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Acrylic resins for manufacturing dental prosthetic restorations – microstructural, micromechanical and tribological tests

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Abstract. When planning and manufacturing a removable dental prosthesis, efforts should be made to optimally distribute pressure without exceeding the threshold of physiological capacity of tissues, especially since this type of restoration often causes prosthetic stomatopathies and atrophy of the bone substrate. The aim is to evaluate acrylic prosthetic structures in terms of microstructure, micromechanical parameters, resistance to movement in sliding friction, and wear resistance in the environment of physiological saline and artificial saliva. The research material are removable prosthetic restorations made of acrylic resins manufactured in the Materials Science Laboratory at the Department of Dental Prosthetics of the Jagiellonian University Medical College. The clinical functionality of the restoration consists of adapting to individual biomechanical forces and creating the most favorable conditions for proper occlusion. Microstructure tests allowed the identification of the surface layer in wear defects and indicated the Vertex Rapid Simplified material as the least susceptible to internal defects and cracks, which may constitute potential places for the growth of fungi and bacteria. Micromechanical tests showed similar values of microhardness and longitudinal elastic moduli of the biomaterials tested. They may determine the strength and extent of the plate. Premacryl Plus had different and lower micromechanical parameters. Tribological tests allowed a positive assessment of the effect of saliva on friction coefficients and forces. Reducing its value protects the tissues of the prosthetic base against the irritating effects of forces generated by the restoration under chewing and occlusion conditions.

Key words: Removable dental prosthesis; microstructure; microhardness; friction coefficient; wear

1. INTRODUCTION

Acrylic resins are widely used in reconstructive dentistry for the production of denture plates, artificial teeth, materials for denture repairs, individual custom trays, temporary reconstructions, and maxillofacial epitheses [1-3]. The clinical functionality of removable structures consists of creating the most favorable conditions for proper occlusion, without the traumatic impact of masticatory forces on the prosthetic base, and adapting to individual biomechanical forces without shifting or damaging the mucous membrane. Biomaterials for these structures should be characterized by: strength and durability, satisfactory thermal conductivity properties, accuracy of the shapes produced and shape-dimensional stability, chemical inertness in the oral environment and low liquid sorption, lack of taste and odor, biocompatibility, aesthetics, adhesion to polymeric materials, metals, and ceramics, and moderate cost and repairability [4-8]. Manufacturers of these materials indicate many characteristics, but experimentally determined indications are valuable, allowing optimal choice of material and manufacturing technique in clinical applications [9-15]. In recent years, work has been carried out on improving the microstructural, mechanical and tribological parameters of acrylic resins modified with various types of fibers, fillers and nanofillers [1, 3, 6-8]. In the conditions of transferring functional loads and the need to evaluate the impact of the structure on the stomatognathic system (SS), important criteria are the mesial and distal resistance of the prosthesis plate, the correct microstructure of the manufactured restorations, the appropriate biomechanical parameters and the ensure a surface layer compatible with oral tissues [6, 8, 16]. When planning and manufacturing the structure, efforts should be made to optimally distribute the pressure on the substrate so that the masticatory loads can be evenly transferred, without exceeding the threshold of the physiological capacity of the tissues, especially since this type of structure often causes prosthetic stomatopathies and atrophy of the bone substrate [17, 18]. The main cause of these symptoms is overload and

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trauma to the mucous membrane caused by occlusive forces generated in SS.

Prosthetic stomatopathy is an inflammatory process of the prosthetic base mucous membrane of varying severity and complex etiology, with the predominant involvement of mechanical trauma from the prosthesis and fungal infection [19-22]. It manifests itself with swelling, pain, bleeding, and taste disturbances.

Mechanical trauma is considered the most common etiological factor of stomatopathy. It may result from the following:

- incorrect design of the prosthesis and insufficient smoothness of the mucosal surface of the denture plate or bridge pontics (Fig. 1),
- incorrect course of the clasps (Fig.2a),
- too long and wide edges of prosthetic crowns (Fig.2b),
- individual predispositions.

The design of the prosthesis has a decisive role in influencing the substrate, bone and periodontal structures, the musculoskeletal system, and the preserved natural teeth. Optimization of the structure requires a holistic approach [23-28]. The basic issues are clinical solutions that ensure functionality, but not less important is the biomechanical and biotribological context, which includes analysis of restoration contact in the oral cavity itself, adhesion of structures and tissue structures, rheological processes in layer contact: the supporting surface of the prosthesis - saliva - mucous membrane [29-34].

Currently, a prosthetist who is to make a prosthetic restoration uses one of the materials available on the market, without having full data on its microstructural, micromechanical or tribological parameters. He can only base himself on information provided by manufacturers, but experimentally determined indications are more valuable. Only a broader perspective on the parameters allows for the optimal selection of a material for clinical applications. In other research centers, the authors conducted tests on selected mechanical and tribological parameters of various acrylic and composite resins, often modified with fibers, fillers and nanofillers, but there are no reports on studies on currently commercially used acrylic resins. The aim of the study was to evaluate acrylic prosthetic structures in terms of microstructure, micromechanical parameters, resistance to movement in sliding friction, and wear resistance in the environment of physiological saline and artificial saliva, which may be an indication for the prosthetist to use a specific material for prosthetic restorations.

