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TRIBOLOGICAL TESTS AND IMPACT TESTS OF ACRYLIC POLYMERS FOR DENTAL PROSTHETICS

BADANIA TRIBOLOGICZNE I PRÓBY UDAROWE POLIMERÓW AKRYLOWYCH DLA PROTETYKI STOMATOLOGICZNEJ

Key words: wear, coefficient of friction, impact resistance, acrylic tooth and gum supported dentures.

Abstract The clinical functionality of the prosthesis structure consists of creating the most convenient conditions without any traumatic effects of chewing forces on the substrate and adapting it to the individual biomechanical exclusions of the stomatognathic system (SS). When transferring functional loads, the optimization of tribological features and the ability to absorb energy is an important design and material parameter. The aim is to evaluate acrylic plastics intended for prostheses in terms of resistance to wear and resistance to movement in sliding contact within the environment of artificial saliva and their ability to absorb energy. Based on the analysis of the test results, it can be pointed out that Vertex is a good material for partial and complete dentures. Villacryl demonstrated similar properties, with Probase and Probase O being slightly worse. The appropriate mechanical parameters of the materials used in the prosthesis allow the production of thin plates that accurately reproduce the prosthetic substrate and improve the patient's comfort of use through such a fit.

Słowa kluczowe: akrylopolimery, protezy osiadające, zużycie, współczynnik tarcia, pochłanianie energii.

Streszczenie Funkcjonalność kliniczna konstrukcji protezy polega na stworzeniu najdogodniejszych warunków bezurazowego oddziaływania sił żucia na podłoże oraz dostosowania jej do indywidualnych wymuszeń biomechanicznych US. Przy przekazywaniu obciążeń czynnościowych istotnym parametrem konstrukcyjno-materiałowym jest optymalizacja cech tribologicznych oraz zdolność do pochłaniania energii. Celem jest ocena tworzyw akrylowych przeznaczonych na protezy w zakresie odporności na zużycie i oporów ruchu w kontakcie ślizgowym w środowisku sztucznej śliny oraz ich zdolności do pochłaniania energii. Na podstawie analizy wyników badań można wskazać, że Vertex jest dobrym materiałem do wykonywania protez częściowych i całkowitych. Zbliżone do niego właściwości posiadał Villacryl, a nieco gorsze Probase i Probase O. Odpowiednie parametry mechaniczne materiałów stosowanych na protezy pozwalają na wykonanie cienkich płyt, które dokładnie odwzorowują podłoże protetyczne i poprzez takie dopasowanie poprawiają pacjentowi komfort użytkowania.

INTRODUCTION

The functionality of the prosthesis is determined by clinical procedures, its manufacturing technology, the material being used, and its mechanical and strength parameters **[L. 1–4]**. Acrylic polymer resins are a group of materials intended for traditional, partial, and complete tooth and gum supported acrylic dentures (**Fig. 1**) **[L. 5–8]**. Despite the undoubted advantages in the area of providing chewing and aesthetics, acrylic structures often cause prosthetic stomatopathies and bone substrate atrophy **[L. 9, 10]**. The main cause of these ailments include overload and mucosal injury with occlusion forces generated in the stomatognathic system (SS) and laboratory performance errors (**Fig. 2**). The design of the prosthesis has a decisive role in prosthetic prophylaxis consisting of proper effects on the substrate, bone structure, and periodontium, the

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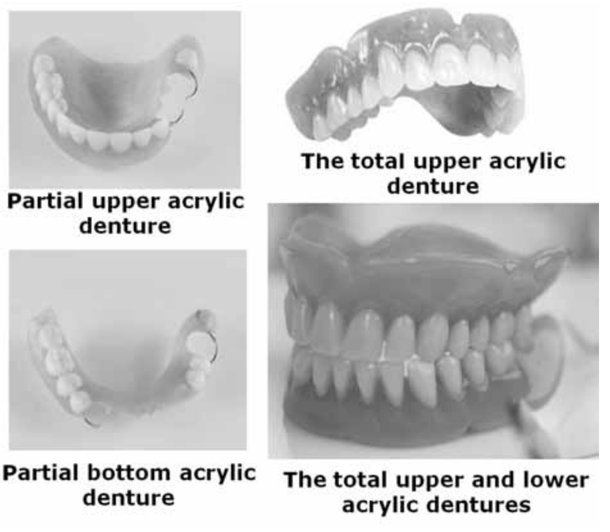

