Łukasz BOJKO[*], Wojciech RYNIEWICZ[**], Anna M. RYNIEWICZ[*], Marcin KOT[*], Paweł PAŁKA[**]

THE INFLUENCE OF ADDITIVE TECHNOLOGY ON THE QUALITY OF THE SURFACE LAYER AND THE STRENGTH STRUCTURE OF PROSTHETIC CROWNS

WPŁYW TECHNOLOGII PRZYROSTOWEJ NA JAKOŚĆ WARSTWY WIERZCHNIEJ I STRUKTURĘ WYTRZYMAŁOŚCIOWĄ KORON PROTETYCZNYCH

Key words: casting, milling, SLM, crown, accuracy of reproduction, surface layer, micromechanical parameters.

Abstract Prosthetic crowns reproduce the damaged hard structures of the patient's own teeth and take over their natural functions, thus securing the correct reconstruction of the stomatognathic system. The aim is to evaluate the crowns for premolars and molars produced by casting, milling, and Selective Laser Melting technologies, in terms of the accuracy of reproducing the degree against the prosthetic pillar, the analysis of the surface layer structure of the step, and the micromechanical parameters of the alloy. The study material included CoCrMo alloy crowns. The conducted study allowed finding that the tightness of prosthetic crowns made using traditional casting technology as well as in SLM milling and technology is comparable and meets clinical requirements. Structural crown analyses confirmed the very good quality of the surface layer obtained with milling technology and SLM technology using the CAD/CAM method. SLM and digital milling allow the formation of precise and durable structures constituting the foundation of crowns in a time much shorter than the casting process.

Słowa kluczowe: odlewanie, frezowanie, SLM, korona, dokładność odwzorowania, warstwa wierzchnia, parametry mikromechaniczne.

Streszczenie Korony protetyczne odtwarzają uszkodzone twarde struktury zębów własnych pacjenta, przejmują ich naturalne funkcje i w ten sposób zabezpieczają prawidłową odbudowę układu stomatognatycznego. Celem jest ocena koron na zęby przedtrzonowe i trzonowe wytwarzane technologią odlewania, frezowania oraz Selective Laser Melting, w zakresie: dokładności odwzorowania stopnia względem filara protetycznego, analizy struktury warstwy wierzchniej stopnia, parametrów mikromechanicznych stopu. Materiałem badań były korony ze stopu CoCrMo. Przeprowadzone badania pozwoliły stwierdzić, że szczelność koron protetycznych wykonanych w technologii tradycyjnego odlewania oraz w technologii frezowania i technologii SLM jest porównywalna i spełnia wymogi kliniczne. Analizy strukturalne koron potwierdziły bardzo dobrą jakość warstwy wierzchniej uzyskiwanej w technologii frezowania oraz w technologii SLM metodą CAD/CAM. SLM i frezowanie metodą cyfrową pozwalają na wytworzenie precyzyjnych i wytrzymałych konstrukcji stanowiących podbudowy koron w czasie znacznie krótszym niż proces odlewniczy.

INTRODUCTION

Prosthetic crowns may constitute independent fillings or be components of multiple tooth permanent dentures and/or serve as an anchorage of partial removable dentures. Prosthetic crowns reproduce the damaged hard structures of the patient's own teeth and take over their natural functions, thus protecting the correct reconstruction of the stomatognathic system (SS). The most important functions of the prosthetic crowns include the following: effective participation in the act of chewing and speaking, maintaining the continuity of

[*] AGH University of Science and Technology, Faculty of Mechanical Engineering and Robotics, al. Mickiewicza 30, 30-059 Cracow, Poland.
[**] Jagiellonian University Medical College, Faculty of Medicine, Dental Institute, Department of Dental Prosthodontics, ul. Montelupich 4, 31-155 Cracow, Poland.
[***] AGH University of Science and Technology, Faculty of Non-Ferrous Metals, al. Mickiewicza 30, 30-059 Cracow, Poland.

dental arches and the occlusal surface, and the protection of periodontal tissues providing physiological conditions for occlusal load transfer.

The shape of the crown edge may include or not include a level (step). In the first case, an excess of thickness is formed at the place where the crown is connected to the tooth, depending on the thickness of the crown wall end. In the second case, a step is formed on the tooth allowing a smooth transition of the crown's wall into the tooth wall without forming retention areas for sediment, tartar, or plaque. Various types of edges are formed in clinical practice **(Fig. 1)**. The shaping of the gingival margin demonstrates great importance for periodontal health, and the positioning of the step and their shapes have great impact on it.

a) b) c) d) e) f) g)

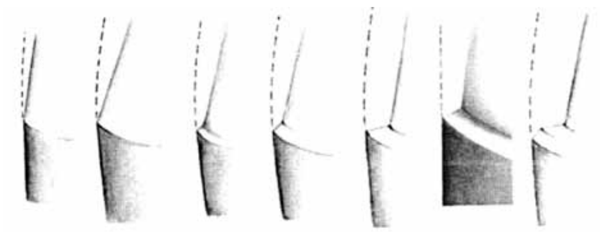

Fig. 1. Edge types: a) edge with a thin edge, b) edge with a chisel-shaped edge, c) edge with a rounded step, d) inclined step, e) step in the form of a stair, f) inclined step in the form of a stair, g) step with slanted edge [L. 1]

Rys. 1. Rodzaje obrzeży: a) obrzeże o cienkiej krawędzi, b) obrzeże o krawędzi w kształcie dłuta, c) krawędź ze stopniem zaokrąglonym, d) stopień skośny, e) stopień w postaci schodka, f) pochylony stopień w postaci schodka, g) schodek ze skośną krawędzią **[L. 1]**

The aim is to evaluate the CoCrMo alloy crowns for premolars and molars produced using traditional casting technology, milling technology, and Selective Laser Melting (SLM) technology with regard to the following areas:

- The accuracy of reconstructing the step with regard to the prosthetic pillar,
- Surface layer structure analysis of the step, and
- Micromechanical parameters of the alloy obtained in three studied technological processes.

