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The study of the connection between the zirconia substructure and veneering porcelain in dental crowns subjected to occlusal forces

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ABSTRACT

Purpose: The aim of the study was to examine the connection between the zirconia substructure and the porcelain in the dental crowns subjected to simulated occlusal forces.

Design/methodology/approach: All-ceramic dental crowns were subjected to Vickers hardness examination, testing of compressive strength and observations of breakthroughs on the SEM.

Findings: Based on the research, it was found that the compressive force at which ceramic crowns brake down, are in the range of maximum occlusal loads exerted by man. There is a mechanical connection between zirconia and porcelain. All-ceramic crowns of premolars showed the highest resistance to compressive force, while the crowns of canines are characterized by the lowest resistance to the loading force. In addition, through the research we found that ceramic crowns under static compressive loads brake down and the fracture line runs through the entire thickness of the wall, because zirconium oxide has more than twice the hardness of the porcelain. There is a difference of stresses between the materials, causing fracture of the restoration.

Practical implications: The research work shows that the porcelain crowns on the substructure of zirconia (all-ceramic restoration) are a very good option of the restorative treatment in dentistry, rebuilding missing teeth.

Originality/value: The article presents a study on the compressive strength of manufactured crowns, followed by a comparison to the natural forces of occlussion in human. The exact mapped tooth geometry and the appropriate veneering porcelain foundation of zirconium allows the use of prosthetic crowns in the patient's mouth without fear that porcelain will be broken.

Keywords: Zirconia; Veneering porcelain; Dental crown; SEM; Static compression test; Hardness; Occlusal froces

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MATERIALS

1. Introduction

Modern dental prosthetics is involved not only in restoring of missing teeth Its goals are much more ambitious and extensive.

As in general medicine, dentistry deals with ensuring good mental and physical health of an individual person and the whole society [1].

The current requirements of patients, in terms of aesthetics of the restorations, are extremely high. For many years, researchers have been looking for a precise method for producing high-quality dental restorations, both permanent and removable [2]. In recent years we have seen significant progress in dental prosthetics which is caused by the introduction of the latest achievements of related sciences, i.e. medicine and engineering. Introduced computer systems to the dental prosthetics, computer aided design and manufacturing (CAD/CAM) revolutionized the way of planning and manufacturing of permanent and removable restoration. In addition, it was possible to produce more durable types of ceramics, and metals without casting process [3].

The main advantage of all-ceramic restorations is their potentially better aesthetics, especially in front of the mouth, because all-ceramic restorations do not have a metal frame. They are made only of ceramic, through which it is possible to achieve a more natural aesthetic effect. In addition, all-ceramic restorations do not require coverage of colourful oxides [4].

Zirconia is characterized by extremely high resistance to bending (900-1200 MPa). Its Young's modulus is similar to steel and is about 200 GPa. Zirconium oxide has a very high stress intensity factor, which reaches a value of about 10 MPa • $m^{1/2}$.

ZrO_2 has a uniform microstructure, without voids, microcracks or cracks, this indicates a very low coefficient of porosity. In addition, this fact means it is non-absorbent material. ZrO_2 shows complete biocompatibility with respect to the oral tissues and eliminates the risk of corrosion [5].

The aim of the study is to examine the connection between the zirconia substructure and the veneering porcelain dental crowns subjected to simulated occlusal forces.

1.1. Zirconia

For a long time people were looking for a material that would have a similar strength to the metal alloys and more favourable biological properties. Ceramic zirconia is the oldest material from the group of oxide ceramics, but only recently it has been refined to form of a dental material with high efficacy [5].

Zirconium oxide is present as a cubic lattice structure above 2300ºC. At the time of cooling is converted to a tetragonal form, and below 1200ºC passes into the monoclinic phase. The various structures are shown in Figure 1 [6].