Fig. 1. Partial and complete acrylic dentures
Rys. 1. Częściowe i całkowite protezy akrylowe

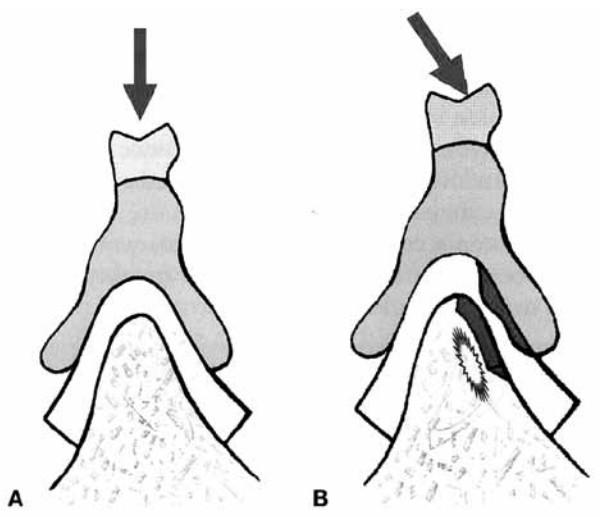

Fig. 2. Diagram presenting the effect of the loaded prosthesis plate on the prosthetic substrate tissues: a) the force causing an even distribution of pressure, b) the force causing plate trauma effect
Rys. 2. Schemat oddziaływania obciążonej płyty protezy na tkanki podłoża protetycznego: a) siła powodująca równomierny rozkład nacisków, b) siła, która powoduje urazowe oddziaływanie płyty

musculo-articular system, and preserved natural teeth. The clinical functionality of the prosthesis structure consists of creating the most convenient conditions without any traumatic effects of chewing forces on the substrate and adapting it to the individual biomechanical exclusions of the stomatognathic system (SS) **[L. 11––13]**. When planning the structures, optimal pressure distribution should be sought on the substrate, so that functional loads can be transferred evenly without exceeding the threshold of physiological tissue capacity. When transferring functional loads, the ability to absorb energy is an important structural and material parameter **[L. 14, 15]**. When preparing dentures, it is necessary to ensure the smoothness of the surface layer, especially directly adhering to the mucous membrane, as well as the mild, non-traumatic rim. Because of the foregoing issues, it is reasonable to research new acrylic materials used for prostheses and to determine their mechanical parameters after the laboratory preparation.

The aim is to evaluate acrylic plastics intended for prostheses in terms of resistance to wear and resistance to movement in sliding contact within the environment of artificial saliva and their ability to absorb energy in impact tests.

MATERIALS AND METHODS

The materials for the tests included the following (in accordance with PN-EN ISO 20795-1: 2013): Probase 0 (self-polymerizing material - polymerization at room temperature), Probase (thermal polymerization), Villacryl (thermal polymerization), and Vertex (thermal polymerization at increased pressure). Acrylate resins used in dental prosthetics are in powder (polymer) and liquid (monomer) forms. The polymerization process is decisive for the quality of the obtained material; therefore, the polymerization of the samples was carried out according to company regulations using a programmed polymerizer. Errors, especially at the stage of laboratory procedures, may reduce the properties of acrylic polymers **[L. 16]**.