MATERIAL AND METHOD

The basic clinical principle of developing a tooth for a prosthetic crown is to save tooth tissues and prevent damage to the pulp as much as possible **(Fig. 2) [L. 2–5]**. The layer of tissues milled from the tooth surface at the contact site with the opposing teeth should form a space slightly larger than the thickness of the future crown in this area. The side walls may be developed cylindrically or slightly convergent to the occlusal surface, and their circumference must be equal to or smaller than the circumference of the crown base. The walls should be smooth. Existing cavities must be filled in prior to taking the impression. When developing a tooth, it should be remembered that the main fixation for the crown is not provided by cement, but by the geometrical shape of its walls **(Fig. 3)**. The better the retention of the crown on the developed tooth, the greater the contact area of its walls with the crown substructure, and the optimal convergence is 2° to 6.5° **[L. 6–11]**.

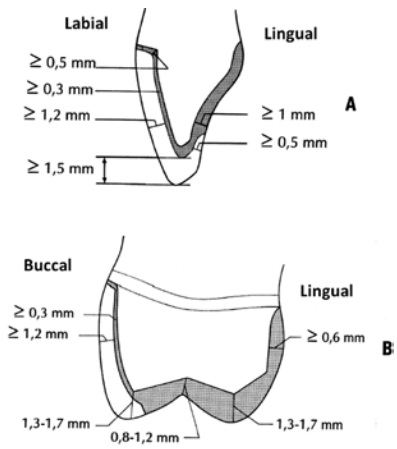

Fig. 2. Recommended minimum thickness of tissue grinding for the metal-ceramic crown on the lateral segment tooth [L. 1]

Rys. 2. Zalecana minimalna grubość szlifowania tkanek pod koronę metalowo-ceramiczną na zębie w odcinku bocznym **[L. 1]**

Fig. 3. The first stage of prosthetic treatment: a) clinically developed dental pillars with an obtuse step, b) negative prosthetic base imitated with silicone masses (two-layer simultaneous impression)

Rys. 3. Pierwszy etap leczenia protetycznego: a) kliniczne opracowane filary zębowe ze stopniem rozwartym, b) negatyw podłoża protetycznego odwzorowany masami silikonowymi (wycisk dwuwarstwowy jednoczasowy)

The study material included the prosthetic crowns from the CoCrMo alloy for the second maxillary premolar on the right side (tooth 15) and the first mandibular molar on the left side (tooth 36) prepared in 5 pieces for tooth 15 and 36, as well as for each technology.

The premolar was ground on 5 phantoms of the toothed maxilla and the molar was ground on 5 phantoms of the toothed mandible. Phantoms obtained from KaVo were used. The crowns of premolars and molars have been ground with a full obtuse angle. The degree of the angle was 140°±4°. Full-arch folded dental working models were prepared using the Fujirock EP Pastel Yellow super hard plaster from Fuji on the base of two-layer impressions, with simultaneous impressions made using Bisico S1 thick additive silicon mass from Bisico, and a supplementing impression with Bisico Super Hydrophil S4 Suhy thin mass from Bisico. The reference models were pillar teeth separated from the working model. For the casting technology on the reference models of the premolars, 5 wax crown models were made, and, for the molar tooth, also 5 models were used in the casting method to produce 10 pieces of suitable CoCrMo alloy crowns (Brealloy, Bredent, Poland). For the milling and SLM technologies based on the CAD/CAM procedure, reference models were scanned and spatial CAD reconstructions were made.

The process of the reconstruction of the shape of the step was carried out using of an optical scanner with a variable width of structural light stripes - Everest scan pro 06 1086 by KaVo. The measurement accuracy was 20 μm, and the spatial resolution was 0.02 mm x 0.02 mm x 0.02 mm. Based on STL files, 5 milled crowns (CoCrMo alloy, Renomed, Poznań, Poland) and 5 pieces of SLM technology crowns (Wirobond C +, Bego Medical GmbH, Bremen, Germany) for tooth 15 and 36 were formed, respectively. The internal shape of the crowns was replicated using an insulator (Dura Lay Lubricant, Reliance Dental Mfg.Co., Worth, IL, USA) and a quick-polymerizing, sharp-contour acrylic mass (Dura Lay II, Reliance Dental Mfg.Co., Worth, IL, USA). Models obtained by doing so were scanned using the same Everest scan pro scanner. As a result, 30 virtual, spatial test models were formed. Spatial resolution of the model grid was 0.1mm x 0.1mm x 0.1mm. The tests involved comparing the degree of match between crowns made using three technologies and the reference models. The *best fit* assessment method was used for the analysis using the Geomagic Qualify 12 program. This program, when using the procedure of the best shape match, automatically sets the compared bodies, and then identifies the positive and negative deviations resulting from the accuracy of the test model crown reconstruction with regard to the reference model. The tightness of crowns in the zone of the step (marginal fit -MF) was identified in the form of deviation distribution maps.

The analysis of the surface layer structure of steps in the CoCrMo alloy crowns made using the casting, milling, and SLM technologies was carried out using the Hitachi S3400N scanning electron microscope **(Fig. 4)**.