Fig.1. The Impact of an incorrect prosthesis construction and insufficient smoothness of the mucosal surface

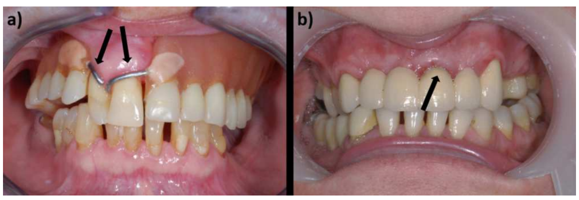

Fig.2. Mechanical injury caused by: a) incorrect placement of the clasps, b) too long and wide edge of the prosthetic crowns

2. MATERIALS AND METHODS

The research material includes removable prosthetic restorations made of acrylic resins intended for denture plates and acrylics for dentures, polymerized according to the manufacturers' recommendations, manufactured in the Laboratory of Materials Science and Dental Technology, Department of Dental Prosthetics, Institute of Dentistry, Faculty of Medicine, Jagiellonian University Medical College. For microstructural, micromechanical and tribological tests of acrylic polymers intended for denture plates and for their repair, samples were made in the shape of ϕ1/4 inch (6.35 mm) discs with a thickness of 1/16 inch (1.59 mm), 15 pieces of each material. The polymers had valid certificates of use. They were made from the following biomaterials:

1. ProBase Hot Pink (Ivoclar Vivadent, Schaan, Liechtenstein) - intended for denture plates. The samples were hot polymerized using the flasking procedure. The framed can was placed in a pot of cold water. The water was heated to 100 ° C. The boiling was maintained for 45 minutes.
2. Vertex Rapid Simplified (Vertex Dental B.V., Soesterberg, Netherlands) – intended for full and partial denture foundations. It is characterized by short-term polymerization using the pressing technique. Starting polymerization in warm water, polymerization at 100 ℃ for 20 minutes.
3. ProBase Cold Polymer Pink (Ivoclar Vivadent, Schaan, Liechtenstein), a self-polymer intended for repairing and rebasing, can be used for denture plates. Polymerization using the infusion technique was carried out on a pressure apparatus for 15 minutes at a temperature of 40 °C and a pressure of 5 bar.
4. Vertex Self – Curing (Vertex Dental B.V. , Soesterberg, Netherlands) – self-polymer intended for the repair and rebasing of dentures. It was briefly polymerized for 10 minutes at a temperature of 45-55ºC and a pressure of 2.5 bar.
5. Villacryl SP V4 (Zhermack Dental, Badia Polesine, Italy) - self-polymer intended for the fabrication of acrylic parts in frame dentures, as well as for the manufacture of full dentures using the infusion method. It can also be used to repair dentures or to make temporary or immediate dentures. The samples were taken using the infusion technique. Polymerized for 20 minutes at 65 °C under a pressure of 2 bar.

6. Premacryl Plus (SpofaDental, Jicin, Czech Republic) - a self-polymer intended for immediate dentures and for repairs of removable dentures. Samples were polymerized at a temperature of 50-60 ºC, 15 minutes at a pressure of 0.2-0.3 MPa.

In addition, microstructural and micromechanical tests of removable prosthetic restorations were carried out. Denture plates were made of ProBase Hot Pink polymer and Gnathostar teeth were used for the lateral section, in accordance with the recommendations of Ivoclar Vivadent. The prostheses were made using hot polymerization using the flasking procedure. After standard processing and polishing, they were intended for further research. The prosthesis fragments were separated:

- In a plane perpendicular to the alveolar arch, including the tooth, its attachment to the plate, and part of the plate contacting the alveolar process of the mandible (Fig. 3a).
- By cutting from the vestibular side, the internal structure and the attachment of the teeth to the denture plate in the plane tangential to the arch were exposed (Fig. 3b).

To perform microstructural and micromechanical tests, the cut fragments were stabilized in resin and polished using a Struers TegraForce-5 device. Using programmed operations, the surface layer required for the testing was achieved.

Microstructural analyzes were performed on a Zeiss Stemi 508 optical microscope and a Hitachi S3400N scanning electron microscope. The microstructure of the surface layer before the wear process and in the wear defect zone was evaluated using a Hitachi S-3400N scanning microscope after carbon sputtering.

Micromechanical properties tests, which included measurements of microhardness and Young's modulus in selected cross sections, were carried out on the NHT^3 device from Anton Paar. They were determined by using a Berkovich indenter. In the measurements, the force and penetration depth values of the blade were continuously recorded during the loading and unloading cycle. 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 indenter load was determined as a function of the penetration depth. The analysis of micromechanical properties was based on the Oliver and Pharr method, according to which the microhardness (HV) and elastic modulus of the tested material (E) were calculated from the indentation curve. Micromechanical parameters for each of the discussed materials were determined as the average of 8 measurements for selected cross sections.

