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MICROSTRUCTURAL AND MICROMECHANICAL TESTS OF TITANIUM CROWNS

BADANIA MIKROSTRUKTURALNE I MIKROMECHANICZNE KORON TYTANOWYCH

Key words: prosthetics, titanium alloy, fixed structure, digital technology, biomechanics.

Abstract: Fixed prosthetic restorations must meet the health requirements in terms of the protection of the tissues of the oral cavity, biomechanical requirements for optimal tissue stress and the strength and wear resistance of the structure, aesthetic requirements related to the location of the gingival margin, as well as the shape, thickness, and colour of the veneers. The aim is to evaluate the impact of manufacturing technology on the microstructure and micromechanical parameters of titanium crowns. The material of the analysis are prosthetic crowns made of Ti6Al4V alloy for the maxilla premolars and the mandible molars, produced using two technologies: Selective Laser Melting (SLM) and CAD/CAM milling. Crown structures were evaluated on the basis of examinations of the microstructure and surface layer of the chamfers, micromechanical parameters in axial sections perpendicular to the dental arches, and the accuracy of mapping the internal shape in sections with horizontal planes perpendicular to the axis of the abutment tooth. The results of this work can be used in a clinical setting. They allow the evaluation of what is the impact of the technology of producing the supporting substructure on the structure of the prosthetic crown. The strength requirements in both technologies are met, while the higher value of the microhardness of the titanium SLM substructure, compared to the milled one, increases the stiffness of the structure under conditions of biomechanical excitation. The errors in mapping the internal shape of the crowns are comparable and slightly higher during sintering.

Słowa kluczowe: protetyka, stop tytanu, konstrukcja stała, technologia cyfrowa, biomechanika.

Streszczenie: Stałe uzupełnienia protetyczne powinny spełniać wymagania zdrowotne w aspekcie zabezpieczenia tkanek jamy ustnej, wymagania biomechaniczne dotyczące optymalnego wytężenia tkanek oraz wytrzymałości i odporności na zużycie konstrukcji, wymagania estetyczne związane z usytuowaniem obrzeża dodziąsłowego, a także kształtem, grubością i kolorem licowania. Celem jest ocena wpływu technologii wytwarzania na mikrostrukturę i parametry mikromechaniczne koron tytanowych. Materiałem analizy są korony protetyczne ze stopu Ti6Al4V na zęby przedtrzonowe szczęki i trzonowe żuchwy wytwarzane dwoma technologiami: Selective Laser Melting (SLM) i frezowania CAD/CAM. Konstrukcje koron oceniano na podstawie badań mikrostruktury i warstwy wierzchniej stopni, parametrów mikromechanicznych w osiowych przekrojach prostopadłych do łuków zębowych oraz dokładności odwzorowania kształtu wewnętrznego w przekrojach płaszczyznami horyzontalnymi, prostopadłymi do osi zęba filarowego. Wyniki tej pracy mogą być wykorzystane w warunkach klinicznych. Pozwalają ocenić, jaki jest wpływ technologii wytworzenia podbudowy nośnej, na konstrukcję korony protetycznej. Wymagania wytrzymałościowe w obu technologiach są spełnione, przy czym wyższa wartość mikrotwardości podbudowy tytanowej z SLM, w porównaniu do frezowanej, wpływa na zwiększenie sztywności konstrukcji w warunkach wymuszeń biomechanicznych. Błędy odwzorowania kształtu wewnętrznego koron są porównywalne i nieco wyższe przy spiekaniu.

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INTRODUCTION

Fixed prosthetic restorations must meet health requirements in terms of biocompatible protection of oral tissues and proper organ function, biomechanical requirements for optimal tissue stress and structural wear resistance, as well as aesthetic requirements. The connection between the cemented crown and the tooth is a potential area for caries. The more precisely the restoration is fitted to the abutment tooth, the lower the probability of secondary caries and periodontal disease **[L. 1–4]**.

Titanium and its alloys are the most preferred metals in the manufacture of fixed prosthetics and implant-prosthetic structures **[L. 5–10]**. Currently, digital technologies are used for the production of personalised crowns and bridges because the traditional casting technology of titanium structures in a noble gas shield did not give satisfactory results. Modern prosthetics use the CAD system to design an individual shape and range of the structure, using specialised software. After the biomaterial from which the prosthesis will be made is determined, the production phase takes place in the CAM system.

In SLM, the structure is manufactured using the additive method from dedicated metal powders based on 3D models, and high-resolution printers are used for printing. Specified types of powders, which have medical certification, affect both the biomechanical properties and the final parameters of the structure **[L. 5, 11–15]**.

In subtractive machining, the CAM process is performed on a special dental milling machine. The system is dedicated to blocks of various sizes for milling structures made of titanium or its alloys. The dimensions of the blocks allow the production of crowns and large multisegmented structures **[L. 6–8, 16]**.

The study aims to evaluate crowns made of Ti6Al4V alloy for premolars and molars produced by two technologies: Selective Laser Melting (SLM) and CAD/CAM milling, based on the analysis:

- microstructure and surface layer of the gingival chamfers,
- micromechanical parameters of crowns in vertical sections, perpendicular to the dental arches,
- accuracy of mapping the internal shape of the crown in horizontal sections.

