Original research article

TiC-composite materials in applications for kinematic denture connections

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ABSTRACT

Purpose: This paper presents an own proposal for the construction of a ball latch intended for use in prosthetic dentistry. Attention was paid to the existing commercial constructions of elements of the same type, indicating their advantages and disadvantages. Based on the analysis of the present solutions, own ones were proposed.
Materials and methods: The following materials were chosen for the tests: pure titanium, 316 L V steel, Ti15Mo2.8Nb obtained using powder metallurgy and through mechanical alloying, 10 and 20% of titanium carbide – obtained using powder metallurgy, as well as 10 and 20% of graphite – obtained using powder metallurgy. For the prepared materials, tribological tests were performed using a friction simulator in a ring/shield system.
Results: Fairly extensive tests were performed to verify the suitability of the selected material for use in the specific conditions of the oral cavity. The performed tests showed that the proposed material is not only beneficial in relation to the existing commercial dental alloys but also meets the general criteria set for this type of elements.
Conclusions: A more beneficial use of two–part ball latches (two key parts – patrix, matrix) was noticed in comparison to latches consisting of three parts (patrix, insert, matrix). On the basis of the obtained test results, it can be concluded that the proposed own design of a ball latch is a good alternative for traditional constructional and material solutions of commercial ball latches.

1. Introduction

In general, a prosthesis is an external reconstruction complementing an anatomical body part, which does not constitute a biological whole with the organism. By reconstructing damaged parts of a tooth or lost teeth, atrophied tooth sockets, or defects of jaw and mandible bone, dental prostheses (dentures) simultaneously reconstruct the disabled functions of the mouth cavity. A properly designed denture can prevent from the appearance of deformations, dental shift, disorders of the occlusal surface plane or the height of occlusion, and even inhibit the processes of base atrophy or the development of periodontal diseases [1–3].

When designing the construction of a denture, special attention must be paid to, among others, the biochemical aspects such as mechanical durability, stability, retention, and even base load [4–9]. The progress in the area of the use of removable dentures is mainly related to the use of different types of precision retention (fixing) elements [1,2]. An appropriate stabilization of the denture on its base facilitates the actions of speaking and chewing, and brings the user numerous

psychological benefits. In order to achieve the appropriate stability and retention of dentures, different types of retention elements are used, e.g. protective caps, ball latches, bar attachments, telescopic crowns, magnets, and numerous others [8–14]. Example retention elements are presented in Hupfauf et al. [1] and Ciaputa et al. [2].

In this context, this paper presents several examples of traditional constructional solutions of ball latches used in removable prosthetic appliances, in addition to an own proposal.

The traditional connection of a denture with the prosthetic base by means of a ball latch consists of two key elements: the patrix (head), usually fixed in the prosthetic base; and the matrix (spherical cap), usually fixed in the denture base (though there are also reversed combinations). Additionally, a plastic insert is most commonly fixed in the matrix socket, which, by wearing out, protects the matrix against damage (Fig. 1). Currently used ball latches of this type include the Vigano by Rhein 83, the OVC/VKS by Bredent, or the Preci Clix by ALPHADENT N.V.

Such an arrangement of elements ensures a longer life of the connection, until it is worn out or the denture is damaged due to the fact
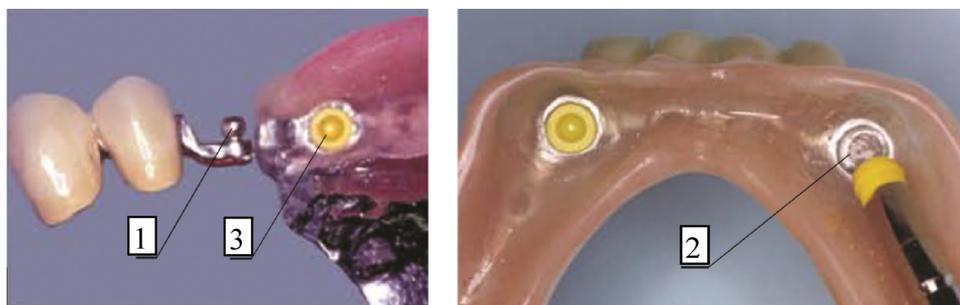
Fig. 1. Examples of retention elements of a ball latch [11]: 1- Patrix, 2- Matrix, 3- Plastic insert.

that the heads of the connections are usually steel, while the inserts are usually plastic. In a frictional contact plastic insert-metal head, tribological wear of the plastic insert is faster, and it can be replaced until the denture loses its operational usability (reverse combinations are also known, i.e. a plastic head; a metal insert) [4–9].

However, based on the general information collected from patients and dentists, the repeated replacement of the plastic insert (its cost and the cost of medical appointments) can be comparable with the cost of a new set of dentures (this obviously depends on its type and construction). This fact inspired the authors to search for new constructional solutions of the ball latch, consisting of only two metal elements, namely the patrix and the matrix (without the need for a plastic insert). Literature data [1,2,11–13] indicates that this guarantees a high quality and a long operating time of the connection. Fig. 2 shows example ball latches made from metal elements only.