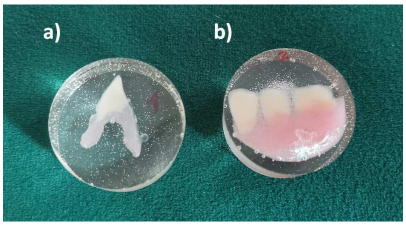

Fig.3. Fragments of the denture intended for testing: a) structure obtained by cutting with a plane perpendicular to the mandibular arch, b) structure obtained by cutting with a plane tangential to the mandibular arch

Tribological tests were performed on a Roxana Machine Works machine, using a friction node of the ball - three disc made of the tested material. Countersamples were standard Sø 1/2" (12.70 mm) ceramic balls made of zirconium oxide, made with a deviation of 0.00013 mm according to ASTM F2094-02a. The discs and countersamples were moistened for 48 hours prior to test - samples from the first group were immersed in physiological saline, and in the second group a commercial preparation of artificial saliva Kserostemin was used.

The geometry of the sliding test node approximated the spatial arrangement found in SS (Fig. 4) [28]. It allowed the imitation of the change in wear intensity observed in in vivo tests, which is associated with an increase in the contact surface area. The tests were performed in the first group in a physiological saline environment and in the second group in an artificial saliva environment, with the following parameters:

- rotational speed n=200 rpm ± 5 rpm,
- operating temperature 36.6°C ± 1°C,
- load P=400 N ± 3N,
- duration 15 min ± 5 s.

The measure of the anti-wear properties of the tested materials was the average diameter of the wear flaw. During the test, the friction torque was continuously recorded, and the friction coefficients were determined on this basis.

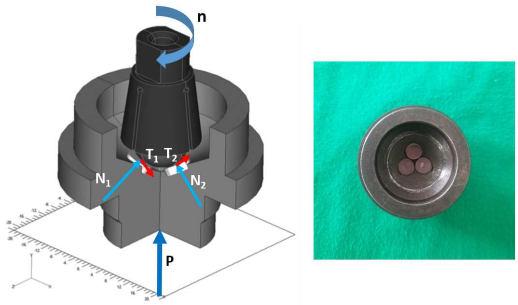

Fig.4. Spatial system of forces in the friction node and a set of 3 discs after the test

3. TEST RESULTS

A. Microstructural studies.

Based on the optical and scanning tests carried out, the microstructures of the surface layer of the discs were determined, wear defects were measured, and their structures were analyzed (Figs. 5 and 6). Optical microscopy tests locate the structure of the surface layer in the defect (Fig. 5). SEM analysis in wear resistance tests allows us to show differences in the size of the defect, but also identifies the surface layer in the defect. Defects in the surface layer, free from flaws, were found for the Vertex Rapid Simplified material. Only minor scratches are visible. There are cracks and delaminations in other materials. A particularly exfoliated and cracked structure is visible in Villacryl SP V4 and Premacryl Plus. Thus, cracks, delaminations, peelings, and empty spaces found in defects may weaken the structure and constitute potential places for

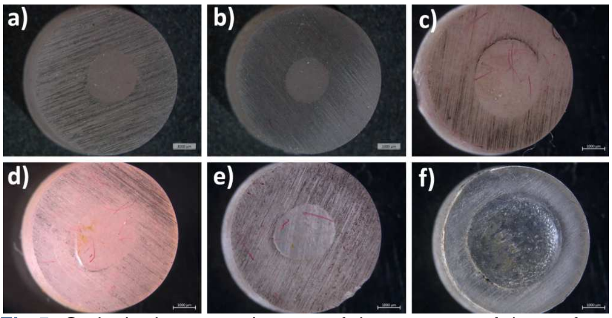

Fig.5. Optical microscopy images of the structure of the surface layer in the defect of discs from: a) ProBase Hot Pink, b) Vertex Rapid Simplified, c) ProBase Cold Polymer Pink, d) Vertex Self Curing, e) Villacryl SP V4, f) Premacryl Plus

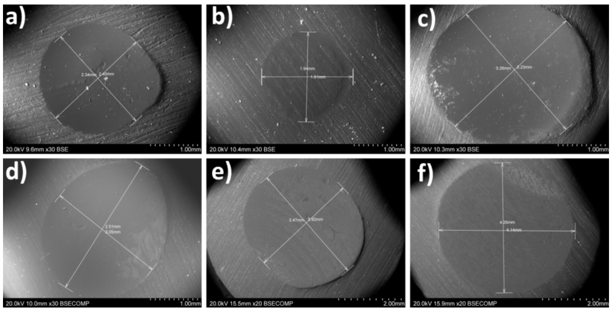

Fig.6. SEM images of the structure, along with defect measurements, of discs from: a) ProBase Hot Pink, b) Vertex Rapid Simplified, c) ProBase Cold Polymer Pink, d) Vertex Self Curing, e) Villacryl SP V4, f) Premacryl Plus

the accumulation of bacteria and fungi. Such defects create the possibility of their multiplication and pathological impact on the oral mucosa. As a consequence, they can cause inflammation and mycosis.