Samples in the form of ø¼ inch discs with a thickness of 1/16 inches were prepared for tribological tests, 15 pieces for each material. The counter-samples were 1/2 inch ZrO_2 balls made with 0.13 µm deviation, according to ASTM F2094-02a standard. Samples and counter-samples were kept for 48 hours in saline solution. The tests of resistance to wear and the coefficient of friction in sliding contact were carried out in the presence of artificial saliva. Saliva is a medium with a high content of enzymes and plays an extremely important role in the lubrication of cooperating occlusion surfaces **[L. 17]**. Tribological tests were carried out on the Roxana Machine Works, using a friction pair consisting of a ball and three discs from the tested material (**Fig. 4**). Due to the tribological extortions present in the chewing conditions, the following test parameters were adopted:

– Rotational speed = 200 RPM±5 RPM,
– Operation temperature = 36.6°C±1°C,
– Load = 300 N±3N, and
– Duration = 30 min±5 s.

The average wear defect diameter was a measure of anti-wear properties of the tested materials. During the tests, continuous friction torque was recorded and, on this basis, the coefficient of friction was determined.

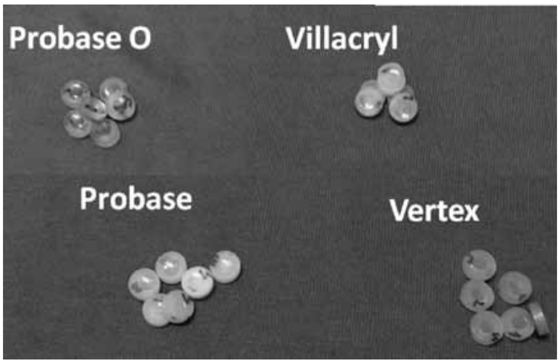

Fig. 3. Samples for tribological tests
Rys. 3. Próbki do badań tribologicznych

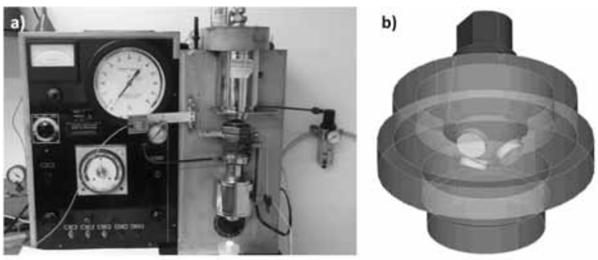

Fig. 4. Four Ball Wear Tester Brown from Roxana Machine Works: a) general view, b) friction pair
Rys. 4. Four Ball Wear Tester Brown firmy Roxana Machine Works: a) widok ogólny, b) węzeł tarcia

Cuboidal samples were prepared in order to test the energy absorption properties of the materials, with 6 pieces from each material (**Fig. 5**). The specimens had incised notches compliant with ISO 179-1 standard. The resistance of acrylic polymers to fracture under dynamic load was tested using the Charpy method. Impact bending of the sample was performed by hitting the sample supported on two supports with a hammer pendulum blade (**Fig. 6**).

