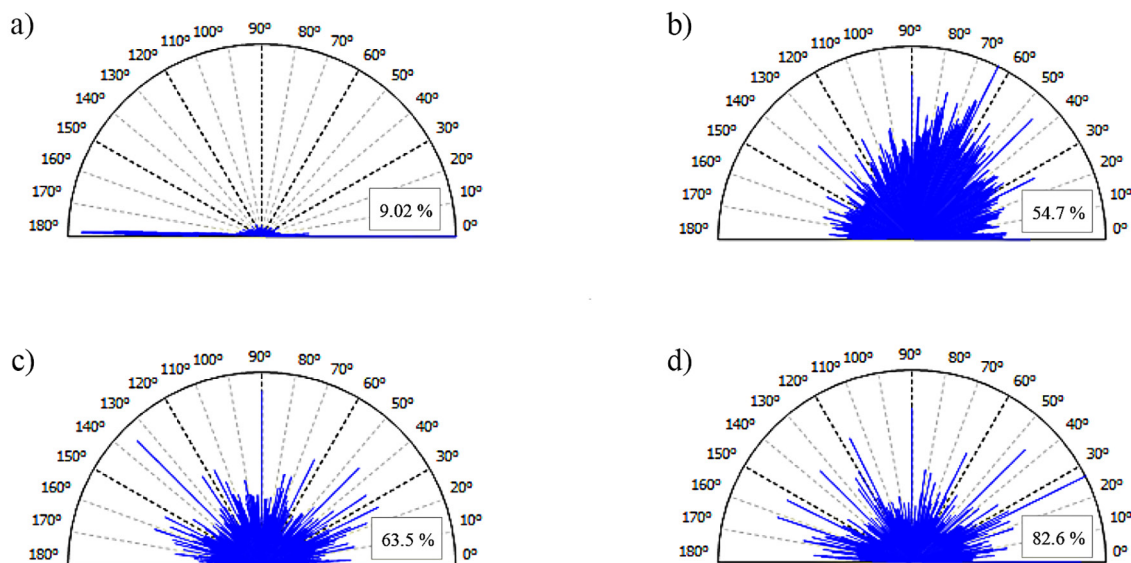
**Table 2.** 2D (profile) and 3D (surface) roughness parameters

Surface	Ra [ $\mu\text{m}$ ]	Sq [ $\mu\text{m}$ ]	Sp [ $\mu\text{m}$ ]	Sv [ $\mu\text{m}$ ]	Ssk [-]	Sku [-]	Spd [ $1/\text{mm}^2$ ]	Spc [ $1/\text{mm}$ ]
TA-I	0.277 $\pm$ 0.030	0.343	0.910	1.20	-0.349	3.18	1951	94.8
TA-II	0.485 $\pm$ 0.041	0.543	1.51	1.94	-0.191	3.25	4366	224.0
TA-III	0.035 $\pm$ 0.010	0.068	0.134	0.395	-1.92	8.49	50.7	19.2
TA-IV	0.031 $\pm$ 0.009	0.061	0.087	0.324	-2.00	8.79	48.0	18.9

values indicate the presence of peaks/pits with steep slopes. On the other hand, negative values of the *Ssk* parameter mean a surface characterised by deep pits/valleys, i.e plateau surfaces. In the case of the studied surfaces, regardless of the machining operation, the *Ssk* parameter value was negative. Larger negative values clearly characterise the TA-III and TA-IV surfaces, which can be described as the highest quality surfaces. The pits/valleys presented on these surfaces in the operation process will constitute the places/areas of accumulation of the lubricant (positive effect) as well as the places/areas of accumulation of the wear products (those that will not be carried away from the friction zone). The *Sku* parameter can be used to monitor and evaluate the surface defects of the machined parts [28]. The *Sku* parameter values below 3 indicate a regular shape of the surface topography (even distribution of peaks and pits), while an increasing *Sku* value indicates an increase in the number and/or size of peaks/pits on the surface [15, 26]. In the case of the TA-I and TA-II surfaces, the surface features are evenly distributed, which is confirmed by the results in Figure 3a–3b and Figure 4a–4b. Visible pits on

the TA-III and TA-IV surfaces in Figure 3c–3d and Figure 4c–4d confirm the higher *Sku* parameter value, Table 2. Taking into account the surface assessment in terms of functional properties, it is likely that such surface topography will have a positive influence on the effects of the operation process (the pits/valleys ensure the presence of a lubricant in the friction zone). The surface features like pits/valleys/cavities are inherited. The TA-III surface is characterised by a smaller number but larger size of pits, while the TA-IV surface has a greater number of smaller sized pits.

Additionally, the two parameters, *Spd* and *Spc*, related to the surface features were analysed. The *Spd* parameter (density of peaks) expresses the number of peaks per unit area, and the *Spc* parameter expresses the arithmetic mean peak curvature. A large number of peaks (a higher *Spd* value) means a greater number of peaks as a support point for the co-acting surface. Surface TA-II had the highest *Spd* parameter value, and the TA-III and TA-IV surfaces had the lowest value of this parameter. A higher value of the *Spc* parameter means that the mentioned peaks or points of support (contact) have a small radius (they are sharp).