B. Micromechanical tests.

Micromechanical tests were preceded by tests using a Zeiss Stemi 508 optical microscope of cut denture structures in areas characteristic of the denture structure (Fig. 7). Three research areas were selected in these cross-sections: the tooth, the tooth-plate connection and the plate. The following cross sections were made for microscopic analysis: cross sections in a plane perpendicular to the mandibular arch through the attached tooth and the plate from the buccal and lingual side, and cross sections in a plane tangential to the mandibular arch through acrylic teeth and the plate in the lingual view. Microscopic images confirmed the correct attachment of the teeth to the denture plates, proving that the polymerization process is taking place properly.

Micromechanical tests were carried out: microhardness and longitudinal modulus of elasticity in cross sections through the

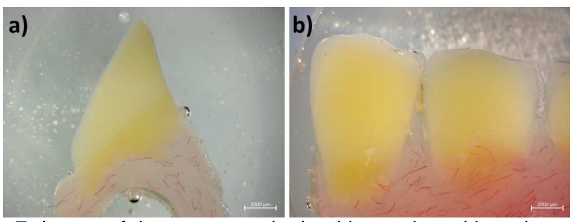

Fig.7. Image of the structure obtained by cutting with a plane: a) perpendicular to the mandibular arch, b) tangential to the mandibular arch

internal structures of the prostheses (Tables 1 and 2). Young's moduli in the cross-sections were very similar. The average value was 4.30 GPa. This proves the homogeneity of the materials for the teeth, the material of the plates, and the correct connection of the teeth with the plate in the polymerization process. No defects were found in the connections analyzed that stabilize the teeth in the denture. The highest microhardness was observed in teeth in axial sections in planes tangential to the alveolar arch - 226.35 GPa and perpendicular - 232.39 MPa.

TABLE 1. List of micromechanical parameters of the prosthesis in the cross section in a plane perpendicular to the alveolar arch

Material of tests	Metrology parameters	Hardness [HV]	Hardness HiT [MPa]	Young's modulus E [GPa]	Depth of penetration hmax [nm]
Tooth	Average value	21.52	232.39	4.45	6721.82
	Standard deviation	0.24	2.60	0.04	40.22
Tooth - Plate Connection	Average value	20.58	222.20	4.38	6851.98
	Standard deviation	0.32	3.48	0.02	39.84
Plate	Average value	20.09	216.92	4.30	6936.10
	Standard deviation	0.01	0.08	0.01	2.06

TABLE 2. List of micromechanical parameters of the prosthesis in the cross section with a plane tangential to the alveolar arch

Material of tests	Metrology parameters	Hardness [HV]	Hardness HiT [MPa]	Young's `modulus E [GPa]	Depth of penetration hmax [nm]
Tooth	Average value	20.96	226.35	4.24	6830.59
	Standard deviation	0.13	1.38	0.03	21.22
Tooth - Plate Connection	Average value	20.76	224.11	4.23	6862.93
	Standard deviation	0.05	0.55	0.01	6.81
Plate	Average value	20.88	225.44	4.22	6852.01
	Standard deviation	0.32	3.47	0.02	43.22

In addition, micromechanical tests were performed on a wider group of biomaterials intended for denture plates. The results of these studies can be presented in three groups (Table 3, Fig. 8):

- the highest and similar values in the range from 244.56 MPa to 250.95 MPa were recorded by ProBase Hot Pink, Vertex Rapid Simplified, and Villacryl SP V4,
- lower, but also similar values ranging from 234.53 MPa to 237.13 MPa had ProBase Cold Polymer Pink and Vertex Self – Curing,
- Premacryl Plus had the lowest and different microhardness value, 202.87 MPa.

The test results for Young's modulus, which characterizes the elasticity of acrylics, were similar in the range of 4.48 GPa to 4.63 GPa for the analyzed group of materials, except for Premacryl Plus, which had a lower Young's modulus value, 4.14 GPa.