MATERIALS AND METHODS

The research material consists of prosthetic crowns made of Ti6Al4V alloy for the second premolar tooth on the right side (tooth 15) and the first molar tooth on the left side (tooth 36), made of 5 for these teeth and each technology.

For the SLM and milling technologies analysed based on the CAD/CAM procedure, reference models of abutment teeth were scanned, and spatial CAD reconstructions were performed. Based on STL files, five crowns in SLM were made of Ti6Al4V powder on the AM 250 device by Renishaw (Renishaw, Warsaw, Poland) and five crowns milled from Starbond Ti5 discs on a five-axis CORiTEC 350i dental milling machine by imes-icore (Scheftner, Mainz, Germany), for teeth 15 and 36, respectively.

The analyses of gingival chamfers in crowns of both technologies were performed on a Hitachi S3400N scanning electron microscope at four magnifications.

Microstructural and micromechanical studies were performed on the axial sections of the crowns. Cross sections were made along the long axis of the abutment teeth perpendicular to the dental arches of the maxilla and mandible. After cutting, the samples were embedded in the resin and subjected to the polishing process on the Struers TegraForce-5 device, on which, by means of programmed operations, the surface layer required for the tests was achieved (**Fig. 1**).

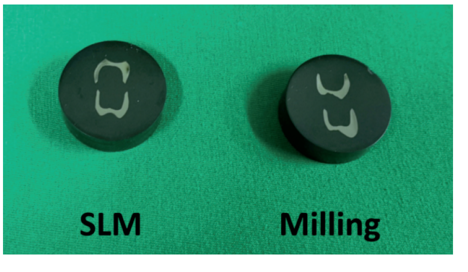

Fig. 1. Samples for microstructural and micromechanical tests – axial sections of the crowns embedded in resin

Rys.1. Próbki do badań mikrostrukturalnych i mikromechanicznych – przekroje osiowe koron inkludowane w żywicy

Micromechanical properties tests, including microhardness and Young's modulus measurements in selected axial sections, were carried out on the Anton Paar MCT[3] device. They were determined on the basis of the indentation of the sample with the use of a diamond penetrator in the shape of a correct pyramid with a square base **[L. 17]**. In the measurements, the values of the force and depth of penetration of the blade in the loading and unloading cycle were continuously recorded. The maximum load value was 200 mN, the loading and unloading speed was 400 mN/min, and the maintenance time of the maximum load was 5 s. For each cycle, the relationships between the indenter load and penetration depth were determined. The analysis of micromechanical properties was based on the Oliver and Pharr method, according to which the microhardness (HV) and modulus of elasticity (E) of the tested material were calculated from the indentation curve. The micromechanical parameters for each of the technologies discussed were determined as the average of 8 measurements for the premolars and the molars in sections through the chamfers, through the side walls, and through the occlusal zones.

In addition, before microstructural and micromechanical examinations, an evaluation of the accuracy of mapping the internal shape of the crowns was performed with reference models in the plane perpendicular to the axis of the abutment tooth. The D750 scanner was used for mapping accuracy procedures. The scanner is equipped with a blue laser and two 1.3 Mpix cameras – 3Shape Dental System 2016 by 3Shape. The accuracy of the measurements was 10 µm, and the spatial resolution was 0.01 mm x 0.01 mm x 0.01 mm. The best-fit method with the use of Geomagic Qualify 12 was used for the analysis.

The results were statistically analysed using Statistica 13.3 (TIBCO Software Inc). The following was designated:

1. Descriptive statistics (mean, median, min, max, standard deviation),
2. Normality of the distribution of variables (Shapiro-Wilk test, Kołmogorow-Smirnow test),
3. Tests of the analysis of variance (ANOVA),
4. Post-hoc multiple comparison test (Tukey, Bonferroni).

The level of statistical significance was assumed to be $\alpha = 0.05$.

RESULTS

SEM images of crowns for premolars and molars, made using the CAD/CAM method in SLM, are characterised by roughness and porosity in all areas (**Figs. 2** and **3**). The surface development is visible outside the veneering zone, inside the crown