**Figure 5.** Textural direction and isotropy (WLI): TA-I (a), TA-II (b), TA-III (c), TA-IV (d)

Such an analysis of the *Spd* and *Spc* parameters is confirmed by the values in Table 2 and the surface topography views (axonometric views) in Figure 3; the highest value is for the TA-II surface, and the lowest for the TA-III and TA-IV surfaces. Taking into account the fact that the TA-III and TA-IV surfaces will be intended for cooperation in the operation process, it should be assumed that the plateau surfaces (small *Spd* value – few points/areas of contact and small *Spc* value – large radius of peaks/summits) will influence the nature of cooperation (low frictional resistance) and the wear mechanism (micro-cutting).

## CONCLUSIONS

This study on the surface topography obtained in the technological process (final sequential processing) of parts made of Ti-6.5Al-1.3Si-2Zr titanium alloy, a material applied to the friction components (i.a. artificial femoral head of hip joint), showed: the influence of the tool – diamond grain/micro-grain (diamond powder), on the machined surface topography and features (pits/valleys), and thus the improvement of potential functional properties. Sequential abrasive machining made it possible to improve the machined surface topography, expressed both qualitatively (surface map, surface axonometric, surface morphology – SEM and AFM) and quantitatively based on the analyses of 2D parameter (*Ra*) and 3D parameters (*Sq*, *Sp*, *Sv*, *Ssk*, *Sku*, *Spd*, *Spc*). The TA-III and TA-IV surfaces obtained in the last machining sequences were characterised by the lowest roughness parameters (parametric analysis, WLIM), which did not differ much from each other (especially parameters *Ra*, *Sq*, *Ssk*, *Spd*, *Spc*). Larger differences (surface features – pits/valleys) were shown by the non-parametric analysis carried out on the basis of the 2D and 3D views (WLIM) as well as images (AFM and SEM). Taking into account the *Ssk*, *Spd* and *Spc* parameters, the TA-III and TA-IV surfaces, as the plateau surfaces, will probably influence the nature of cooperation due to their low frictional resistance as well as the wear mechanism (micro-cutting) during the operation process. The pits/valleys on the TA-III and TA-IV surfaces (visible on the 2D and 3D views as well as the *Sku* parameter) seem to be surface defects, but they can play a positive role in the operation process because they could be a place/area for accumulation/retaining of lubricant in the friction zone. Surface features such

as isotropy or pits/valleys were inherited in the two final machining sequences. The obtained results are a starting point for conducting in-depth studies of the surface topography of components made of titanium alloy, shaped in technological processes in order to eliminate irrelevant parameters, thus enabling the construction of an adequate model.

## Acknowledgements

This work was financed from the funds of the Ministry of Education and Science by Agreement No. DNK/SP/513880/2021 of 22 December 2021, the project “14<sup>th</sup> School of Machining and the 43<sup>rd</sup> Scientific School of Abrasive Machining”, under the programme “Perfect Science”.

## REFERENCES

1. Bazaka O., Bazaka K., Kingshott P., Crawford R.J., Ivanova E.P. *Metallic Implants for Biomedical Applications. The Chemistry of Inorganic Biomaterials* (ed. Spicer Ch.). Royal Society of Chemistry; 2021.
2. Nicholson J.W. *Titanium Alloys for Dental Implants: a Review. Prosthesis.* 2020; 2(2): 100–116.
3. Gierzyńska-Dolna M., Lijewski M. *Application of Titanium and Its Alloys in Biomedical Engineering. Materials Engineering.* 2012; 33(4): 315–318.
4. Fraczek T., Olejnik M., Tokarz A. *Evaluations of Plasma Nitriding Efficiency of Titanium Alloys for Medical Applications. Metalurgija.* 2009; 48(2): 83–86.
5. Kustas F.M., Misra M.S. *Friction and Wear of Titanium Alloys. Friction, Lubrication and Wear* (ed. Totten G.E.). ASM International; 2018.
6. Schmeidl K., Wieczorowski M., Grocholewicz K., Mendak M., Janiszewska-Olszowska J. *Frictional Properties of the TiNbTaZrO Orthodontic Wire - a Laboratory Comparison to Popular Archwires. Materials.* 2021; 14(21): 6233.
7. Czerniec M., Zubrzycki J. *Study of Contact Pressures in Total Hip Replacement. Advances in Science and Technology Research Journal.* 2021; 15(2): 176–183.
8. Dziejczak K., Zubrzycka-Wróbel J., Józwiak J., Barszcz M., Siwak P., Chałas R. *Research on Tribological Properties of Dental Composite Materials. Advances in Science and Technology Research Journal.* 2016; 10(32): 144–149.
9. Kumaran T.S., Ko T.J., Uthayakumar, M., Khan A.M., Niemczewska-Wójcik, M. *Surface Texturing by Dimple Formation in TiAlSiZr Alloy Using  $\mu$ -EDM. Journal of the Australian Ceramic Society.* 2017; 53(2): 821–828.