As mentioned earlier, metal retention elements of the ball latch make it possible to achieve a high quality and a long life of the connection.

However, in the face of the constantly growing demands of both the patients and the dental technicians struggling with this issue, as well as the continuously developing prosthetic materials science, solutions which could significantly improve the stability and life of such connections are being sought for. An additional factor that provides a wide range of technological possibilities is the increasing (also in the field of design and production of retention elements) use of CAD-CAM and Rapid Prototyping techniques. This gives practically unlimited manufacturing possibilities.

In this context, this paper presents an own material and constructional proposal of a ball latch intended for the attachment of dentures.

2. Materials and methods

2.1. Material proposal

We decided to focus on well-known and commonly used materials, as well as our own proposals. Hence, several samples of materials made of surgical grade stainless steel as well as titanium (Ti) and its alloys were prepared. We chose the following materials for the tests: pure Ti, 316LV steel, Ti15Mo2.8Nb alloy obtained using powder metallurgy (PM) and through mechanical alloying, 10 and 20% of titanium carbide (TiC) – obtained using PM (Ti + TiC: Ti + 10%TiC and Ti + 20%TiC), 10 and 20% of graphite (Gr) – obtained using PM (Ti + Gr: Ti + 10%Gr and Ti + 20%Gr). For the prepared materials, tribological tests were performed using a friction simulator in a ring/shield system (Fig. 3).

The friction node performs a circular reciprocating motion at a load alternating in a sine-wave form, which simulates the variable operating conditions in the oral cavity. In order to carry out the experiment, the following operational conditions of the device were assumed: angle of rotation of the counter sample $\alpha = \pm 30°$, operating frequency $T = 1$ Hz, maximum linear velocity $v_{pmax} = 0.018$ m/s, sine-wave alternating load $N = 0 \div 350$ N, friction time $\tau = 1.5$ h - which corresponds to 5400 load cycles. The tests were carried out in a distilled water environment. The counter sample was made of Ti6A14 V alloy.

2.2. Constructional proposal

Considering the existing constructional solutions, a decision was made to make use of the tried constructions, yet with modifications. In relation to ball latches (Figs. 1 and 2), their construction usually consists of three key elements: 1 – a metal patrix (ball) with a substructure for fixing in bone, 2 – a metal matrix or a matrix socket (a socket for the spherical cap), and 3 – a plastic insert for the matrix socket, or a plastic matrix. The main idea behind this solution is based on eliminating the third element i.e. the plastic insert or the plastic matrix. Then, the construction of the latch will be reduced to two elements, namely the metal patrix and the metal matrix, as shown in Fig. 2.

Fig. 4 shows a general drawing and view of the elements of the designed ball latch. It should be pointed out that the dimensions shown in the drawing apply to this particular solution only, not being its essence. The actual dimensions of the latch depend on several aspects, e.g. its location, constructional considerations, or the possibility of incorporating it into a general outline of a denture. The essence of the
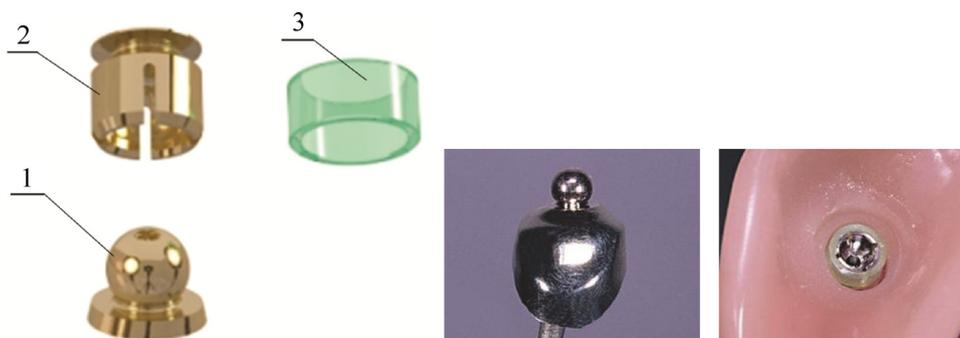