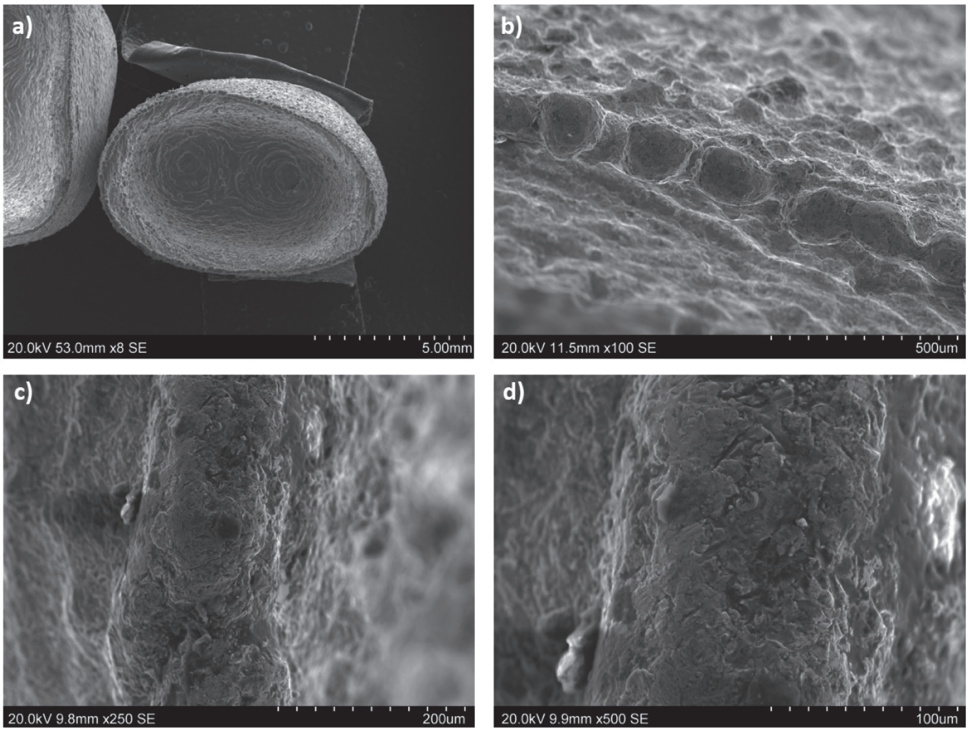

Fig. 2. SEM image of a premolar crown using SLM – view from the side of the chamfer at magnifications: a) x8, b) x100, c) x250, d) x500

Rys. 2. Obraz SEM korony na ząb przedtrzonowy z technologii SLM – widok od strony stopnia przy powiększeniach: a) x8, b) x100, c) x250, d) x500

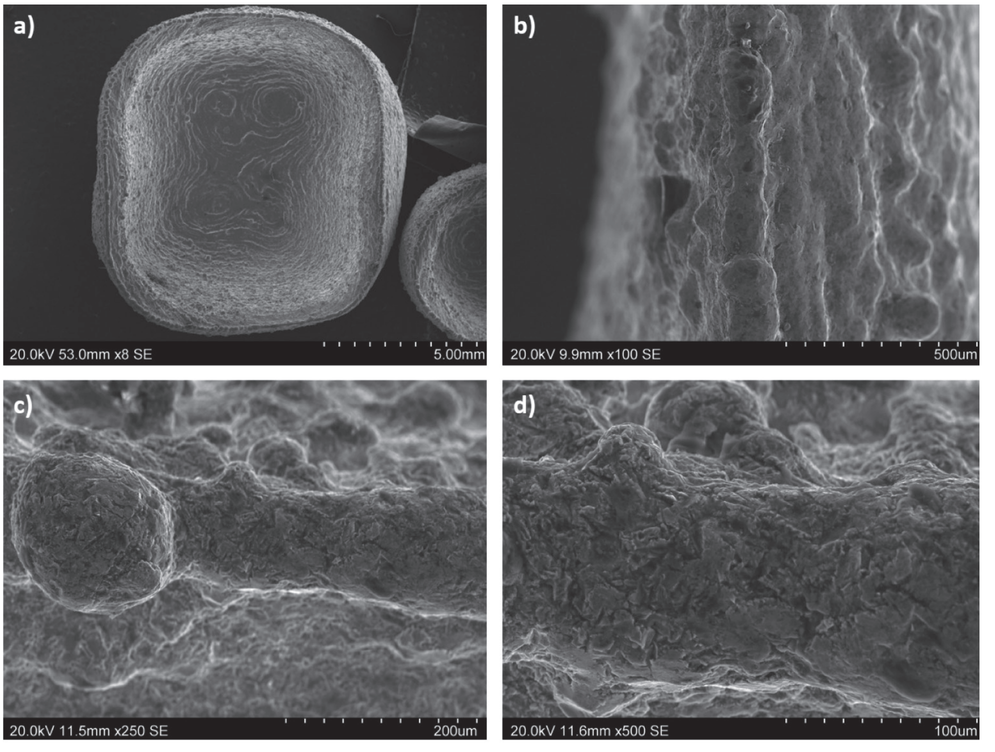

Fig. 3. SEM image of a molar crown using SLM – view from the side of the chamfer at magnifications: a) x8, b) x100, c) x250, d) x500

Rys. 3. Obraz SEM korony na ząb trzonowy z technologii SLM – widok od strony stopnia przy powiększeniach: a) x8, b) x100, c) x250, d) x500

and on the chamfer. The structure in the chamfer zone is highly developed and irregular. Visible are unmelted particles with a size of 90-120 µm, corresponding to the size of the powder particles used in the technological process. The surface development will allow the creation of permanent cement joints between the crown and the abutment tooth and may affect the adhesion of the veneering ceramics.

The sequence of **Figures 4** and **5** shows selected representative SEM images of the microstructure of Ti6Al4V crowns made using the CAD/CAM method in the milling. They have a surface layer on the inside and outside in the veneering zone, as well as in the chamfer zone, shaped into characteristic parallel peripheral recesses after digital processing with milling cutters. The structure is homogeneous, and there are few separations in it. The top layer of the chamfer is especially notable, which bears regular traces of concentric, linear, parallel recesses at a distance of approximately 50 µm (**Figs. 4** and **5**). Additionally, between the recesses on the molar step, there is a structure of scales (**Fig. 5c, d**). Both the linear recesses and the transverse scaling will also secure the proper bonding of the cement used to sit the crown on the abutment tooth.