Micromechanical tests were carried out on axial cross-sections of crowns. In order to do so, the samples were cut and embedded in the resin and subjected to a polishing process using the Struers TegraForce-5 device, on which, by means of programmed operations, the top layer of the samples required for the tests was reached **(Fig. 5)**. Investigations of micromechanical properties, which included measurements of microhardness and Young's modulus in selected axial cross-sections, were performed on a Micro Combi Tester from CSEM Instruments. They were determined on the basis of sample indenting using a diamond penetrator in the form of regular pyramid with a square base **[L. 12]**. The values of the force and depth of blade penetration in the loading and unloading cycle were continuously recorded in the measurements. The maximum load value was 200 mN, the loading and unloading speed was 400 mN/min, and the time for maintaining maximum load was 5 s. For each cycle, the relation between the indenter load and the penetration depth function was calculated. The analysis of micromechanical properties was based on the Oliver and Pharr method, according to which microhardness (HV) and modulus of elasticity of the material (E) were calculated from the indenting curve. The micromechanical parameters were determined as the mean of 15 measurements for crowns from each technology.

a) b) c)

Fig. 4. Crowns for premolars and molars in the mucous-approaching side, made using the following technologies: a) casting, b) milling, c) SLM

Rys. 4. Korony na zęby przedtrzonowe i trzonowe w widoku od strony dośluzowej wykonane w technologiach: a) odlewania, b) frezowania, c) SLM

Fig. 5. Samples for micromechanical tests – axial cross-sections of crowns embedded in resin

Rys. 5. Próbki do badań mikromechanicznych – przekroje osiowe koron inkludowane w żywicy

RESULTS

The Geomagic Qualify 12 program allowed comparing the match between the pillar teeth and the respective tooth crowns formed using the discussed technologies. In the study procedures, seal tests were carried out using 10 cast crowns, 10 milled crowns, and 10 crowns made using SLM, with regard to the corresponding model of the pillar tooth, constituting the reference model. **Figures 6** and **7** contain selected maps of shape mapping errors for pillar premolars and molars in crown formation in the three analysed technologies in the mucous side view. Shape mapping errors in all technologies are characterized by small values of positive and negative shape deviations within the range of ± 0.25 mm, with -0.20 mm to 0.05 mm in the step zone. The best reproduction of step shape was obtained using the milling technology, where reproduction errors ranged from -0.09 mm to 0.02 mm. In SLM technology, the mapping errors were in the range of -0.15 mm to 0.02 mm, with small error areas up to 0.05 mm. The largest errors in degree mapping occurred in the casting technology and ranged from -0.20 mm to 0.04 mm.

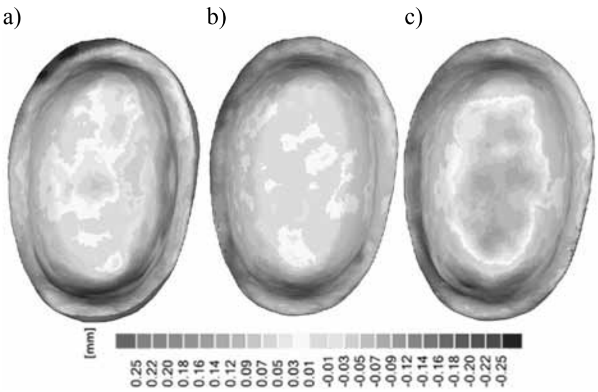

Fig. 6. Shape reconstruction error maps of CoCrMo alloy crowns for premolars formed using the following technologies: a) casting, b) milling, c) SLM

Rys. 6. Mapy błędów odwzorowania kształtu koron ze stopu CoCrMo na zęby przedtrzonowe w technologiach: a) odlewania, b) frezowania, c) SLM

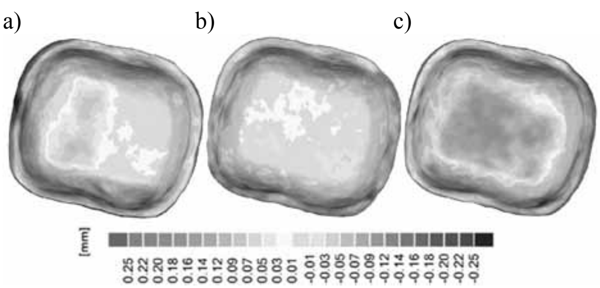

Fig. 7. Shape reconstruction error maps of CoCrMo alloy crowns for molars formed using the following technologies: a) casting, b) milling, c) SLM

Rys. 7. Mapy błędów odwzorowania kształtu koron ze stopu CoCrMo na zęby trzonowe w technologiach: a) odlewania, b) frezowania, c) SLM

The analysis of the crown top layer structure for the premolar and molar teeth from the centrifugal casting technology indicates their manual finishing milling development (**Figs. 8** and **9**). Their internal structure is characterized by depressions, scratches, and few areas of crystallized accretion and segregation. Steps have much higher accuracy than the interior of the crown. There are small increments and recesses visible in the zone of the step remaining despite manual milling. The recesses may result from unavoidable casting defects. They may constitute air bubble remains, resulting from the granularity of the covering material or the shrinking of the metal in the cooling process.

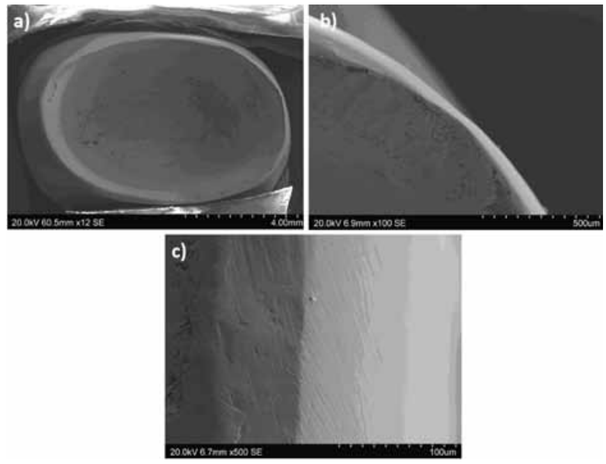

Fig. 8. SEM image of the crown step for the premolar tooth formed with the casting technology at magnifications: a) x12, b) x100, c) x500

Rys. 8. Obraz SEM stopnia korony na ząb przedtrzonowy z technologii odlewania przy powiększeniach: a) x12, b) x100, c) x500