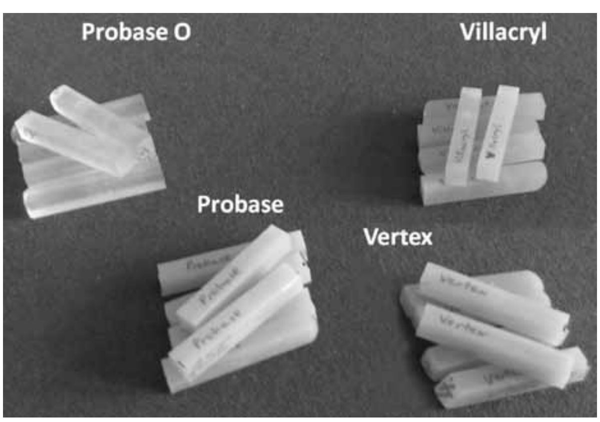

Fig. 5. Samples for impact tests
Rys. 5. Próbki do badań udarności

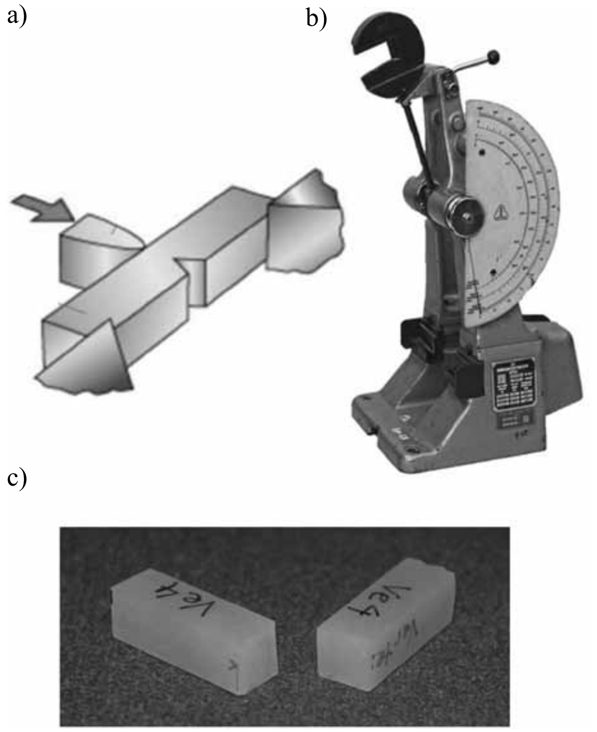

Fig. 6. Impact tests: a) sample load diagram, b) Charpy hammer, c) sample after breaking
Rys. 6. Próby udarności: a) schemat obciążenia próbki, b) młot Charpy'ego, c) próbka po złamaniu

The test results were statistically analysed using Statistica 13.1 software (StatSoft).

The following were determined:

1) Descriptive statistics (average, median, min, max, std. deviation);
2) Normality of variable distribution (Shapiro-Wilk, Kolmogorov-Smirnov test);
3) Analysis of variance tests (ANOVA); and,
4) Test of multiple post-hoc comparisons (Tukey, Bonferroni).

The statistical significance level was assumed as $p = 0.05$.

RESULTS

The results of the plastic wear resistance tests Probase O, Probase, Villacryl, and Vertex were the following: Vertex was characterized by the smallest diameter of the wear defect [**Fig. 7, Tab. 1**]. The Vertex defect was 2.94 mm. Other materials showed similar values in terms of the mean diameters of wear defect: Probase O - 3.55 mm, Probase - 3.63 mm, and Villacryl - 3.47 mm, respectively. The wear defects for these materials were within the range of 3.25-3.98 mm.

No clear differences in the nature of the course and in coefficients of friction were found in tests of resistance to motion in sliding friction in the presence of artificial saliva in the tested polymers. In case of the

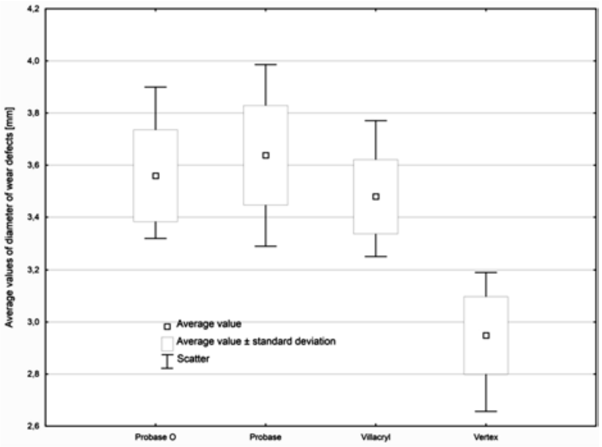

Fig. 7. Tests of wear resistance of acrylic materials
Rys. 7. Badania odporności na zużycie materiałów akrylowych

Table 1. Comparison of friction coefficient results for the materials tested
Tabela 1. Zestawienie wyników współczynnika tarcia dla badanych materiałów

Tested material	Statistical parameters for description				
	Number of samples	Average value	Minimum value	Maximum value	Standard deviation
Probase O	30	3.55	3.32	3.89	0.17
Probase		3.63	3.29	3.98	0.19
Villacryl		3.47	3.25	3.77	0.14
Vertex		2.94	2.65	3.18	0.14

materials, Probase O, Probase, Villacryl, and Vertex, at the beginning of the test period, the coefficients increased and reached the maximum and at the end of the trial stabilized within the range of 0.12-0.14. The highest maximum values (nearly 0.20) were achieved by two materials - Probase and Villacryl. For Vertex, the maximum value was at the level of 0.18, and for Probase O, the maximum value was at the level of 0.17 (**Fig. 8**).