The results of micromechanical tests performed on axial sections through the crowns on teeth 15 and 36, from both technologies, allowed to evaluate of the microhardness, Young's modulus and the maximum depth of penetration in the following zones: chamfer, side walls and occlusal (**Tab. 1** and **2**).

First, the test results for the premolar tooth were compiled (**Tab. 1, Figs. 6–8**). The results of tests in crowns with SLM showed that in the zone close to the chamfer, the microhardness was at a level of 4940.39 MPa, which is 789.79 MPa higher than in the milling. Higher microhardness in the chamfer zone, which affects wall stiffness, is advantageous because of the lower probability of ceramic cracking after the crown veneering process. The microhardness in the zone close to the chamfer was evenly distributed in both technologies. In the area of the side walls in SLM, the microhardness value was 4899.82 MPa, and in the milling – 4324.95 MPa, which was a value higher by 574.87 MPa compared to the milling. In

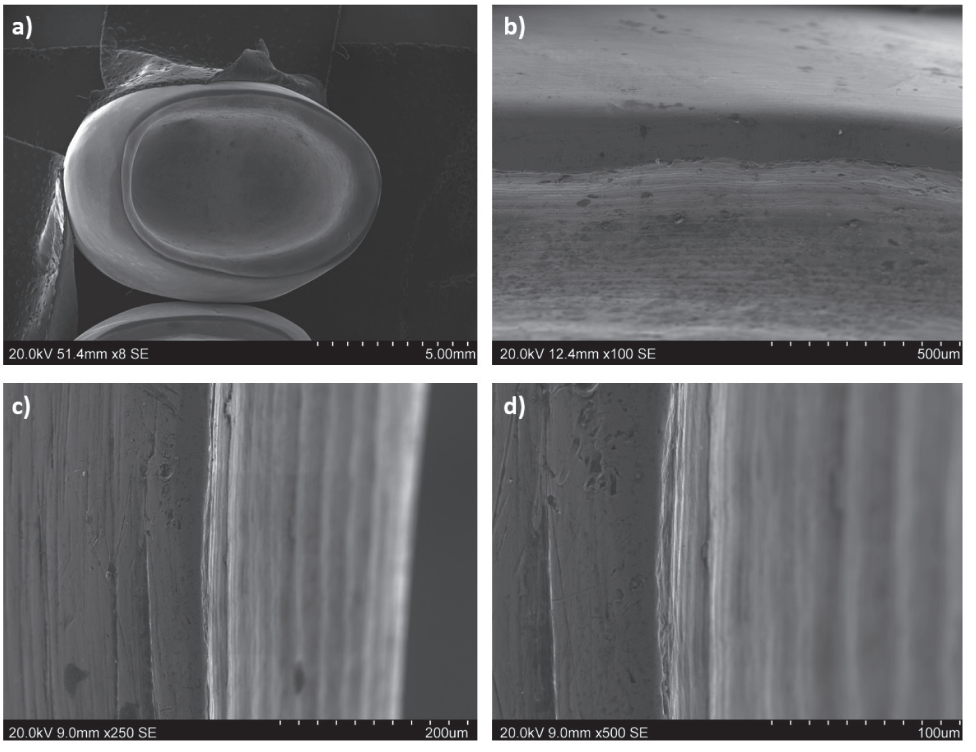

Fig. 4. SEM image of a premolar crown using milling – view from the side of the chamfer at magnifications: a) x8, b) x100, c) x250, d) x500

Rys. 4. Obraz SEM korony na ząb przedtrzonowy z technologii frezowania – widok od strony stopnia przy powiększeniach: a) x8, b) x100, c) x250, d) x500