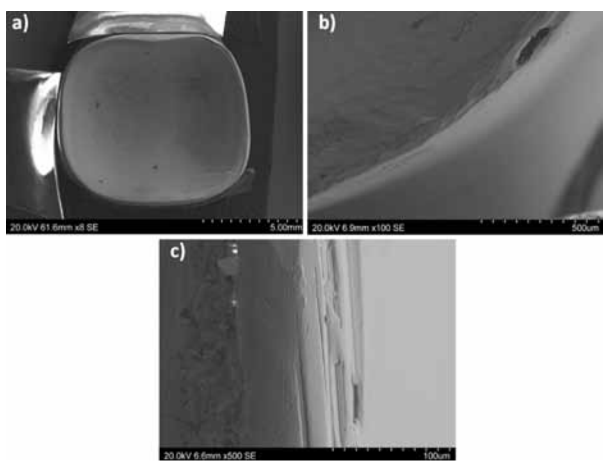

Fig. 9. SEM image of the crown step for the molar tooth formed with the casting technology at magnifications: a) x8, b) x100, c) x250

Rys. 9. Obraz SEM stopnia korony na ząb trzonowy z technologii odlewania przy powiększeniach: a) x8, b) x100, c) x500

The sequence of **Figures 10** and **11** shows selected representative SEM images of the CoCrMo alloy crown microstructure made using CAD/CAM in milling technology. They have a top layer in the inner area and outside in the veneering zone, as well as in the step area, formed in characteristic parallel peripheral recesses after digital milling. The superficial layer of the step, which presents regular traces of concentric, linear, parallel pits at distances of about 50 µm (**Figs. 10** and **11**) is particularly noteworthy. In addition, there is a scale-like structure between the recesses (**Figs. 10b, c**). Both linear recesses and additionally transversely present a scale-like structure that will secure the proper connection of the cement used to embed the crown in the pillar tooth. The structure is homogeneous. There are few separations in it.

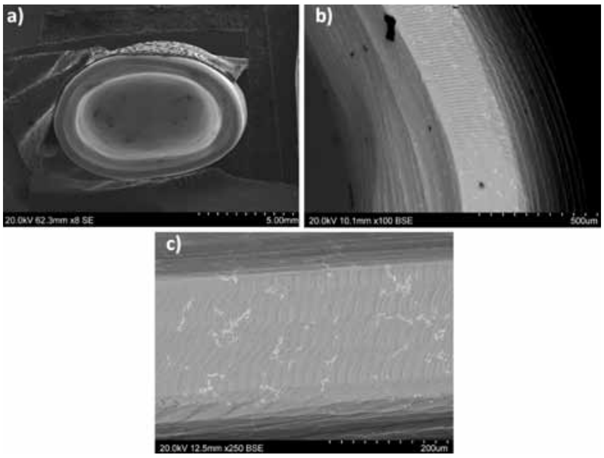

Fig. 10. SEM image of the crown step for the premolar tooth formed with the milling technology at magnifications: a) x8, b) x100, c) x250

Rys. 10. Obraz SEM stopnia korony na ząb przedtrzonowy z technologii frezowania przy powiększeniach: a) x8, b) x100, c) x250

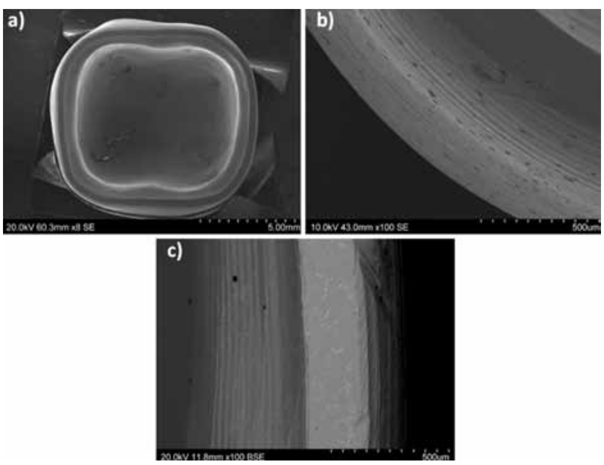

Fig. 11. SEM image of the crown step for the molar tooth formed with the milling technology at magnifications: a) x8, b) x100 SE, c) x250 BSE

Rys. 11. Obraz SEM stopnia korony na ząb trzonowy z technologii frezowania przy powiększeniach: a) x8, b) x100 SE, c) x100 BSE

SEM images of crowns made with the CAD/CAM method in SLM technology have much higher roughness and porosity in all areas (**Figs. 12** and **13**). It causes the development of a surface that is visible outside in the veneering zone, inside and on the step. The structure in the zone of the degree is strongly developed and homogeneous. It will enable the formation of permanent connections with cement.

The results of micromechanical tests performed on axial crown cross-sections allowed the assessment of microhardness, Young's modulus, and the maximum depth of penetration in the buccal and lingual walls zone as well as in the occlusal zone substructure. **Table 1** presents the results of micromechanical tests using the Oliver and Pharr method in the step-reaching zone on the axial cross-section of the buccal wall.

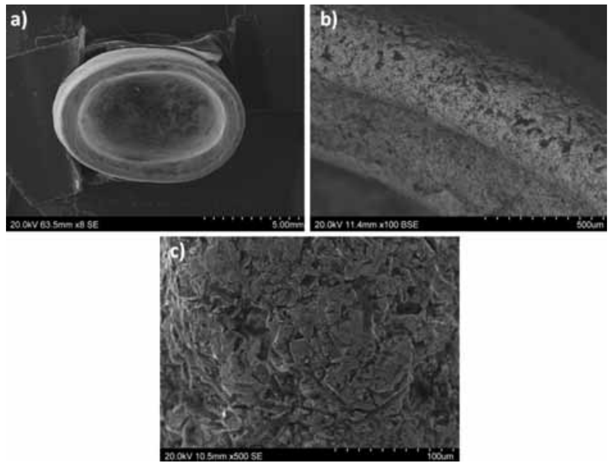

Fig. 12. SEM image of the crown step for the premolar tooth formed with the SLM technology at magnifications: a) x8, b) x100, c) x500