10. Lauro C.H., Ribeiro Filho S.L.M., Cardoso Brandão L., Davim J.P. Analysis of Behaviour Biocompatible Titanium Alloy (Ti-6Al-7Nb) in the Micro-cutting. Measurement. 2016; 93: 529–540.
11. Affatato S., Ruggiero A., Logozzo S. Metal Transfer Evaluation on Ceramic Biocomponents: a Protocol Based on 3D Scanners. Measurement. 2021; 173: 108574.
12. Zabala A., Blunt L., Tejero R., Llavori I., Aginagalde A., Tato W. Quantification of Dental Implant Surface Wear and Topographical Modification Generated During Insertion. Surface Topography: Metrology and Properties. 2020; 8(1): 015002.
13. Lipiński D., Banaszek K., Mathia T.G. New Methodology for Discrimination of Topography Diversity of Engineering Surfaces – Case of Grinding. Measurement. 2022; 190: 110659.
14. Krolczyk G.M., Legutko S. Experimental Analysis by Measurement of Surface Roughness Variations in Turning Process of Duplex Stainless Steel, Metrology and Measurement Systems. 2014; 21(4): 759–770.
15. Niemczewska-Wójcik M., Wójcik A. The Multi-Scale Analysis of Ceramic Surface Topography Created in Abrasive Machining Process. Measurement. 2020; 166: 108217
16. Szala M., Kot E.A. Influence of Repainting on the Mechanical Properties, Surface Topography and Microstructure of Polyester Powder Coatings. Advances in Science and Technology Research Journal. 2017; 11(2): 159–165.
17. Macek W., Rozumek D., Królczyk G.M. Surface Topography Analysis Based on Fatigue Fractures Obtained with Bending of the 2017A-T4 Alloy. Measurement. 2020; 152: 107347.
18. Macek W., Branco R., Costa J.D., Pereira C. Strain Sequence Effect on Fatigue Life and Fracture Surface Topography of 7075-T651 Aluminium Alloy. Mechanics of Materials. 2021; 160: 103972.
19. Kowalski S., Cygnar M. The Application of TiSiN/TiAlN Coatings in the Mitigation of Fretting Wear in Push Fit Joints. Wear. 2019; 426–427: 725–734.
20. Szala, M., Walczak, M., Pasierbiewicz, K., Kamiński, M. Cavitation Erosion and Sliding Wear Mechanisms of AlTiN and TiAlN Films Deposited on Stainless Steel Substrate. *Coatings*. 2019; 9(5): 340.
21. ISO 25178-2:2012, Geometric Product Specifications (GPS)–Surface Texture: Areal-Part 2: Terms, Definitions and Surface Texture Parameters; International Organization for Standardization: Geneva, Switzerland. 2012.
22. Grechishnikov V.A., Pautov G.A., Yurasov S.Y., Yurasova O.I. Technological Inheritance in the Machining of Titanium Alloys. Russian Engineering Research. 2017; 37(3): 270–272.
23. Li J., Wang B., Fang S., Chen P. Investigation of the Microstructure Evolution and Mechanical Properties of a TC6 Alloy Blade Preform Produced by Cross Wedge Rolling. Archives of Civil and Mechanical Engineering. 2020; 20(70).
24. Bartkowiak T., Grochalski K., Gapiński B., Wieczorowski M. Discrimination of Surface Topographies Created by Two-Stage Process by Means of Multiscale Analysis. Materials. 2021; 14(22): 7044.
25. Fangaia S.I.G., Nicolau P.M.G., Guerra F.A.D.R.A., Melia Rodrigo M., Ribeiro A.C.F., Valente A.J.M., Santos J.R.C., Marques J.M.C., Esteso M.A. The Behaviour of Aluminium Ions in Artificial Saliva and the Impact of the Chlorhexidine Digluconate on Its Removal – a Diffusion Model. Journal of Molecular Liquids. 2022; 353: 118749.
26. Niemczewska-Wójcik M. The Dual System for Characterizing the Technological and Operational Surface Layer of Friction Elements. Publishing House of the Institute for Sustainable Technologies; 2018.
27. Niemczewska-Wójcik M., Pethuraj M., Uthayakumar M., Abdul Majid M.S. Characteristics of the Surface Topography and Tribological Properties of Reinforced Aluminum Matrix Composite. Materials. 2022; 15(1): 358.
28. Krolczyk G.M., Maruda R.W., Krolczyk J.B., Nieslony P., Wojciechowski S., Legutko S. Parametric and Nonparametric Description of the Surface Topography in the Dry and MQCL Cutting Conditions. Measurement. 2018; 121: 225–239.