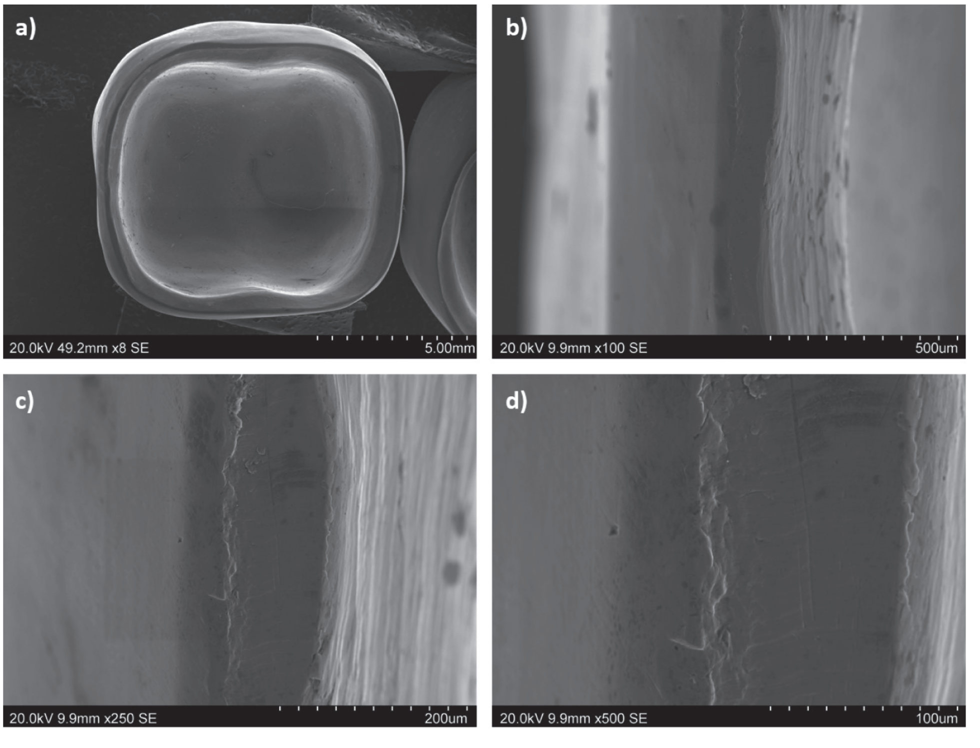

Fig. 5. SEM image of a molar crown using milling – view from the side of the chamfer at magnifications: a) x8, b) x100, c) x250, d) x500

Rys. 5. Obraz SEM korony na ząb trzonowy z technologii frezowania – widok od strony stopnia przy powiększeniach: a) x8, b) x100, c) x250, d) x500

Table 1. Results of micromechanical tests of crowns made of Ti6Al4V alloy for the premolar tooth, manufactured using SLM and milling, in vertical sections perpendicular to the dental arches

Tabela 1. Wyniki badań mikromechanicznych koron ze stopu Ti6Al4V na ząb przedtrzonowy, wytworzonych w technologii SLM i frezowania, w przekrojach pionowych prostopadłych do łuków zębowych

Material of tests		Metrology parameter	Microhardness HV	Microhardness HiT [MPa]	Young's modulus, E [GPa]	Depth of penetration, hmax [nm]
Chamfer zone	Crowns made of SLM	Average value	466.30	4940.39	138.08	1446.06
		Standard deviation	22.10	234.17	5.47	30.44
	Milled crowns	Average value	391.76	4150.60	135.42	1549.82
		Standard deviation	22.25	235.77	5.53	39.39
Side walls zone	Crowns made of SLM	Average value	462.47	4899.82	137.48	1455.39
		Standard deviation	22.59	239.30	3.98	23.45
	Milled crowns	Average value	408.21	4324.95	141.17	1524.15
		Standard deviation	39.17	415.02	10.49	59.49
Occlusal zone	Crowns made of SLM	Average value	456.21	4833.48	135.66	1458.90
		Standard deviation	21.03	222.78	5.45	29.53
	Milled crowns	Average value	416.49	4412.65	143.91	1509.28
		Standard deviation	46.90	496.84	12.60	67.22

Table 2. The results of micromechanical tests of crowns made of Ti6Al4V alloy for the molar tooth, manufactured using SLM and milling, in vertical sections perpendicular to the dental arches

Tabela 2. Wyniki badań mikromechanicznych koron ze stopu Ti6Al4V na ząb trzonowy, wytworzonych w technologii SLM i frezowania, w przekrojach pionowych prostopadłych do łuków zębowych

Material of tests		Metrology parameter	Microhardness HV	Microhardness HiT [MPa]	Young's modulus, E [GPa]	Depth of penetration, hmax [nm]
Chamfer zone	Crowns made of SLM	Average value	470.57	4985.60	146.72	1430.66
		Standard deviation	28.86	305.81	6.24	34.24
	Milled crowns	Average value	364.09	3857.41	139.15	1590.91
		Standard deviation	17.70	187.51	8.18	34.42
Side walls zone	Crowns made of SLM	Average value	460.57	4879.68	143.79	1398.39
		Standard deviation	17.72	187.73	6.23	65.08
	Milled crowns	Average value	376.77	3991.76	139.37	1570.01
		Standard deviation	27.38	290.12	5.45	49.68
Occlusal zone	Crowns made of SLM	Average value	463.96	4915.53	138.71	1452.48
		Standard deviation	32.69	346.36	4.89	40.62
	Milled crowns	Average value	383.73	4065.58	140.33	1559.83
		Standard deviation	35.05	371.35	6.44	59.22

the cross-section of the occlusal zone of the sintered crown, a slightly lower microhardness value was found in relation to the previously mentioned zones – at the level of 4833.48 MPa. In the milling, the microhardness was 4412.65 MPa. By comparing the microhardness in the occlusal zone of crowns made in both technologies, it can be stated that the SLM value was higher by 420.83 MPa.