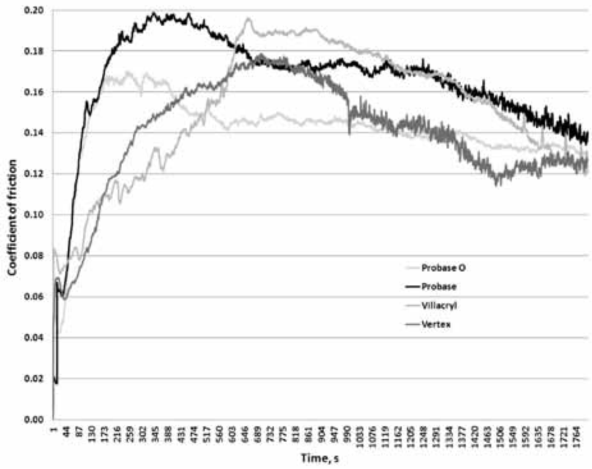

Fig. 8. Representative coefficients of frictions for the tested acrylic polymer composites in cooperation with ZrO_2
Rys. 8. Reprezentatywne współczynniki tarcia badanych tworzyw akrylopolimerowych we współpracy z ZrO_2

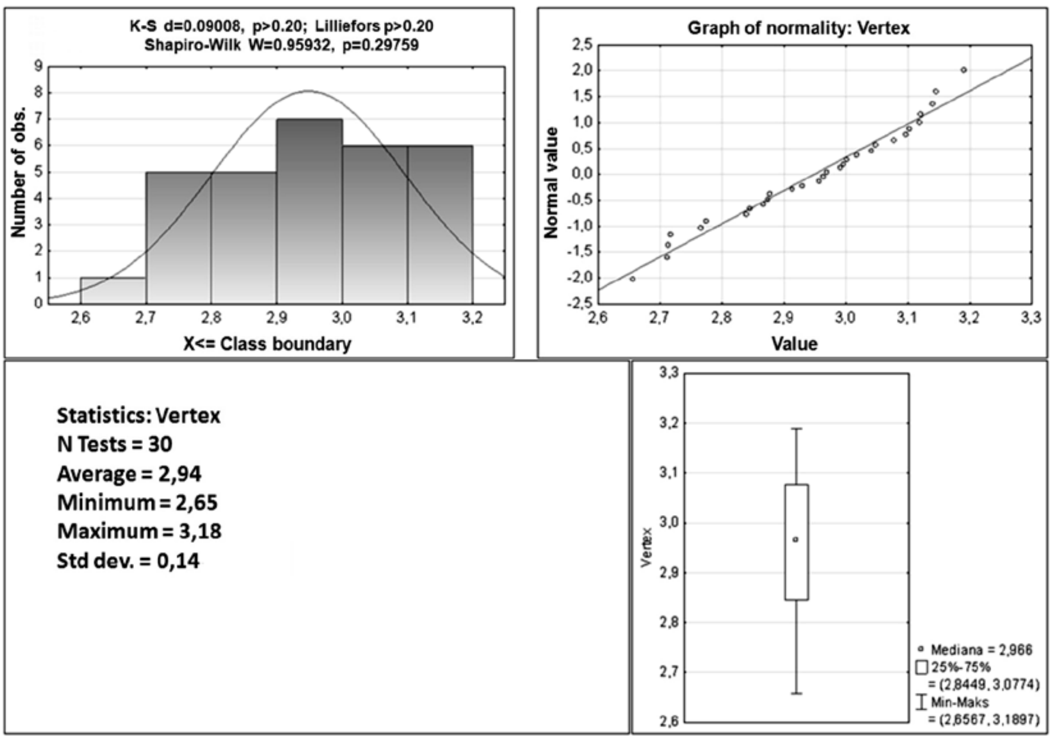

Fig. 9. Example analysis of the normality of the wear resistance distribution, determined by the mean diameters of wear defect, for the Vertex material
Rys. 9. Przykładowa analiza normalności rozkładu odporności na zużycie określonej średnią średnicą skazy dla materiału Vertex