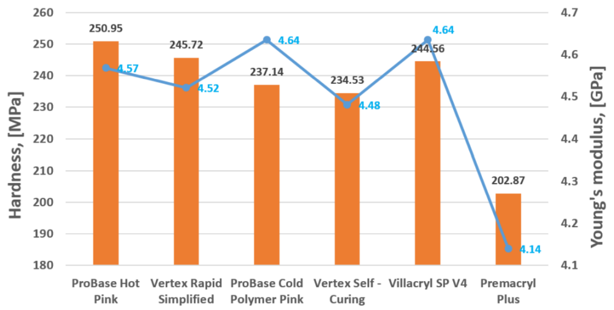

Fig.8. Microhardness graph and Young's modulus of acrylic resins for denture plates

TABLE 3. List of micromechanical parameters of acrylic resins for denture plates

Material of tests	Metrology parameters	Hardness [HV]	Hardness HiT [MPa]	Young's modulus E [GPa]	Depth of penetration hmax [nm]
ProBase Hot Pink	Average value	23.24	250.95	4.57	6507.97
	Standard deviation	23.24	1.20	0.01	9.79
Vertex Rapid Simplified	Average value	22.76	245.72	4.52	6570.46
	Standard deviation	0.06	0.65	0.01	8.31
ProBase Cold Polymer Pink	Average value	21.96	237.14	4.64	6637.16
	Standard deviation	0.06	0.63	0.04	10.61
Vertex Self – Curing	Average value	21.72	234.53	4.48	6691.13
	Standard deviation	0.16	1.75	0.01	22.53
Villacryl SP V4	Average value	22.65	244.56	4.64	6557.12
	Standard deviation	0.07	0.74	0.02	11.64
Premacryl Plus	Average value	18.79	202.87	4.14	7116.00
	Standard deviation	0.21	2.29	0.02	41.49

C. Tribological tests.

The results of tribological tests of materials intended for denture plates made of 6 different materials, in cooperation with ZrO_2, showed different degrees of friction coefficients both in the physiological saline environment (Fig. 9) and in the presence of artificial saliva (Fig. 10).

In the case of tribological tests performed in a physiological saline environment, a similar nature of the course of friction coefficients can be observed. All materials first achieved the maximum value of friction coefficients, and then the value of friction coefficients decreased until they stabilized in the final phase. Taking into account the final phase of the study, the materials are arranged into 3 groups.

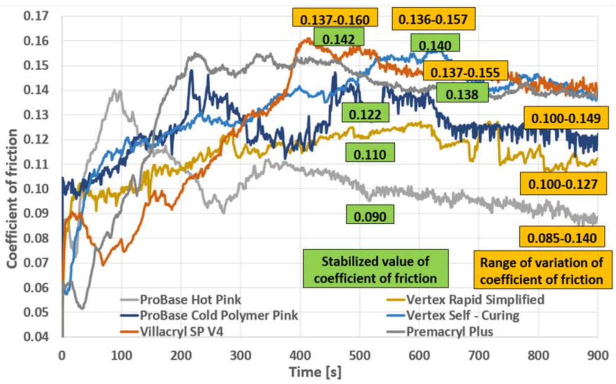

Fig.9. Sliding friction coefficients of acrylic polymers in physiological saline

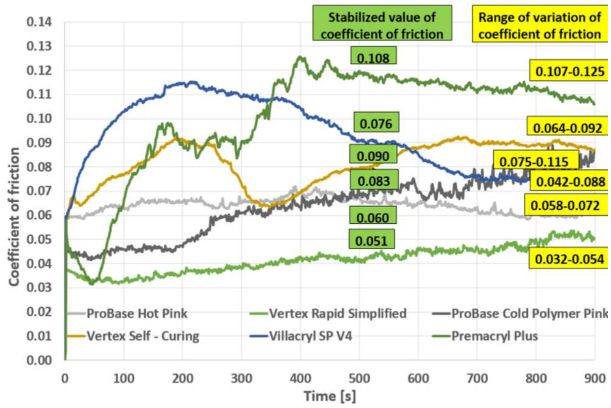

Fig.10. Sliding friction coefficients of acrylic polymers in artificial saliva

The group with the lowest friction coefficient values includes ProBase Hot Pink, which had friction coefficients from 0.085 to 0.140, and after stabilization at the level of 0.090.

The group with higher friction coefficient values included Vertex Rapid Simplified and ProBase Cold Polymer Pink. In the case of Vertex Rapid Simplified, the friction coefficients during the test were in the range of 0.100-0.127 and stabilized at 0.110. In turn, ProBase Cold Polymer Pink denture materials had friction coefficients throughout the test range of 0.100-0.149, which stabilized in the final phase at the level of 0.122.

The third group with the highest friction coefficient values included the following polymers: Vertex Self - Curing, Villacryl SP V4 and Premacryl Plus. In the case of Vertex Self-Curing acrylic plates, the friction coefficients were in the range of 0.136-0.157 and stabilized at 0.140. For Villacryl SP V4, the friction coefficients were in the range of 0.137-0.160 and in the final phase they reached the value of 0.142. In turn, for Premacryl Plus, the friction coefficients were in the range of 0.137-0.155 and stabilized at the level of 0.138.

In tribological tests in the presence of artificial Kserostemin saliva, characteristic variations were observed in the course of the friction coefficient values. It is possible to distinguish materials that had a similar stabilized course of coefficients throughout the research period. These materials include: Vertex Rapid Simplified and ProBase Hot Pink. In the second group of materials, the friction coefficients increased and only in the final phase of the test did stabilization occur, namely ProBase Cold Polymer Pink and Vertex Self - Curing. In the remaining test nodes, first achieved the maximum values of friction coefficients, and then these values decreased until they stabilized in the final phase - Villacryl SP V4 and Premacryl Plus. Taking into account the final phase of the study, it can also be observed that the materials are arranged in 3 groups.