Fig. 2. Example metal retention elements of a ball latch by ALPHADENT N.V. [13]: 1- Patrix (gold alloy), 2- Matrix (gold alloy), 3- External supporting ring (acrylic resin).
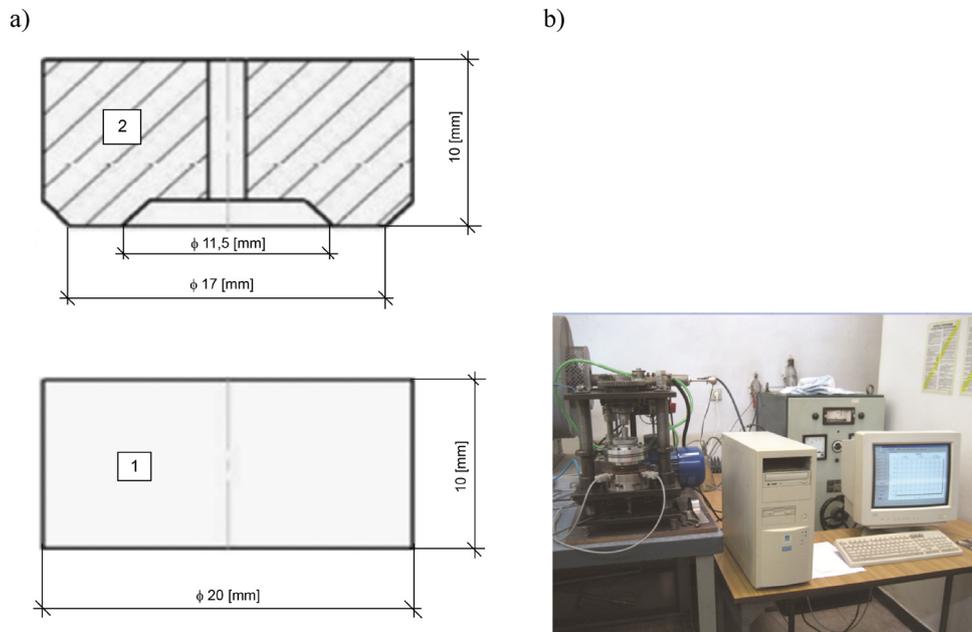
a)

b)

Fig. 3. The ring/shield friction simulator: a) Friction pair: 1- Sample, 2- Counter sample; b) View of the test stand.

latch, however, is its construction.

The most important construction assumptions of the designed bracket are connected with the construction of the patrix and the matrix. The patrix is a ball with a truncated cap (in the case of the solution presented in this study, by approx. 1 mm; Fig. 4a, counting from its upper "pole". The matrix, on the other hand, is a socket whose geometry is a negative of the patrix's one. A characteristic feature of the matrix are the notches (as illustrated in Fig. 4b), whereby two types of notches are possible: a criss-cross notch – 4 cuts 90° each (Fig. 4b, Fig. 5c), or a small star-shaped notch – 6 cuts 60° each (Fig. 5a). Fig. 5 shows the view of a designed and manufactured ball bracket.

3. Results and discussion

Selected results of the tribological tests are presented in Fig. 6. On the basis of the presented data, it can be concluded that the highest values of coefficient of friction were obtained for pure Ti, which is confirmed by the literature data [15]. By far the lowest values of movement resistance were obtained for Ti + 20%Gr and Ti + 20%TiC samples.

This can be explained by the presence of a hard ceramic phase of TiC and the well-known lubricating action of Gr. The Ti + 10%Gr and Ti + 10%TiC samples were also characterized by good tribological characteristics. Less beneficial values of coefficients, on the other hand, were obtained for the samples of Ti15Mo2.8Nb alloy and the 316LV
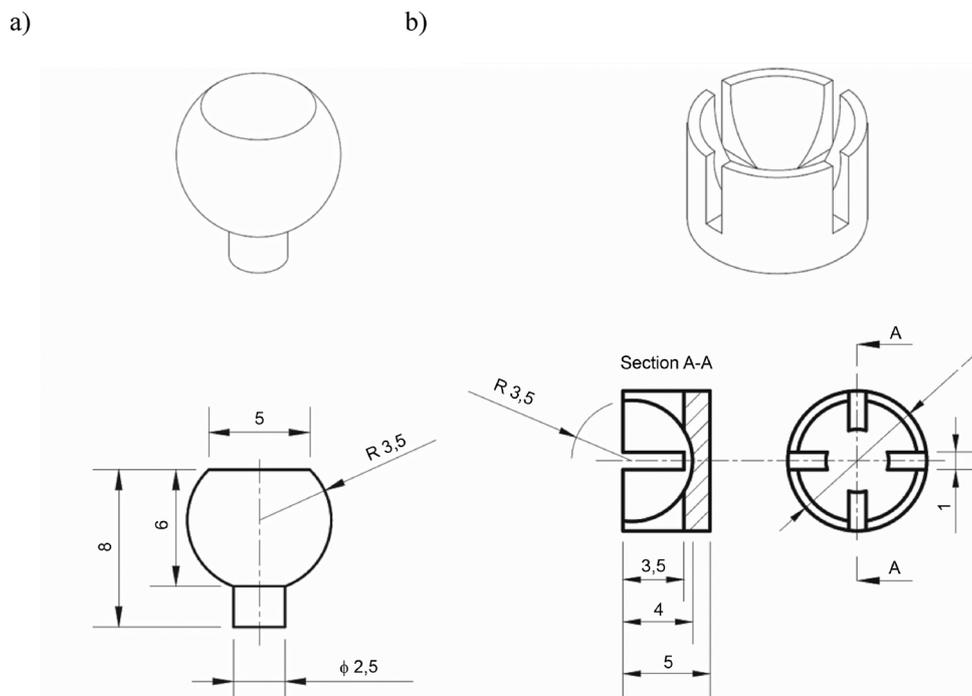
a)

b)