Rys. 12. Obraz SEM stopnia korony na ząb przedtrzonowy z technologii SLM przy powiększeniach: a) x8, b) x100, c) x500

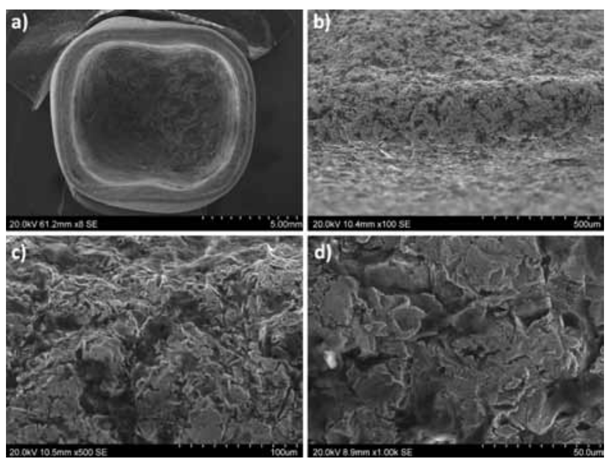

Fig. 13. SEM image of the crown step for the molar tooth formed with the SLM technology at magnifications: a) x8, b) x100, c) x500, d) x1000

Rys. 13. Obraz SEM stopnia korony na ząb trzonowy z technologii SLM przy powiększeniach: a) x8, b) x100, c) x500, d) x1000

The results of micromechanical tests indicate that the CoCrMo alloy crowns from traditional casting technology demonstrate the mean microhardness value equal to 4704.26 MPa in the cross-section of the buccal wall close to the step. It is possible to observe an even distribution of microhardness in the entire zone. For comparison, in the occlusive zone, the average value of microhardness is at a similar level – 4812.47 MPa, which proves the even distribution of microhardness in the entire crown (**Tab. 2**). Having considered the Young's modulus, the cast crown near the step demonstrated a longitudinal modulus of elasticity of 189.62 GPa, and in the occlusal zone, this value slightly increased to 200.78 GPa.

In the case of crowns formed through milling technology (CAD/CAM), microhardness was observed in the vicinity of 4390.6 MPa, while Young's modulus was 219.84 MPa. For comparison, in the occlusive zone, microhardness increased significantly to 4897.92 MPa, while Young's modulus remained at the same level – 218.43 GPa. It is noteworthy that microhardness is the lowest in the area close to the step, and the Young's modulus increases there the most, and moving distally from the step, the microhardness increases while the modulus of elasticity decreases. This phenomenon is caused by the processing.

On the other hand, the results of micromechanical tests in crowns with SLM technology showed that, in the zone of step vicinity, the micro-hardness zone was 4331.73 MPa, which is comparable to milling technology and almost 400 MPa lower than in traditional casting technology. The lower microhardness in the step zone is advantageous due to the less likely ceramic chipping after the crown veneering process. A uniform distribution of microhardness was present in the proximity zone. In the occlusion zone, a significant increase in microhardness was found to be 4928.67 MPa, constituting an increase of 600 MPa compared to the step zone. Small differences up to around 110 MPa can be found when comparing the microhardness in the occlusion zone of crowns formed through the foregoing three technologies. The lowest value occurred in casting technology – 4812.47 MPa, in case of the milling technology it was 4897.92 MPa, and the highest was found in SLM technology – 4828.67 MPa. Having considered the Young's modulus, SLM crowns in the zone near the step showed a modulus of elasticity of 199.31 GPa, which is 20 GPa lower compared to milling technology and 10 GPa higher than in casting technology. When forming a crown, we want to obtain the most optimal strength parameters, which is a low Young's modulus similar to one presented by a tooth. When analysing Young's modulus in the occlusion zone,

Table 1. List of micromechanical results of CoCrMo alloy crowns, made using casting, milling, and SLM technology – in the cross-sectional area of the buccal step

Tabela 1. Zestawienie wyników badań mikromechanicznych koron ze stopu CoCrMo, wykonanych w technologii odlewania, frezowania i SLM – w strefie przekroju stopnia policzkowego

Material of tests	Metrology parameter	Hardness HV	Hardness HiT [MPa]	Young's modulus, E [GPa]	Depth of penetration [nm]
Crown with casting technology	Average value	444.01	4704.26	189.62	1288.74
	Standard deviation	18.58	196.84	10.50	40.81
Crown with milling technology	Average value	406.38	4305.51	219.84	1322.00
	Standard deviation	29.64	314.06	28.87	62.07
Crown with SLM technology	Average value	408.85	4331.73	199.31	1333.27
	Standard deviation	23.65	250.57	13.33	33.02

Table 2. List of micromechanical tests results for CoCrMo alloy crowns made using casting, milling, and SLM technology – in section through the substructure of the occlusion zone

Tabela 2. Zestawienie wyników badań mikromechanicznych koron ze stopu CoCrMo wykonanych w technologii odlewania, frezowania i SLM – w przekroju przez podbudowę strefy okluzyjnej

Material of tests	Metrology parameter	Hardness HV	Hardness HiT [MPa]	Young's modulus, E [GPa]	Depth of penetration [nm]
Crown with casting technology	Average value	454.23	4812.47	200.78	1268.17
	Standard deviation	47.89	507.35	26.00	56.41
Crown with milling technology	Average value	462.23	4897.92	218.43	1251.77
	Standard deviation	30.19	319.25	14.88	37.72
Crown with SLM technology	Average value	465.20	4928.67	227.30	1241.62
	Standard deviation	33.25	352.35	14.21	42.55

SLM crowns had the highest value equal to 227.3 GPa. A slightly lower value was found in the technology of sintered pressed powder disc milling (218.43 GPa), while the lowest was in casting technology – 200.78 GPa (**Figs. 14** and **15**).