The first group consisted of materials with the lowest friction coefficients: Vertex Rapid Simplified and ProBase Hot Pink. These materials were obtained by hot polymerization. In the case of Vertex Rapid Simplified, the friction coefficients throughout the test range were in the range of 0.032-0.054 and stabilized at the level of 0.051. In turn, in the case of the ProBase Hot Pink material, higher values of friction coefficients were observed, but the most stable course of all the materials tested over the entire research range was 0.058-0.072 and stabilized at 0.060.

The second group with slightly higher friction coefficient values were Villacryl SP V4, ProBase Cold Polymer Pink, and Vertex Self – Curing materials. During the test, Villacryl SP V4 denture plates had friction coefficients ranging from 0.042 to 0.088. In the final phase, these coefficients amounted to 0.076. In the case of ProBase Cold Polymer Pink, the friction coefficients throughout the test range were 0.075-0.115 and stabilized at 0.083. In turn, Vertex Self – Curing had friction coefficients during the test in the range of 0.064-0.092, which stabilized at 0.090.

The last group was the material with the highest friction coefficient value - Premacryl Plus. Throughout the research range, it had the highest friction coefficients among all tested materials, in the range of 0.107-0.125, and they stabilized at the value of 0.108.

The results of the wear resistance tests of the plates materials were evaluated on the basis of the average diameter of the wear defect (Fig. 11). The highest wear resistance under sliding friction conditions in the presence of saline was found for the following materials: ProBase Hot Pink - the average diameter of the wear defect was 2.60 mm and Vertex Rapid Simplified - the average diameter of the wear defect was 2.64 mm. In turn, the lowest wear resistance was found for the Premacryl Plus sample - the average diameter of the wear defect was 3.93 mm. When the artificial saliva preparation Kserostemin was used in the test nodes, significantly lower values of wear defects were observed. The highest wear resistance was found for the following materials: Vertex Rapid Simplified - the average diameter of the wear defect was 1.93 mm. The following materials were characterized by poorer wear resistance: ProBase Hot Pink - average defect diameter was 2.23 mm, Vertex Self - Curing - defect 2.32 mm, ProBase Cold Polymer Pink - 2.47 mm, and Villacryl SP V4 – 2.58 mm. Premacryl Plus demonstrated the lowest wear resistance of all the tested materials, for which the average diameter of the wear defect was found to be 3.17 mm.

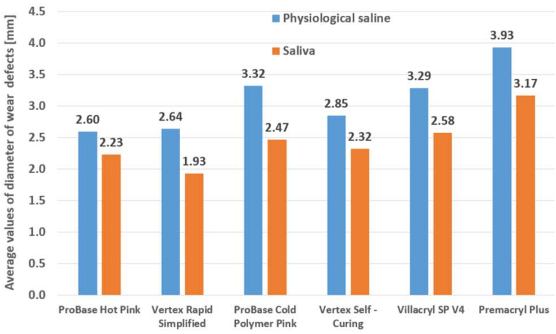

Fig.11. Wear resistance in sliding friction of acrylic resins on denture plates, in the presence of physiological saline and artificial saliva

4. Discussion

In the conditions of transferring functional loads and the need to evaluate the impact of the structure on SS, important criteria are the correct microstructure of the manufactured restorations, appropriate mechanical parameters and surface layers of the prosthesis compatible with oral tissues. Compatibility with tissues is determined by friction coefficients that ensure micro-slips without disturbing the structure of the mucous membrane and ensure the generation of optimal friction forces under chewing conditions, which will be balanced by the interaction of the substrate in the presence of physiological saline or artificial saliva. Another important parameter is the wear resistance of the denture plate and teeth [28].

Comparison of test results with studies by other authors was difficult, because our tests analyzed modern commercial acrylic resins dedicated to the production of prosthetic restorations. Comprehensive micromechanical and tribological tests were conducted, which may indicate to the prosthetist to use a specific material for prosthetic restorations. In other research centers, the authors conducted tests of selected mechanical and tribological parameters of various acrylic and composite resins, often modified with fibers, fillers and nanofillers. Dayan et al. [35] compared different acrylic and composite materials with respect to microhardness and wear. Materials with the highest microhardness were the most wear-resistant. Gallab et al. [36] evaluated the mechanical and tribological properties of PMMA-based dentures strengthened by a low content of alumina (Al_2O_3) nanoparticles. Yu et al. [37] evaluated the influence of 3D printing process parameters on the tribological and mechanical properties of acrylic resin. Wyszyńska et al. [38] compared the parameters of 10 materials used for the soft lining of acrylic dentures. Among the materials tested were Vertex Rapid Simplified and Villacryl, which were also evaluated in our tests. Raszewski [39] presented studies comparing the mechanical properties, biocompatibility and clinical use of acrylic resins from CAD/CAM technology. Rana et al. [40] evaluated the fracture loads of PMMA complete denture bases reinforced with glass-fiber mesh and orthopedic casting tape, in comparison to conventional PMMA dentures under artificial aging. Yadav et al. [41] performed a comprehensive review of the physical, mechanical, and tribological parameters of dental resin composite materials. Al.-Qahtani et al. [42] evaluated the flexural strength of PMMA denture base repaired with heat-polymerized, auto-polymerized and light-polymerized acrylic resins after thermocycling. Chhabra et al. [43] evaluated and compared the flexural strength and impact strength of a heat-cured acrylic denture base resin and 3D-printed denture base resin. Tzeng et al. [44] developed potential composite resins with tunable mechanical properties for 3D printers based on digital light processing technology.