The development of tests results was carried out with descriptive statistics tests. The normality of the distribution for the tested materials was verified, resulting in information that all variables demonstrated normal distribution (**Fig. 9**). *Post-hoc* tests showed that the groups Probase O, Probase, and Villacryl have no statistically significant differences. There were statistically significant differences between Vertex and the other groups.

Acrylic polymers, Probase O, Probase, Villacryl, and Vertex, were subjected to Charpy impact tests (**Tab. 2**). It has been shown that the highest energy absorption capacity at cracking was shown by Villacryl at 3.24 kJ/m^2, which was slightly lower than Vertex at 3.16 kJ/m^2. Probase O and Probase had lower and comparable values at cracking.

Table 2. List of test results for impact strength of acrylic materials on the Charpy hammer

Tabela 2. Zestawienie wyników badań udarności materiałów akrylowych na młocie Charpy'ego

Material	Average value of impact work, K [J]	The surface area of the sample in the place of the notch, S [cm²]	Impact strength, KC [kJ/m²]
Probase O	0.171	0.68	2.51
Probase	0.178		2.62
Villacryl	0.220		3.24
Vertex	0.215		3.16

DISCUSSION

The obtained results allowed us to compare and evaluate acrylic polymers in terms of using partial and complete tooth and gum based acrylic dentures **[L. 18, 19]**. The determined wear defects indicate that the highest resistance among the 4 tested materials is shown by Vertex, with a defect of 2.94 mm, and the remaining 3 materials demonstrate comparable resistance. The wear defects in Probase O, Probase, and Villacryl were within the range of 3.25–3.98 mm. The wear resistance of the tested polymers (with the same test parameters) was lower than the composites used to reconstruct the defects. Wear defects of nanocomposites, e.g., CeramX Sphere, Rok, Solitare, Charisma, and Empress Direct, ranged between 2.03 to 2.72 mm **[L. 17–22]**, Enamel Plus, Essentia, G-aenial, G-aenial FLO and Charisma Diamond are within the 1.80–2.44 mm range (paper publication in progress). The defects of acrylic polymers were similar to the resistance to wear of natural enamel, which was characterized by a 3.14 mm defect **[L. 17]**. It can be estimated that the coefficients of friction of the studied polymers demonstrate comparable and smaller values with respect to nanocomposites for direct reconstruction, which had coefficients of friction (at the same test parameters) within the range of 0.09–0.68 and approx. 3 times lower values compared to enamel, the coefficient of friction of which ranged from 0.48 to 0.62 **[L. 17]**. Tribological evaluation of both material groups (acrylic polymers and composites) indicates satisfactory parameters in dental applications **[L. 23–25]**. It is worth stressing the adjustment of properties to functioning within the SS.

Acrylic polymers, belonging to the group of viscoelastic materials, when used in structures affecting the mucous membrane, must be characterized by a much greater susceptibility, allowing the transfer of occlusal loads to a larger contact surface and their dampening and limiting the traumatic effects on the mucous and bone substrate **[L. 2, 3, 26]**. Such parameters ensure proper adaptive wear resistance with simultaneous reduction in the resistance to movement in sliding friction. In the conducted impact tests of acrylic polymers, Villacryl and Vertex demonstrated the best resistance to cracking. These materials differed from each other only slightly. The ability to absorb energy is a desired property, not only when securing the denture plate against cracking and breaking during hygienic procedures, but primarily in the conditions of its functioning in the SS **[L. 27]**. This feature is desirable in the one-sided chewing process in which flexion and balancing of the prosthesis plate may occur.