Fig. 4. Components of the designed ball latch: a) Patrix, b) Matrix.
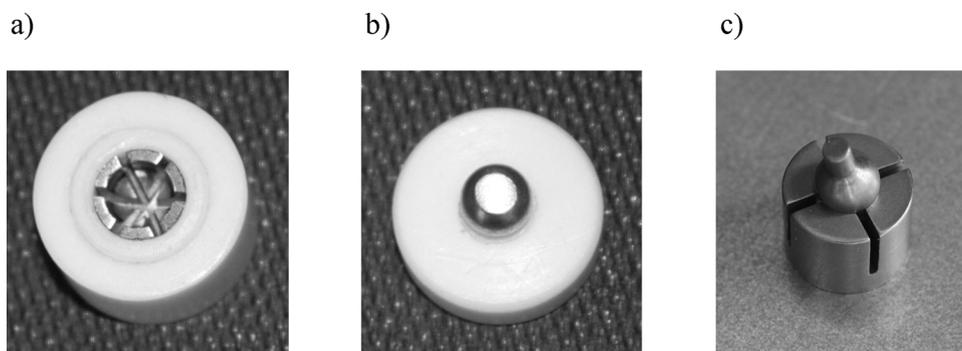
a)　　　　　　　　　b)　　　　　　　　　c)

Fig. 5. View of the elements of a manufactured ball bracket: a) Matrix, b) Patrix, c) criss-cross notched bracket.
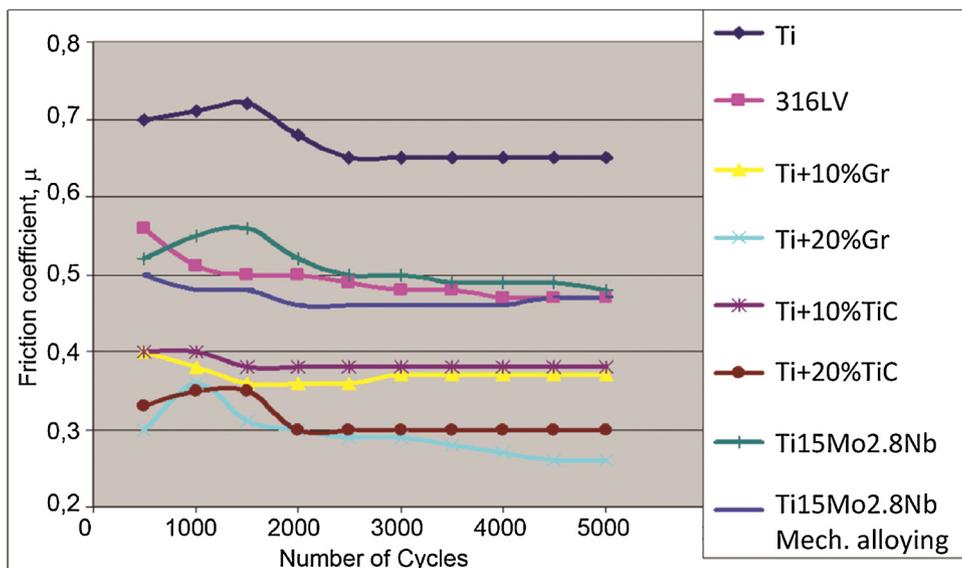

Fig. 6. Results of tribological tests for the prepared samples.

steel (not counting pure Ti). In this context, considerations concerning the most tribologically effective material were undertaken in relation to two groups of materials, i.e. those with Gr content and those with TiC content.

To achieve this aim, tests of tribological wear of the selected materials were performed, among others. The assessment of wear was performed using the gravimetric and the straight-line methods (through the analysis of the depth of friction traces in the sample). Table 1 summarizes the test results.

Regarding the tests of wear, it turned out that despite the extremely low movement resistance in the case of the TiC samples, their wear was the highest even in comparison with pure Ti. This can be a result of abrasive action of primary grains of the hard TiC. Especially beneficial wear characteristics, on the other hand, were obtained for the Gr

samples. It is worth mentioning that for the Gr samples, the obtained values of wear were lower than those for the commercial Ti6A14V alloy. It also needs to be pointed out that in spite of the small difference in favor of the model materials (in comparison to the commercial one), this may be of considerable importance in the case of elements with small dimensions and mass, including denture brackets.

For a more complete inference, a comparative analysis was performed only for the Gr samples. An additional tribological test was performed at an hour-long friction time. Fig. 7 presents the results of this test.

On the basis of the presented data, it can be concluded that the lowest values of the coefficient of friction were obtained for the Ti

Table 1
Wear of the tested materials.