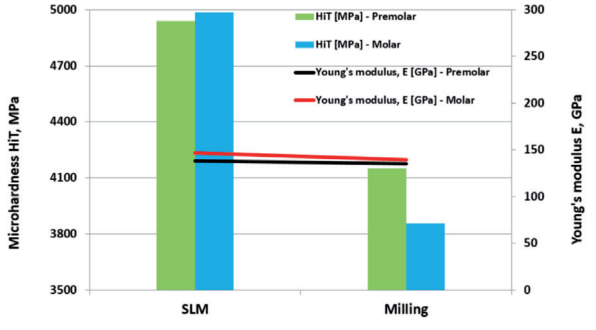

Fig. 6. List of micromechanical parameters of crowns in vertical sections through the chamfer zones

Rys. 6. Zestawienie parametrów mikromechanicznych koron w przekrojach pionowych przez strefy stopnii

The test results for the molar tooth from both technologies indicate a similar regularity of the microhardness distribution in the analysed zones (**Tab. 2, Figs. 6–8**). The results in the SLM crowns showed that in the zone close to the chamfer, the microhardness was at the level of 4985.60 MPa, which is a value higher by 1128.19 MPa than in the milling. In the area of the side walls in SLM, the microhardness value was 4879.68 MPa, and in the milling, 3991.76 MPa, which was a value higher by 887.92 MPa compared to the milling. In the cross-section of the sintered crown's occlusal zone, a comparable microhardness value was found in relation to the previously mentioned zones – at the level of 4915.53 MPa. In the milling, the microhardness was 4065.58 MPa. When comparing the microhardness in the occlusal zones of the crowns made in both technologies, it can be stated that the SLM showed a higher value of 849.95 MPa.

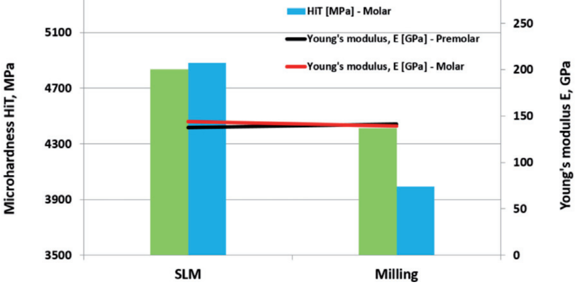

Fig. 7. List of micromechanical parameters of crowns in vertical sections through the side walls

Rys. 7. Zestawienie parametrów mikromechanicznych koron w przekrojach pionowych przez ściany boczne

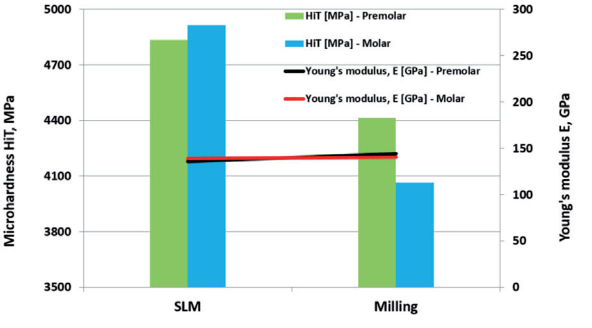

Fig. 8. List of micromechanical parameters of crowns in vertical sections through the occlusal zones

Rys. 8. Zestawienie parametrów mikromechanicznych koron w przekrojach pionowych przez strefy dookluzyjne

The micromechanical tests performed allowed us to determine the longitudinal elasticity modules in SLM and CAD/CAM milling technologies in both teeth in the analysed vertical sections perpendicular to the dental arches (**Tab. 1** and **2, Figs. 6–8**). Crowns made of SLM for premolars in the zone close to the chamfer showed the longitudinal elasticity modules at the level of 138.08 GPa, which is 2.66 GPa higher than the milling, and in the case of a molar, Young's modulus was slightly higher, 146.72 GPa, which was 7.57 GPa higher than in the milling (**Fig. 6**). In the area of the side walls, crowns made of SLM for premolars showed Young's modulus at the level of 137.48 GPa, and in milling – 141.17 GPa. In turn, in the case of crowns sintered premolar, Young's modulus was 143.79 GPa, and milled crowns 139.37 GPa (**Fig. 7**). In the case of Young's modulus in the occlusal zone of the crown, the premolar tooth with SLM had the lowest value in relation to the zones mentioned above – equal to 135.66 GPa and was 8.25 GPa lower than in the case of milled crowns. For molar crowns, a slightly lower value of Young's modulus was found in the SLM – 138.71 GPa than in the milling – 140.33 GPa (**Fig. 8**). Note that as a result of the biomechanical stimulation of the periodontium, the values of Young's modulus of the structure should be similar to the values of Young's modulus of the hard tissues of the teeth.

When analysing Young's modulus, it can be noticed that there are no significant differences in values depending on the technology of manufacturing the structure. They range from 135 to 146 GPa. In the area of chamfers, the modules were higher for SLM than for milling, and in the area of occlusion, they were slightly higher for milling than for SLM. Depending on the analysed tooth, there are also no significant differences in Young's modulus.

The technologies of titanium crown manufacturing were also evaluated based on mapping the internal shape of the crowns in relation to the abutment teeth in horizontal sections with planes perpendicular to the axis of the teeth (Figs. 9 and 10). In the case of the premolar, the fit in the area of the side walls was from -0.065 mm to 0.133 mm for SLM and from -0.088 mm to 0.133 mm for milling (**Fig. 9**). For a molar, the fit in the area of the side walls ranged from -0.020 mm to 0.155 mm for SLM and from -0.043 mm to 0.120 mm for milling (**Fig. 10**).