One could also point out the fatigue resistance curves determined for the materials Probase O, Probase, Villacryl, and Vertex (paper publication in progress) **[L. 28–31]**. The most durable of them in the aforementioned conditions (Vertex) had a resistance about 33% higher than the weakest Villacryl. It should be emphasized that the polymerization of acrylics was performed in professional procedures at the Jagiellonian University Medical College Institute of Dentistry Laboratory, and one can be sure about the impartiality of the performed laboratory processes.

CONCLUSIONS

Based on the analysis of the test results, it can be indicated that Vertex is an appropriate material for partial and complete dentures. Villacryl demonstrated similar properties, with Probase and Probase O being slightly worse.

Acrylic polymers used in dental prosthetics must meet a number of requirements; however, for the sake of clinical functionality, tribological and resistance assessment of materials used for these structures is very important.

For acrylic polymers, it is important to combine wear resistance with a simultaneous energy absorption capacity and fatigue strength.

The appropriate mechanical parameters of the materials used in the prosthesis allow the production of thin plates that accurately reproduce the prosthetic substrate and improve the patient's comfort of use through such a fit.

The ability to absorb energy and fatigue resistance in newly developed materials should be considered as the characteristics of acrylic materials that are important in the conditions of functioning in the SS.

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REFERENCES

1. Shetty M.S., Shenoy K.K.: An in vitro analysis of wear resistance of commercially available acrylic denture teeth. The Journal of Indian Prosthodontic Society, 10, 3(2010), 149–153.
2. Faur N., Bortun C., Marsavina L., Cernescu A., Gombosi O.: Durability studies for complete dentures. In Key Engineering Materials, 417(2010), 725–728. Trans Tech Publications.
3. Singh J.P., Dhiman R.K., Bedi R.P.S., Girish S.H.: Flexible denture base material: A viable alternative to conventional acrylic denture base material. Contemporary clinical dentistry, 2, 4(2011), 313.
4. Acosta-Torres L.S., López-Marín L.M., Nunez-Anita R.E., Hernández-Padrón G., Castaño V.M.: Biocompatible metal-oxide nanoparticles: nanotechnology improvement of conventional prosthetic acrylic resins. Journal of Nanomaterials, 12(2011).
5. Burgess J., Cakir D.: Comparative properties of low-shrinkage composite resins. Compendium of continuing education in dentistry, 31(2010), 10–15.
6. Braden M., Clarke R.L., Nicholson J., Parker S.: Polymeric dental materials. Springer Science & Business Media, 2012.
7. Reyes-Sevilla M., Kuijs R.H., Werner A., Kleverlaan C.J., Lobbezoo F.: Comparison of wear between occlusal splint materials and resin composite materials. Journal of oral rehabilitation, 45, 7(2018), 539–544.
8. Majewski S.W.: Współczesna protetyka stomatologiczna. Podstawy teoretyczne i praktyka kliniczna. Elsevier Urban & Partner publishing house, Wrocław, 2014.
9. Gebelein C., Koblitz F.: Biomedical and dental applications of polymers. Springer Science & Business Media, 14, 2013.
10. Gautam R., Singh R.D., Sharma V.P., Siddhartha R., Chand P., Kumar R.: Biocompatibility of polymethylmethacrylate resins used in dentistry. Journal of Biomedical Materials Research Part B: Applied Biomaterials, 100, 5(2012), 1444–1450.
11. Stober T., Henninger M., Schmitter M., Pritsch M., Rammelsberg P.: Three-body wear of resin denture teeth with and without nanofillers. Journal of Prosthetic Dentistry,103, 2(2010), 108–117.
12. Heintze S.D., Zellweger G., Grunert I., Muñoz-Viveros C.A., Hagenbuch K.: Laboratory methods for evaluating the wear of denture teeth and their correlation with clinical results. Dental Materials, 28, 3(2012), 261–272.
13. Stober T., Heuschmid N., Zellweger G., Rousson V., Rues S., Heintze S.D.: Comparability of clinical wear measurements by optical 3D laser scanning in two different centers. Dental Materials, 30, 5(2014), 499–506.
14. da Cruz Perez L.E., Machado A.L., Canevarolo S.V., Vergani C.E., Giampaolo E.T., Pavarina A.C.: Effect of reline material and denture base surface treatment on the impact strength of a denture base acrylic resin. Gerodontology, 27, 1(2010), 62–69.
15. Mowade T.K., Dange S.P., Thakre M.B., Kamble V.D.: Effect of fiber reinforcement on impact strength of heat polymerized polymethyl methacrylate denture base resin: in vitro study and SEM analysis. The journal of advanced prosthodontics, 4, 1(2012), 30–36.
16. Abdulwahhab S.S.: High-impact strength acrylic denture base material processed by autoclave. Journal of prosthodontic research, 57, 4(2013), 288–293.
17. Ryniewicz W., Herman M., Ryniewicz A.M., Bojko Ł., Pałka P., Ryniewicz A., Madej T.: Tribological tests of the nanomaterials used to reconstruct molars and premolars with the application of the direct method. Tribologia, 3(2017), 155–164.
18. Meng G.K., Chung K.H., Fletcher-Stark M.L., Zhang H.: Effect of surface treatments and cyclic loading on the bond strength of acrylic resin denture teeth with autopolymerized repair acrylic resin. The Journal of prosthetic dentistry, 103, 4(2010), 245–252.
19. Alla R.K., Sajjan S., Alluri V.R., Ginjupalli K., Upadhya N.: Influence of fiber reinforcement on the properties of denture base resins. Journal of Biomaterials and Nanobiotechnology, 4, 1(2013), 91.
20. Ghazal M., Kern M.: Wear of denture teeth and their human enamel antagonists. Quintessence International, 41, 2(2010).
21. Friedrich K., Schlarb A.K.: Tribology of polymeric nanocomposites: friction and wear of bulk materials and coatings, 55(2011). Elsevier.