It should be noted that in the tested dentures the highest microhardness of the tooth construction materials is recommended due to their direct tribological contact with opposing teeth during food grinding and chewing [11, 12, 35-37, 45-47]. Very similar values of the longitudinal modulus of elasticity indicate the similarity of chemical bonds and do not have a significant impact on the strength comparison of structures made of these biomaterials [13, 16, 38-41, 48]. Differences in microhardness values are much more important. Here, it can be noticed that only Premacryl Plus has lower values, which indicates that it should not be used in support structures.

In the clinical aspect, a more optimal solution will be a plate with a higher microhardness and a higher elastic modulus value. Higher microhardness and Young's modulus provide improved structural stability and greater compressive strength under chewing conditions [10, 42-44]. Moreover, such parameters determine the possibility of making an extensive structure with a smaller plate thickness. The anatomical structure and physiology of the SS should be taken into account. Of course, it can be noted that microhardness and Young's modulus cannot have too high values. Plates may cause excessive pressure on the mucous membrane, especially in the absence of saliva or its inappropriate rheological parameters. Too high of a value of microhardness and elastic modulus may prevent the creation of negative pressure conditions between the denture plate and the substrate tissues.

In the case of natural tooth tissues, the mechanical parameters are significantly higher than for acrylic materials. Enamel is the most mineralized tissue and at the same time the hardest substance in the human body - it is even harder than bone. This allows it to perform its functions well, i.e. to cover the remaining tooth tissues and protect them from external factors. Enamel has a microhardness of 2500-6000 MPa, and Young's modulus in the range of 55-120 GPa. Underneath the enamel is dentin. This is a mineralized connective tissue. It is a yellow porous material, the role of which - similarly to enamel - is to protect the tooth. As a protective layer, dentin is not as hard as enamel and is more susceptible to damage. It contains microscopic dentinal tubules. Dentin has a microhardness of 500-800 MPa, and Young's modulus in the range of 15-22 GPa. In turn, cortical bone has micromechanical parameter values comparable to dentin: microhardness in the range of 600-700 MPa and longitudinal modulus of elasticity at the level of 13-21 GPa [49].

The results of tribological tests allowed the determination of the friction coefficients and wear resistance of acrylic polymers in sliding contact, in tests in the presence of physiological saline and in the presence of artificial saliva. The introduction of two fluids in the test nodes and the significant differences in the results of tests on friction coefficients and wear resistance demonstrate the important physiological and tribological function of saliva.

The evaluation of resistance to movement in sliding friction allows the determination of friction coefficients, and the sizes of wear defects indicate the resistance of biomaterials to destruction as a result of concentrated contact. The given force P - loading the node, generates 3 reactions on the Hertzian diameter: $N_1 = N_2 = N_3$ (Fig. 4). With the symmetry of the friction node and the same thickness of the disks, it can be assumed that the load on the node P is divided into three normal reactions.

$$N_1=N_2=N_3=N \qquad (1)$$

The value of the normal reaction is:

$$N_1 = \frac{P}{\sqrt{6}} \qquad (2)$$

If the force P corresponds to the resulting chewing force, then based on the experimentally determined values of the friction coefficients $\mu 1=\mu 2=\mu 3$, we can determine the friction forces in chewing, acting on the SS (Table 4). These forces must be balanced by the resistance of the prosthetic base tissues.

The decrease in wear resistance, which is manifested by an increase in the average diameter of the wear defect under sliding contact conditions, indicates a greater susceptibility of the material to destruction and may reveal defects in the polymerized biomaterial. Structure discontinuities, cracks, and delaminations create potential areas for colonization by plaque, bacteria, and fungi. These types of defects in material may also negatively affect the deterioration and scraping of the structure used by the patient.

The analysis of tribological processes in the sliding contact of the prosthesis plate with SS tissues indicates that there are two causes of movement resistance: mechanical friction resulting from the deformation of the irregularities of the contact of the surface layers of the plate and tissues in the presence of a lubricating medium, and molecular friction caused by the need to overcome adhesion forces resulting from the interactions of surface particles (molecules) of both structures. On the basis of the conducted research, it can be evaluated that this molecular interaction is particularly important and results from the nature of the lubricating medium, in this case saliva. The patient's saliva and its rheological spectrum influence the possibility of using the prosthesis and the conditions of its operation. In clinical situations, the application of SS reconstruction should be preceded by saliva rheological tests of the patient.