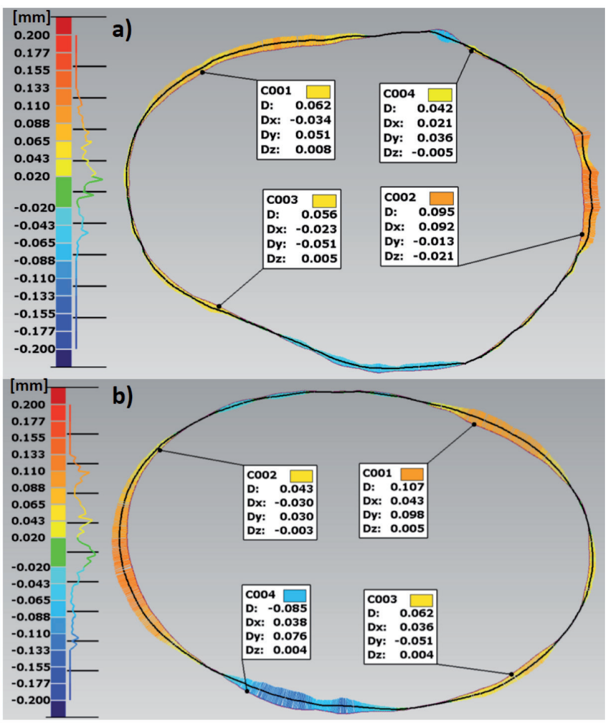

Fig. 9. Distribution of deviations in the accuracy of mapping the shape of the side walls of the crowns, in relation to the premolars of the abutment teeth, in cross sections with horizontal planes: a) SLM, b) milling

Rys. 9. Rozkład odchyłek dokładności odwzorowania kształtu ścian bocznych koron względem przedtrzonowych zębów filarowych w przekrojach płaszczyznami horyzontalnymi: a) SLM, b) frezowanie

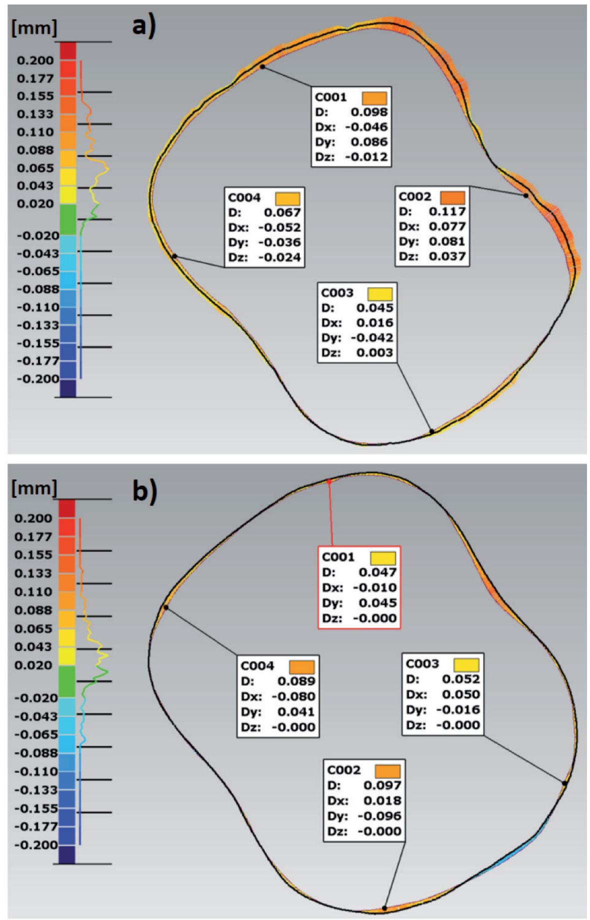

Fig. 10. Distribution of deviations in the accuracy of mapping the shape of the side walls of the crowns, in relation to the molars of the abutment teeth, in cross sections with horizontal planes: a) SLM, b) milling

Rys. 10. Rozkład odchyłek dokładności odwzorowania kształtu ścian bocznych koron względem trzonowych zębów filarowych w przekrojach płaszczyznami horyzontalnymi: a) SLM, b) frezowanie

DISCUSSION

In order to evaluate the impact of the technology for manufacturing titanium crown supporting structures, microstructure and surface layer tests were carried out, with particular emphasis on the gingival chamfer zone, micromechanical tests in vertical sections, and tests on errors in mapping the shape of abutment teeth in horizontal sections. Many authors analyse tests of titanium alloys for prosthetics due to implant-prosthetic procedures and the increasing need to apply these alloys. Many centres conduct microstructural and micromechanical tests **[L. 10, 18–23]**, phase analyses **[L. 24, 25]**, strength and fatigue tests **[L. 26–28]**, modelling and assessment of the accuracy of mapping **[L. 8, 13–15, 29–31]**, and comparison of the technology for the manufacture of prosthetic structures **[L. 6, 16, 32–37]**.

Our research program was closely correlated with the clinical and operational requirements of fixed dentures used by an individual patient. Prosthetic restorations must functionally rebuild and protect the tissues of the oral cavity, as well as the conditions of occlusion and chewing. The biomaterials used for their construction are certified and have standardised parameters. Therefore, for SLM, a titanium alloy powder was used for medical and dental applications in accordance with document H-5983-9026 (**Fig. 11**). For milling, discs used for the production of dental prosthetic elements were used, made of Ti6Al4V grade 5 ELI titanium alloy in accordance with ISO 5832-2 and ASTM F136 (**Fig. 12**).