22. Suwannaroop P., Chaijareenont P., Koottathape N., Takahashi H., Arksornnukit M.: In vitro wear resistance, hardness and elastic modulus of artificial denture teet. Dental materials journal, 30, 4(2011), 461–468.
23. 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.
24. Ryniewicz W., Ryniewicz A.M., Bojko Ł.: Modelowanie koron i ocena dokładności odwzorowania kształtu filarów protetycznych. Przegląd Elektrotechniczny, 90, 5(2014), 146–149.
25. Ryniewicz W., Ryniewicz A.M., Bojko Ł.: Ocena szczelności koron protetycznych w zależności od technologii ich wykonania. Przegląd Elektrotechniczny, 91, 5(2015), 45–48.
26. Lee H.H., Lee C.J., Asaoka K.: Correlation in the mechanical properties of acrylic denture base resins. Dental materials journal, 31, 1(2012), 157–164.
27. Ajaj-ALKordy N.M., Alsaadi M.H.: Elastic modulus and flexural strength comparisons of high-impact and traditional denture base acrylic resins. The Saudi dental journal, 26, 1(2014), 15–18.
28. Asar N.V., Albayrak H., Korkmaz T., Turkyilmaz I.: Influence of various metal oxides on mechanical and physical properties of heat-cured polymethyl methacrylate denture base resins. The journal of advanced prosthodontics, 5, 3(2013), 241–247.
29. Gurbuz O., Unalan F., Dikbas I.: Comparative study of the fatigue strength of five acrylic denture resins. Journal of the mechanical behavior of biomedical materials, 3, 8(2010), 636–639.
30. Kappert P.F., Kelly J.R.: Cyclic fatigue testing of denture teeth for bulk fracture. Dental Materials, 29, 10(2013), 1012–1019.
31. Salih S.I., Oleiwi J.K., Hamad Q.A.: Investigation of fatigue and compression strength for the PMMA reinforced by different system for denture applications. International Journal of Biomedical Materials Research, 3, 1(2015), 5–13.