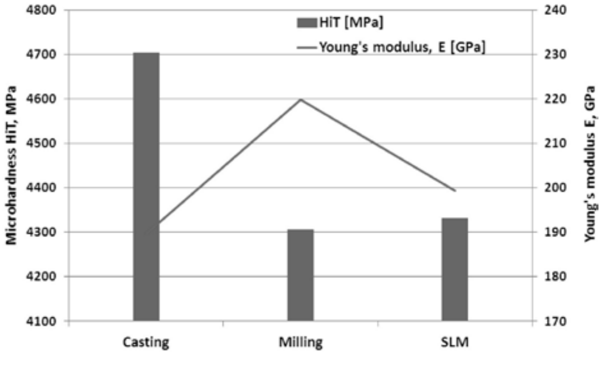

Fig. 14. List of micromechanical parameters in the buccal step cross-section zone in the studied technologies
Rys. 14. Zestawienie parametrów mikromechanicznych w strefie przekroju policzkowego stopnia w badanych technologiach

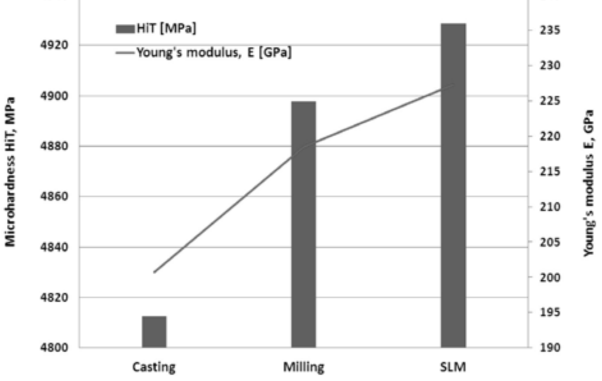

Fig. 15. List of micromechanical parameters in the occlusive zone substructure in studied technologies
Rys. 15. Zestawienie parametrów mikromechanicznych w podbudowie strefy okluzyjnej w badanych technologiach

DISCUSSION

The analysis of the results shows that the crowns formed using the casting, milling, and SLM technologies are clinically correct. In all technologies, the tightness was at a satisfactory level, ranging from -0.15 mm to 0.10 mm with a slight predominance of milling technology (from -0.015 mm to 0.05 mm) (**Fig. 7**). Crown formation ensured tightness in the step zone and in the side wall zone. The alignment of the side walls was comparable in all three technologies. The premolar showed deviations of ±0.05 mm, and, for the molar tooth, the deviations were ±0.07 mm. Alignment in the crown step zone in CAD/CAM procedures for the premolar and the molar teeth was characterized by deviations of -0.15 mm to 0.02 mm (**Figs. 16** and **17**). Alignment in the crown step zone in the casting technology for the premolars was characterized by deviations of -0.15 mm to 0.30 mm. The worst alignment was found in the casting technology of the molar tooth crown step, due to the presence of positive and negative deviations ranging from -0.20 mm to 0.04 mm (**Fig. 17**).

The assessment of crown formation technology in terms of geometric accuracy and quality of the surface layer leads to the conclusion that crowns from the CAD/CAM method are characterized by the pillar shape accuracy of reconstruction, with the milling technology being the leading one **[L. 11, 13, 14]**. However, the structure of superficial crown layer is good in both technologies. One can notice a very good quality of the surface layer in the step resulting from the milling technology and the sintering technology. Both developed structures will have a positive effect on clinical production, i.e. a tight connection of the crown with the pillar tooth **[L. 11, 15, 16]**. The worst structural parameters were observed in the superficial layers of traditional casting technology. It is influenced by a complicated lost-wax casting process and finishing crown processing in the manual milling procedure.

When analysing the micromechanical parameters of crowns, it can be pointed out that in conditions of biomechanical cooperation with pillar tooth tissues (in terms of load transfer and contact pressure), crowns from casting technology and SLM technology demonstrate the best parameters (**Figs. 14** and **15**) **[L. 17, 18]**. Young's modulus is the closest to the module of natural, normal tooth tissues **[L. 19, 20]**. However, Young's modulus for milled crowns demonstrates a much higher value. Microhardness has the lowest values for milling and SLM technology, which seems to be more beneficial for the adhesion of the veneering ceramics to the substructure. High microhardness values can result in ceramics chipping from metal, which can be often observed in clinical settings **[L. 21, 22]**. Micromechanical parameters in the occlusal area of the substructure are less significant. Young's modulus is the lowest in the case of casting, which may be due to the dendritic structure that develops in the condition of cooling. With milling and SLM, its values are quite close, which results from the technological process. SLM technology has the ability to reduce material losses that are typical for casting and milling technology.

Studies and experiments prove that the CoCrMo alloy crowns from all studied technologies show sufficient micromechanical parameters **[L. 23-29]**. This is an extremely significant observation in the assessment of biomaterials for the production of dental structure, because this innovative additive sintering technology can be used in prosthetics, implantoprosthetics, and cranio-maxillo-facial surgery. Strength parameters of biomaterials, adapted to optimal biomechanical contact with pillar teeth, cortical bone, or cancellous bone are required in these diversified applications. **[L. 28–33]**.