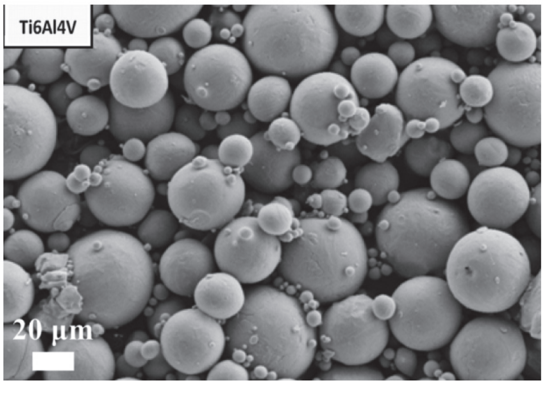

Fig. 11. SEM image of Ti6Al4V powder [L. 38]
Rys. 11. Obraz SEM proszku Ti6Al4V **[L. 38]**

Fig. 12. Factory Starbond Ti5 disc from which the test specimens were made
Rys. 12. Fabryczny dysk Starbond Ti5 Disc, z którego wykonano próbki do badań

In SEM images of crowns from the SLM, a different "ball" surface development was found resulting from the sintering process, and in the milling – the development of the surface layer in the form of linear recesses and additionally transverse occurring scaling created by interference with a cutting tool. Appropriate surface development in both technologies is important for the next procedure of ceramic veneering and the connection of the crown with the abutment tooth with the use of appropriate cement.

The manufactured substructures of the prosthetic crowns were subjected to micromechanical tests in vertical sections perpendicular to the dental arches. Structures for patient supply must meet biomechanical requirements, including complex load-bearing strength and adequate stimulation of the SS tissues **[L. 19, 21, 22]**. The higher value of the microhardness of the titanium substructure obtained in SLM, compared to the milled one, increases the structure's stiffness under biomechanical excitation conditions. In SLM, there is the highest microhardness in the chamfer zone. This is of particular importance to prevent the chipping of veneering ceramics. In the milling, the highest value of microhardness was in the occlusal zone (the highest wall thickness). The microhardness value decreases as you approach the chamfer (the smallest wall thickness). The generation of such a microhardness distribution in milling was typical for substructures on the premolars and molars. This may result from the essence of the milling process and the possibility of cooling the contact zone between the structure and the tool. The technology of manufacturing titanium biomaterials does not cause fundamental differences in the modulus of elasticity in the sintering and the milling **[L. 23, 26, 27, 35]**. The modulus of elasticity for titanium alloys is, on average, for the tested zones at the level: for SLM, 140.07 GPa and milling, 139.89 GPa. Previous tests of cobalt alloy crowns in vertical sections in the tested zones showed the average value of Young's modulus for SLM technology at the level of 213.31 GPa, for milling technology – 219.13 GPa, and for casting technology – 195.20 GPa **[L. 39]**. This may be due to the type and nature of the chemical bonds (bond stiffness) specific to certain titanium and cobalt alloys. However, it can be concluded that when a high elastic modulus value characterises an object, the stress effect is small, which is the case with CoCrMo alloys. In the case of titanium alloys with much lower values of the modulus of elasticity, the stress causes much greater strain, and greater deformation of the object may occur. Significant microhardness differences exist between technologies and biomaterials, which were identified based on previous micromechanical studies carried out by our team and other centres **[L. 7, 10, 18, 20, 38, 39]**.

Based on previous tests, it was found that the fitting of prosthetic crowns made of Ti6Al4V alloy in SLM, and milling is characterised by appropriate accuracy and meets clinical requirements. The errors in mapping the shape of crowns made of the Ti6Al4V alloy with SLM are in the range of -0.178 ÷ 0.200 mm for the premolar and -0.138 ÷ 0.246 mm for the molar and in the milling range: -0.143 ÷ 0.200 mm for the premolar and from -0.168 mm to 0.247 mm for a molar **[L. 4]**. Analyses of previously prepared reports, in the form of summary lists and maps, show that the determined distributions of accuracy deviations of mapping the shape of the side walls of titanium crowns on premolars and molars in cross sections with a horizontal plane fall within the above-mentioned ranges of SLM and milling.

CONCLUSIONS

Microstructural analyses of crowns obtained with the CAD/CAM method in SLM, and milling showed a diversified surface development resulting from the technology.

The higher value of the microhardness of the titanium substructure obtained in SLM, compared to the milled one, increases the structure's stiffness under biomechanical excitation conditions in the stomatognathic system. This is of particular importance in preventing the chipping of the veneering ceramics in the chamfer area.

In SLM, there is the highest microhardness in the chamfer zone. In the milling, the highest value of microhardness was in the occlusal zone (the highest wall thickness). The microhardness value decreases as you approach the chamfer (the smallest wall thickness). The generation of such a microhardness distribution in milling was typical for substructures on the premolars and molars. This may result from the essence of the milling process and the possibility of cooling the contact zone between the structure and the tool.

The research carried out shows that the technologies for manufacturing structures made of titanium biomaterials do not cause significant differences in the modulus of elasticity.

The contact stiffness in the gingival zone of the chamfer in the tested constructions is comparable for both methods.

SLM technology and digital milling technology allow the production of precise and durable structures that meet clinical requirements.

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