TABLE 4. List of friction coefficients and forces for denture plate materials tested in a physiological saline environment and in an artificial saliva preparation

Material of tests	Occlusal force [N] $N_1=N_2=N_3$	Physiological saline		Artificial saliva	
		Coefficient of friction μ_{PS}	Friction force [N] T_{PS}	Coefficient of friction μ_S	Friction force [N] T_S
ProBase Hot Pink	163.30	0.090	**14.70**	0.060	**9.80**
Vertex Rapid Simplified		0.110	**17.96**	0.051	**8.33**
ProBase Cold Polymer Pink		0.122	**19.92**	0.083	**13.55**
Vertex Self – Curing		0.140	**22.86**	0.090	**14.70**
Villacryl SP V4		0.142	**23.19**	0.076	**12.41**
Premacryl Plus		0.138	**22.54**	0.108	**17.64**

To analyze the influence of the lubricant in the form of physiological saline and artificial saliva, three materials with the best tribological parameters were compared on a graph (Fig. 12). From the comparison, it can be observed that for each of the materials tested, the use of the artificial saliva preparation Kserostemin resulted in a significant reduction in the friction coefficients. Moreover, it can be observed that in test nodes using artificial saliva, there are much more stable courses of friction coefficients throughout the entire test range. The largest decrease in the friction coefficient value in the stabilized phase was observed for Vertex Rapid Simplified

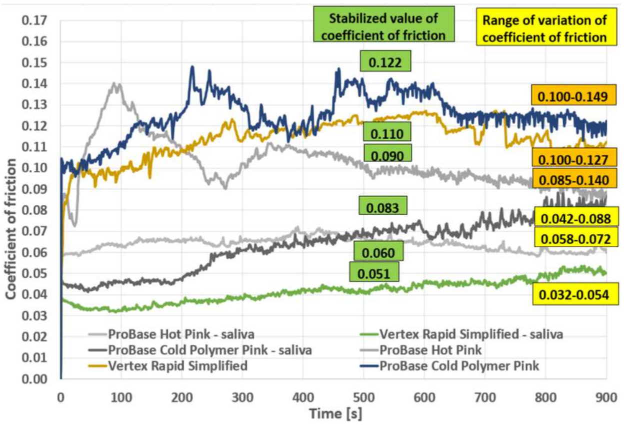

Fig.12. List of friction coefficients of selected acrylic resins for denture plates in physiological saline and artificial saliva

from 0.110 to 0.051, and the smallest for ProBase Hot Pink - from 0.090 to 0.060. The results of tribological tests indicate that the presence of saliva has a significant impact on reducing the values of friction coefficients and increasing the wear resistance. Lower coefficient values under normal loads are due to the increased adhesion and molecular nature of the saliva preparation compared to physiological saline.

Lowering the friction coefficients in contact of the denture plate with the substrate tissues may result in lower microdisplacement resistances, which reduces the irritating effect on the substrate. It is a basic factor that improves the conditions of use of the prosthesis by the patient.

5. CONCLUSIONS

Lowering the values of friction coefficients results in a reduction in the values of friction forces that are generated by normal forces resulting from occlusion, especially in mastication. This situation results in a reduction in the irritating effect of friction forces on the tissues of the prosthetic base.

Lowering the values of the friction coefficients protects the structure against the formation of wear-related irregularities in the surface layer, which protects the denture against plaque deposition and the formation of potential fatigue cracks.

The values of the friction coefficients and their stabilization depend on the tribological parameters of the lubricating medium. In the case of artificial saliva, thanks to its rheological and adhesive parameters, the coefficient values are much lower and the waveforms are much more stable.

Reduced wear resistance, which is manifested by the size of wear defects under sliding contact conditions, may reveal defects in the polymerized biomaterial. Structure discontinuities, cracks, and delaminations create potential areas for colonization by plaque, bacteria, and fungi.

The implemented method of testing acrylic resins for removable dentures allowed them to be evaluated in terms of structural, strength, and tribological aspects, which significantly translates into optimal selection and application in clinical conditions.

Microstructure tests allowed the identification of the surface layer in wear defects and indicated the Vertex Rapid Simplified material as the least susceptible to internal defects and cracks, which may constitute potential places for the growth of fungi and bacteria. Micromechanical tests showed similar values of microhardness and longitudinal elastic moduli of the biomaterials tested. They may determine the strength and extent of the plate. Premacryl Plus had different and lower micromechanical parameters.

Taking into account the microstructural, micromechanical and tribological tests, the best plate material for applications in clinical settings is Vertex Rapid Simplified, followed by ProBase Hot Pink. The least favorable material was Premacryl Plus.

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