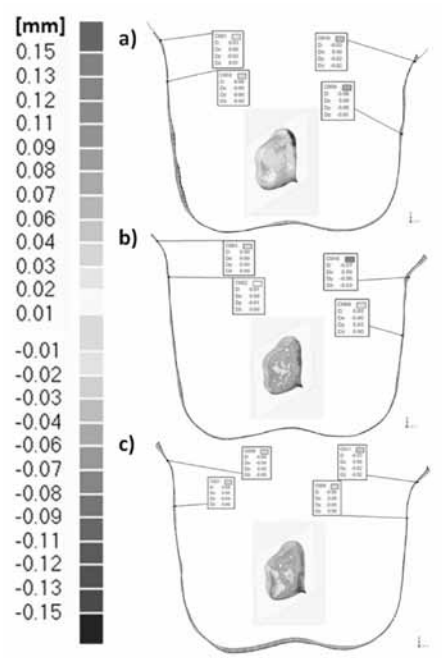

Fig. 16. Distribution of reconstruction accuracy deviations for the step shape in the frontal plane cross-section, for the premolar tooth, formed using the following technologies: a) casting, b) milling, c) SLM

Rys. 16. Rozkład odchyłek dokładności odwzorowania kształtu stopnia w przekroju płaszczyzną frontalną, na ząb przedtrzonowy w technologiach: a) odlewania, b) frezowania, c) SLM

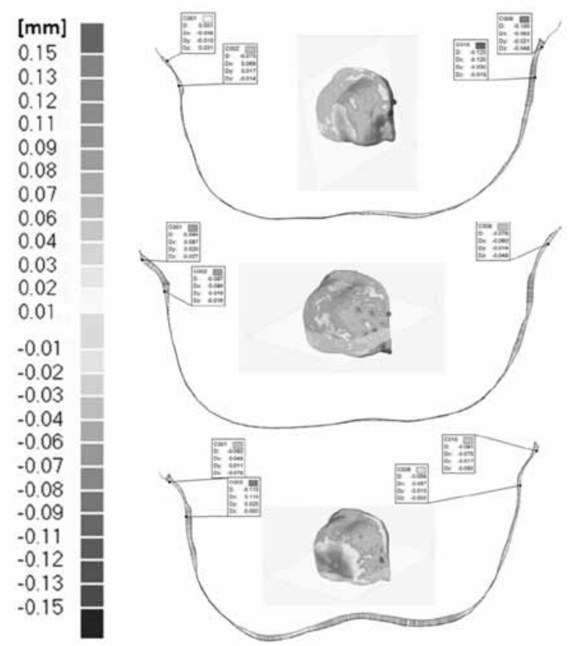

Fig. 17. Distribution of step shape reconstruction accuracy deviations in case of frontal section of a molar tooth, using the following technologies: a) casting, b) milling, c) SLM

Rys. 17. Rozkład odchyłek dokładności odwzorowania kształtu stopnia w przekroju płaszczyzną frontalną, na ząb trzonowy w technologiach: a) odlewania, b) frezowania, c) SLM

CONCLUSIONS

The conducted study allowed finding that the tightness of prosthetic crowns from CoCrMo alloy made using traditional casting technology, as well as in SLM and milling technologies, is comparable and meets clinical requirements.

The applied Geomagic Qualify 12 program is a reliable 3D analysis tool for assessing the crown technology, and indicating errors in the lateral crown surface area alignment, as well as errors in the shape of the step zone.

Structural analysis of the crowns confirmed the very good quality of the surface layer obtained for the CAD/CAM method with milling technology and SLM technology.

Contact stiffness in the paragingival region of the studied structures is better for the CAD/CAM method (milling and SLM) than for traditional casting, because it provides greater flexibility in transferring complex loads resulting from occlusion.

SLM technology and digital milling technology allow the formation of a precise and durable structure constituting the substructure of crowns in a time much shorter than the casting process.

ACKNOWLEDGEMENT:

This work is financed by AGH University of Science and Technology, Faculty of Mechanical Engineering and Robotics: research program No. 11.11.130.174 and a research project No. 2018/K/ZDS/006974 of Jagiellonian University Medical College, Poland.

REFERENCES

1. Rosenstiel S.F., Land M.F., Fujimoto J.: Contemporary Fixed Prosthodontics, 5th Edition, Mosby 2015.
2. Quante K., Ludwig K., Kern M.: Marginal and internal fit of metal-ceramic crowns fabricated with a new laser melting technology, Dental Materials, 24, 10(2008), 1311–1315.
3. Renne W., McGill S.T., Forshee K.V., DeFee M.R., Mennito A.S.: Predicting marginal fit of CAD/CAM crowns based on the presence or absence of common preparation errors, The Journal of prosthetic dentistry,108, 5(2012), 310–315.
4. Schaefer O., Watts D.C., Sigusch B.W., Kuepper H., Guentsch A.: Marginal and internal fit of pressed lithium disilicate partial crowns in vitro: a three-dimensional analysis of accuracy and reproducibility, Dental Materials, 28, 3(2012), 320–326.