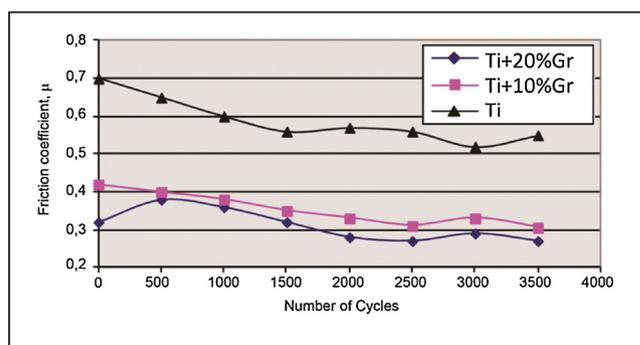| Sample material	Sample wear	
	Straight-line wear z_L, [μm]	Gravimetric wear z_m, [*10^{-3} g]
Ti + 10%Gr	16.6	11.5
Ti + 20%Gr	9.8	7.2
Ti + 10%TiC	33.9	23.7
Ti + 20%TiC	49.1	35.8
pure titanium (Ti)	30.4	21.5
Ti6A14 V alloy	20.1	No data

Fig. 7. The distribution of the coefficient of friction as a function of the number of cycles for titanium-based materials.

Table 2
Selected mechanical properties of Ti + 10%Gr and Ti6A14 V alloy.

Properties	Ti + 10%Gr	Ti6A14V
HB hardness	220	334
Microhardness, $HV_{0,1}$	350	No data
$R_{C,}$ [MPa]	1120	1000
$R_{0,2,}$ [MPa]	610	820
$A_{C,}$ [%]	30	18
Elastic modulus E, [GPa]	80	114

+ 20%Gr composite. However, as it turned out in factory practice, this material, due to its exceptional hardness and brittleness, was practically unworkable, rendering it useless considering the planned processing procedures. Moreover, owing to the fact that in the case of the Ti + 10%Gr material, the obtained values of the coefficient of friction were very similar, whereas their mechanical properties are comparable to those of the commercial Ti6A14 V alloy (Table 2), this composite was chosen as the material for the production of a ball latch for dentures.

The final verification of the usability of Ti + 10%Gr as a material for prosthetic constructions was done using the corrosion tests and the in vitro tests – these studies are described in more detail in the study by Menaszek et al. [16]. For the purpose of a comparison, these tests were also carried out for the commercial Ti6A14V alloy.

Table 3 summarizes the values of corrosion potentials and currents calculated using the method of extrapolation of anode and cathode curve segments using the POL-99 software. In the case of porous sinters, it is difficult to estimate their real surface, which makes it impossible to compare the current density for sintered materials and solid alloys. Therefore, Table 3 presents the values of current intensity.

The obtained results indicate the appropriate corrosion properties of Ti + 10%Gr produced using the PM. The value of current is at an acceptable level.

The results of biological tests (in vitro) of the examined materials showed a lower cell adhesion on the composite surface in comparison with the commercial Ti6A14V alloy. The cytotoxicity test did not show any differences between the tested materials.

Normal human osteoblasts (NHOst) cell life, determined using the Vialight test on the 3rd and the 7th day of culturing on a tissue culture polystyrene plastic (TCPS) control surface and on the composite surface, was nearly twice lower than on a Ti surface. This is proved by the data shown in Table 4.

It seems that the performed tests and their results prove that in the context of the required biofunctional features [17], and especially the tribological characteristics laid down at the Department of Material and Biological Engineering of Bialystok University of Technology (Poland), the Ti + 10%Gr composite is an innovative proposal for a material to be used in the prosthetic dentistry.

In order to assess the functional quality of the bracket, tribological properties of the manufactured coupling were assessed. The tests were performed using a friction simulator in a head/bearing system (patrix/matrix). The description of simulator operation was presented above, however, in the present study, the elements of the friction node were changed. A full cycle of simulator operation consists of the pressure phase (sine-wave increasing) and the simultaneously following reciprocating circular motion; and the phase of offload and complete separation of the cooperating elements. The following parameters were assumed for the tests: $\alpha = \pm 30°$, operating frequency T = 1 Hz,

Table 3
Corrosion characteristics of Ti + 10%Gr sinter and Ti6A14 V alloy.

Material	E_{kor} [mV]	I [μA]
Ti6Al4V	− 267	0.0497
Ti + 10%Gr	− 157	1.28

maximum linear velocity $v_{pmax} \approx 0.01$ m/s, sine-wave alternating load N = 0 ÷ 150 N, friction time $\tau = 3$ h – which corresponds to 10 800 load cycles. The tests were performed in conditions of technically dry friction and in the environment of a saliva substitute marked as Mucin III (a 2% mucin type III solution in a buffered saline solution – PBS, pH = 7).

Selected results of the tribological tests for the manufactured ball bracket are presented on Fig. 8. The data shows that in the case of dry friction the value of friction couple initially stays at the level of 0.125 N m. Then, after about 1.5 h of friction, the value decreases to approx. 0.06 N m and stays at this level until the end of the friction cycle. This could mean that after performing 5400 cycles of dry work, there occurs a complete adaptation of the cooperating elements and a stabilization of movement resistance in the coupling (bracket). Assuming that the denture user removes it at least twice a day for the purpose of cleaning (in the morning and in the evening), then the latch would perform 4 cycles (4 cycles/day). Dividing 5400 cycles by 4 cycles/day amounts to 1350 days = 3 years and 255 days. This means that at a minimum number of removals and insertions of dentures, after about 4 years the working surfaces of the bracket will have only completely adapted (in the case of dry friction). This state continues until the end of the friction process, which at similar calculations amounts to 7 years and 145 days. Probably only after this time their more intense wear, or a significantly lower retention force (keeping the dentures in place) can be expected, due to wear and increase of play between the patrix and the matrix. Considering the life of the current dental prostheses, this time period is perfectly enough for a full cycle of the dentures' operational usability.

In the case of friction in the Mucin III environment, initially there is a peak of the friction couple up to the maximum value of approx. 0.13 N m; then it gradually (almost linearly) falls down to the minimum value of approx. 0.034 N m. Due to the completed friction process, there is no information concerning what would happen afterwards - in the following cycles of operation.

Inferring from the results obtained for dry friction, it may be expected that further friction in the Mucin III environment would have lead to a stabilization of movement resistance at a constant level, and possibly a more intensive wear later. After performing 10 800 cycles in the Mucin III environment, however, the movement resistance between the bracket elements continuously decreases, which may indicate further running in of the surfaces or an increasing play due to the wear of the cooperating surfaces.

In order to examine this aspect, we measured the bracket elements before and after friction using a coordinate measuring machine. Fig. 9 shows the method for collecting the measurements. Fig. 9a illustrates the "cloud" of points that was collected from the external surface of the cap (matrix). As these points were collected on the circumference at specific heights (Fig. 9b), circles described on them were created from the collected cloud. Moreover, each time an additional point was collected as a measurement basis (BP) (Fig. 9c). Then, 3 mm upwards from this point, measurements around the cap were taken by lifting the measuring tip by 0.5 mm, as illustrated by Fig. 9c. Similar operations were performed for the patrix (ball). For the circles created this way (O1,..,O5), measurements of their diameters were taken before and after friction. The difference in diameter was taken as the measure of wear, both for the matrix and the patrix. In the case of the patrix, the distances between the measurement circles were slightly different, and so a larger number of them were created (O1′,..,O7′). These differences are presented in Fig. 10. Obviously, in the case of the matrix, it was expected that the diameters of the circles would increase. In the case of the patrix, they were expected to decrease. It also needs to be added that due to the geometry of the patrix (a truncated spherical cap) and the real surface of the tip, a comparative analysis was performed only for selected circles. The results of these analyses are summarized in Tables 5 and 6.

On the basis of the data shown in Tables 5 and 6, it can be

Table 4
Results of in vitro tests (NHOst 7 days).

Material	Cell adhesion [OD]	Cytotoxicity Luminescence [CPS]	Life Luminescence [CPS]	Nitrogen oxide [OD]	Protein [OD]
Ti + 10%Gr	0.1	4200	16000	0.07	0.8
Ti6A14V	0.15	4200	35000	0.055	0.65

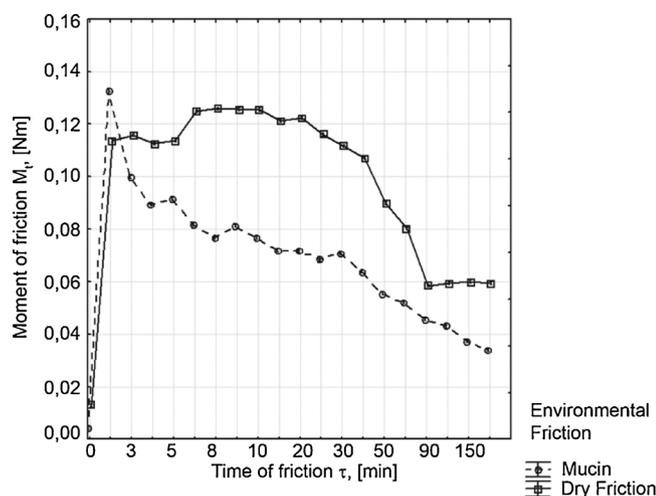OD – optical density, CPS - capsular polysaccharide.

Fig. 8. Distribution of friction couple as a function of time (friction pair – ball bracket).

concluded that in the case of friction in the Mucin III environment, there occurs a higher wear of the cooperating surfaces than in the case of dry friction. This can be explained by the fact that the lubricant, by rinsing the cooperating surfaces, could have simultaneously flushed the products of friction away from the friction zone. In this way, during the subsequent cycles of operation, contact between freshly "uncovered" surfaces, and thus their wear, could have occurred. This rinsing was probably the most intense during the unfastening of the latch. Lifting the matrix (during the offload cycle) caused an upward movement of layers of liquid (absorptively connected with the surface). Additionally, a downward movement of the matrix could have caused a sort of overpressure, which squeezed the excess lubricant, together with the wear products, out of the friction zone. Moreover, it should be remembered that the matrix had notches (Fig. 5a) that performed the role of lubricating channels (similarly as in a self lubricating sliding bearing), facilitating the flow of the lubricating liquid and the ejection of wear products from the friction zone [18]. Additionally, the disjoining action of oil, pressed alternately in two directions, should also be noted.