5. Ryniewicz W., Ryniewicz A.M., Bojko Ł.: Modeling crowns and assessment of the accuracy of mapping the shape of prosthetic abutments, Przegląd elektrotechniczny, 90(2014), 146–149.
6. Yuan F., Sun Y., Wang Y., Lv P.: Computer-aided design of tooth preparations for automated development of fixed prosthodontics, Computers in biology and medicine, 44(2014), 10–14.
7. Wöstmann B., Rehmann P., Trost D., Balkenhol M.: Effect of different retraction and impression techniques on the marginal fit of crowns, Journal of dentistry, 36, 7(2008), 508–512.
8. Ryniewicz W., Ryniewicz A.M., Bojko Ł.: Evaluation of tightness prosthetic crowns depending on the technology of their execution, Przegląd Elektrotechniczny, 91(2015), 45–48.
9. Litzenburger A.P., Hickel R., Richter M.J., Mehl A.C., Probst F.A.: Fully automatic CAD design of the occlusal morphology of partial crowns compared to dental technicians' design, Clinical oral investigations, 17, 2(2013), 491–496.
10. Zhou L.B., Shang H.T., He L.S., Bo B., Liu G.C., Liu Y.P., Zhao J.L.: Accurate reconstruction of discontinuous mandible using a reverse engineering/ computer-aided design/rapid prototyping technique: a preliminary clinical study, J. Oral Maxillofac. Surg., 68, 9(2010), 2115–2121.
11. Ryniewicz W., Ryniewicz A.M., Bojko Ł.: The effect of a prosthetic crown's design on the accuracy of mapping an abutment teeth's shape. Measurement, 91(2016), 620–627.
12. PN-EN ISO 6507-1:2007: Metals-Vickers hardness test – Part 1: Test method.
13. Kim K.B., Kim W.C., Kim H.Y., Kim J.H.: An evaluation of marginal fit of three-unit fixed dental prostheses fabricated by direct metal laser sintering system, Dental Materials, 29, 7(2013), 91–96.
14. Ortorp A., Jonsson D., Mouhsen A., von Steyern P.V.: The fit of cobalt-chromium three-unit fixed dental prostheses fabricated with four different techniques: a comparative in vitro study, Dental Materials, 27, 4(2011), 356–363.
15. Nicoll R.J., Sun A., Haney S., Turkyilmaz I.: Precision of fit between implant impression coping and implant replica pairs for three implant systems, The Journal of prosthetic dentistry, 109, 1(2013), 37–43.
16. Huang Z., Zhang L., Zhu J., Zhang X.: Clinical marginal and internal fit of metal ceramic crowns fabricated with a selective laser melting technology, The Journal of prosthetic dentistry, 113, 6(2015), 623–627.
17. Jevremovic D., Puskar T., Kosec B., Vukelic D., Budak I., Aleksandrovic S., Williams R.: The analysis of the mechanical properties of F75 Co-Cr alloy for use in selective laser melting (SLM) manufacturing of removable partial dentures (RPD), Metalurgija, 51, 2(2012), 171–174.
18. Yoda K., Takaichi A., Nomura N., Tsutsumi Y., Doi H., Kurosu S., Hanawa T.: Effects of chromium and nitrogen content on the microstructures and mechanical properties of as-cast Co–Cr–Mo alloys for dental applications, Acta biomaterialia, 8, 7(2012), 2856–2862.
19. Herman M., Ryniewicz A.M., Ryniewicz W .: Analiza czynników determinujących odporność na zużycie szkliwa. Pt. 1, Identyfikacja biologicznej i mechanicznej struktury szkliwa i jego kształtu w koronach zębów. Engineering of Biomaterials, 13, 95 (2010), 10–17.
20. Ryniewicz W., Herman M., Ryniewicz A.M .: Analiza odporności szkliwa na czynniki determinujące zużycie. Pt. 2, Badanie warstwy wierzchniej i mikrotwardości w szkliwie zębów. Engineering of Biomaterials, 14, 102 (2011), 23–27.
21. Henriques B., Soares D., Silva F.S.: Microstructure, hardness, corrosion resistance and porcelain shear bond strength comparison between cast and hot pressed CoCrMo alloy for metal–ceramic dental restorations, Journal of the mechanical behavior of biomedical materials, 12(2012), 83–92.
22. Wu L., Zhu H., Gai X., Wang Y.: Evaluation of the mechanical properties and porcelain bond strength of cobalt-chromium dental alloy fabricated by selective laser melting, The Journal of prosthetic dentistry, 111, 1(2014), 51–55.
23. Rodrigues W.C., Broilo L.R., Schaeffer L., Knörnschild G., Espinoza F.R.M.: Powder metallurgical processing of Co–28% Cr–6% Mo for dental implants: Physical, mechanical and electrochemical properties, Powder Technology, 206, 3(2011), 233–238.
24. España F.A., Balla V.K., Bose S., Bandyopadhyay A.: Design and fabrication of CoCrMo alloy based novel structures for load bearing implants using laser engineered net shaping, Materials Science and Engineering: C, 30, 1(2010), 50–57.
25. Bojko Ł., Ryniewicz A.M., Bogucki R., Pałka P.: Microstructural and strength studies Co-Cr-Mo alloy on prosthetic reconstructions in casting technology and laser sintering. Przegląd elektrotechniczny, 91(2015), 29–32.
26. Giacchi J.V., Morando C.N., Fornaro O., Palacio H.A.: Microstructural characterization of as-cast biocompatible Co– Cr–Mo alloys, Materials Characterization, 62, 1(2011), 53–61.
27. Ram G.J., Esplin C.K., Stucker B.E.: Microstructure and wear properties of LENS® deposited medical grade CoCrMo, Journal of Materials Science: Materials in Medicine, 19, 5(2008), 2105–2111.
28. Bojko Ł., Ryniewicz W., Ryniewicz A.M., Kot M.: Study of the impact of incremental technology on mechanical and tribological properties of biomaterials, Tribologia, 3(2017), 137–146.

29. Ryniewicz A., Ryniewicz W.: The Estimation of Selected Properties of Titanium to Performance of Prosthetic Restorations in CAD/CAM, Polish Journal of Enviromental Studies, 16, 6C(2007), 348–353.
30. Takaichi A., Nakamoto T., Joko N., Nomura N., Tsutsumi Y., Migita S., Hanawa T.: Microstructures and mechanical properties of Co–29Cr–6Mo alloy fabricated by selective laser melting process for dental applications, Journal of the mechanical behavior of biomedical materials, 21 (2013), 67–76.
31. Grądzka-Dahlke M., Dąbrowski J.R., Dąbrowski B.: Modification of mechanical properties of sintered implant materials on the base of Co–Cr–Mo alloy, Journal of materials processing technology, 204, 1(2008), 199–205.
32. Karaali A., Mirouh K., Hamamda S., Guiraldenq P.: Microstructural study of tungsten influence on Co–Cr alloys, Materials Science and Engineering: A, 390, 1(2005), 255–259.
33. Sato Y., Nomura N., Fujinuma S., Chiba A., Microstructure and tensile properties of hot-pressed Co-Cr-Mo alloy compacts for biomedical applications, Journal of the Japan Institute of Metals, 72, 7(2008), 532–537.