In the case of dry friction, on the other hand, the Gr which is a component of the matrix and the patrix plays an important role. It is known that due to its hexagonal structure, Gr is more susceptible to shearing stresses, creating a specific lubricating film in the area of the friction, thus reducing the movement resistance in the friction node. In addition, its susceptibility to abrasion can translate into the creation of thin secondary lubricating layers with a content of the products of wear, and (in this way) into a reduction of changes to the measured diameters.

Fig. 11 shows a photograph of friction traces of the cooperating elements (after dry friction). Fig. 11a illustrates friction traces on the patrix (ball) at the height of the O2′ circle area. On the observed surface, distinct friction traces are visible, as well as black particles of Gr. As expected, a selective transport of matter from the surface of the patrix to the surface of the matrix and the other way round probably occurred in this case. This can be proved by the photograph shown in

Fig. 11b. The surface of the matrix is covered with secondary "smeared" (as a result of mechanical adhesion) layers of wear products from the friction zone, the process having taken place both ways. Such mechanisms could have had a significant impact on the obtained test results in relation to the practically non-wear friction of the elements of the ball bracket at dry friction.

The most significant conclusion stemming from the results of wear measurements is the possibility of a correlation between geometry and the number of notches on the matrix; and the creation of a lubricating film and the effectiveness of the action of the lubricant during bracket operation. This means that other modifications to this solution may be considered in order to seek a solution with the highest possible reliability index and operational stability.

3.1. Key details concerning the construction and material of a ball bracket

Below we summarized the key details:

1. The bracket construction consists of two metallic elements, i.e. the patrix and the matrix.
2. The construction is characteristic in that the patrix has a spherical cap truncated in a plane perpendicular to its main axis at the height of 6/7D (D- ball diameter). The matrix, with the internal shape of the spherical cap, has 4 notches 90° each, or 6 notches 60° each. A detailed data and dimensions are shown in construction drawings (Fig. 4).
3. The construction is characteristic in that the material that the bracket was made of is a Ti + 10%Gr composite manufactured using the PM method. To produce the material, a commercial Ti powder was used with granulation less than 150 μm. After preparing the ingredients, the mixture was cold-pressed under a pressure of 500 M Pa and then sintered for a period of 3 h in vacuum at a temperature of 1230 °C.

4. Conclusions

On the basis of the performed analysis of the literature data and our own research, we noticed a more beneficial use of two-part ball latches (two key parts – patrix, matrix) in comparison to latches consisting of three parts (patrix, insert, matrix).

Additionally, tribological tests and tests of mechanical properties of the own construction (Ti + 10%Gr) indicate its beneficial tribological, mechanical and operational characteristics in comparison with commercial dental alloys. In relation to corrosion tests and in vitro tests, we confirmed the beneficial properties of the Ti + 10%Gr composite in comparison with commercial materials.

On the basis of the obtained test results, it can be concluded that the proposed own design of a ball latch is a good alternative for traditional constructional and material solutions of commercial ball latches.

A full material inference in the area of the own proposal requires further in-depth research studies, including clinical trials.

Conflict of interest

The authors declare no conflict of interests
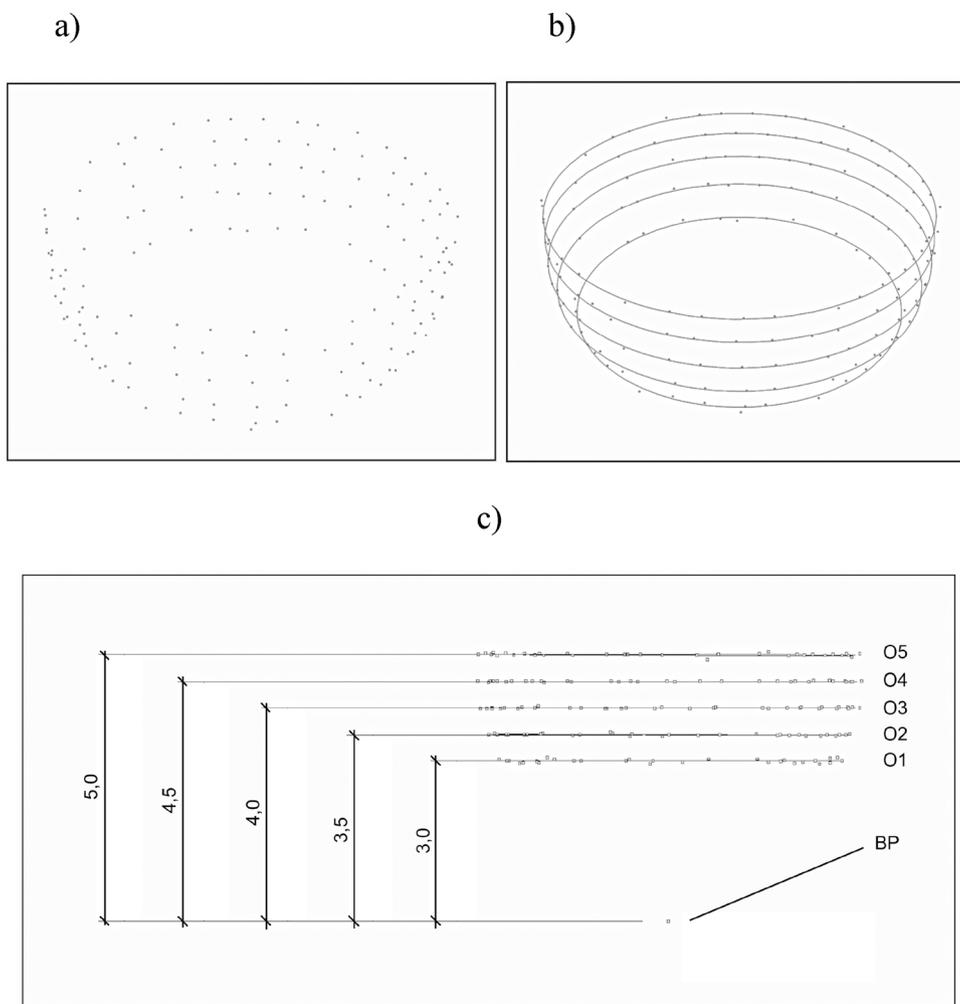
a)

b)

c)

Fig. 9. The method of matrix wear assessment: a) "Cloud" of measurement points, b) Circles described on the points, c) Distance from the measurement basis on which measurements for the points were taken.
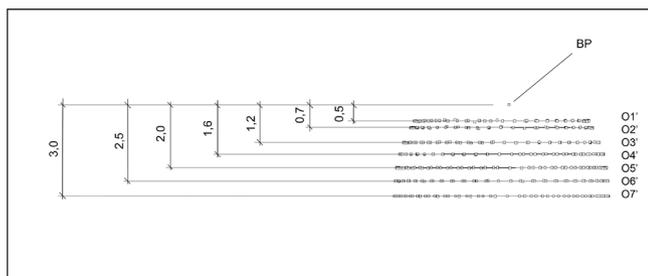

Fig. 10. Distances of measurement circles from the measurement basis for the patrix.

Table 5
Measurements of circle diameters for the matrix.

Conditions of friction			
Measured circle	Measurements before friction, ϕ [mm]	Amount of wear (change of circle diameter), ϕ [mm]	
		Dry friction	Mucin III
O3	7.00	+0.01[a]	−0.02[a]
O4	7.02	0.00	−0.03
O5	7.00	0.00	−0.01

[a] the "+" sign means a decrease of the circle diameter; the "−" sign means an increase of the circle diameter.

Table 6
Measurements of circle diameters for the patrix.

Conditions of friction			
Measured circle	Measurements before friction, ϕ [mm]	Amount of wear (change of circle diameter), ϕ [mm]	
		Dry friction	Mucin III
O2'	5.93	−0.02[*]	−0.06[*]
O3'	6.38	−0.01	−0.04
O4'	6.63	0.00	−0.02
O5'	6.84	0.00	−0.01
O6'	6.95	−0.01	−0.01
O7'	6.98	0.00	−0.03

[*] the "−" sign means an increase of the circle diameter.

The author contribution

Study Design: Jan R. Dąbrowski, Marek Jałbrzykowski
Data Collection: Marek Jałbrzykowski, Łukasz Minarowski
Statistical Analysis: Marek Jałbrzykowski
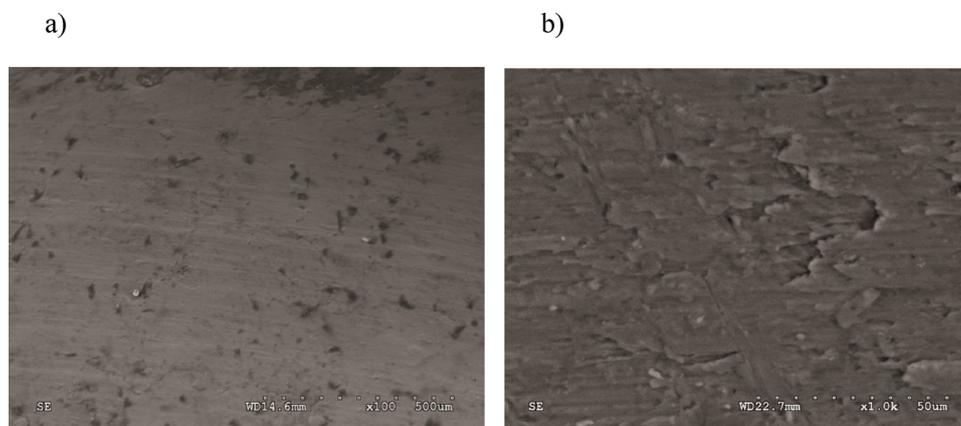Data Interpretation: Jan R. Dąbrowski, Marek Jałbrzykowski,

a)   b)

Fig. 11. View of the surface of the bracket elements after dry friction (Ti + 10%Gr): a) Patrix, b) Matrix.

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Literature Search: Marek Jałbrzykowski, Łukasz Minarowski
Funds Collection: Jan R. Dąbrowski

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