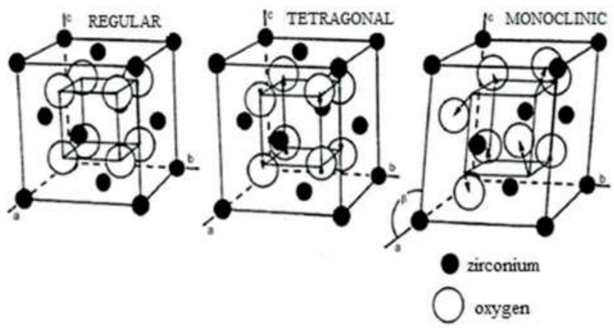

Fig. 1. The unit cell polymorphs Zirconium oxide [6]

Only monoclinic form is thermodynamically stable at room temperature. The cycle phase transitions of zirconium dioxide under atmospheric pressure are shown in Figure 2 [6].

$$\text{liquid} \xrightarrow{2680°C} \text{regular phase} \xrightarrow{2370°C}$$

$$\xrightarrow{2370°C} \text{tetragonal phase} \underset{1150°C}{\overset{950°C}{\rightleftarrows}} \text{monoclinic phase}$$

Fig. 2. A series of phase transitions of ZrO_2 at atmospheric pressure [6]

The density of the dioxide zirconia is about 6 g/cm^3 Accordingly, we can conclude that compared to noble metals such as gold (19 g/cm^3) or platinum (21 g/cm^3), the material is relatively light. ZrO_2 has a uniform microstructure, without voids, microcracks or cracks.

In addition, this fact means that it is non-absorbent material. A very important property (especially for dental prosthetics) is its resistance to bending, which may reach the value of 1200-1400 MPa and this is the highest value of all the materials that are used to produce all-ceramic restorations. This feature can be described as a stress value, beyond which the material is destroyed. Another feature of the zirconia is Young's modulus, which defines the flexibility or rigidity of the material. 200 gp Zirconium oxide has a very high stress intensity factor which is about 10 MPa • $m^{1/2}$ [7].

Zirconia has many advantages but also some drawbacks. One of these is the so-called susceptibility to aging. This process involves the spontaneous change of phase from tetragonal to monoclinic form which is more stable at low temperatures and is also referred to as "low temperature degradation". In addition, an increase of the volume of material about 3% and the formation of microcracks [7].

1.2. Veneering ceramic

Ceramics used for veneering are characterized by extremely high modules and crush strength, but a relatively low tensile strength and elongation. The hardness of ceramics and glass-ceramics with the majority of the glass is much greater than the hardness of human enamel. Therefore, when the ceramic restorations occludes the natural teeth, the enamel of natural teeth is first to crack. Another very important property is its coefficient of thermal expansion (CTE), which is the degree of expansion or contraction of the material by appropriate heating or cooling. Ceramics with high CTE substantially not expand when heated, and equally shrink during cooling. This factor is very important in binding of the ceramic to metal or to the ceramic core. The expansion of the core and the veneering ceramic must be properly selected, because the ceramic will break during the cooling process from the firing temperature to room temperature [8].

In the optical properties of ceramics it is very important to distinguish reflectance, translucency, half trnslucency and opacity [8].

1.3. Occlusal forces

Occlusive forces are passive forces, which describe the reaction of contact between opposing teeth. The values of the forces which are exerted between the teeth when the jaws bite down is the subject of many studies. Despite the frequent analysis of this issue in the literature one can find a range of different values. The reason may be a variety of testing methods, measuring equipment, choice of population and analysis of results. The forces exerted by the teeth depend, among others, on the width of the jaw opening and pressure zones in the dental arch. The greatest forces are generated typically by biting on the molars.

The values of the occlusal forces are summarized in Table 1 [9].

The forces, in the range of maximum, are reached by relatively small group of people. An important issue is the fact that during the normal chewing cycle the maximum occlusal force are not triggered. It was found that the fragmentation of most food (from 60 to 100 N for the incisors and 80 to 130N for the premolars and molars) [9].

Table 1.
Average forces exerted on the dynamometer during the bite on individual teeth: 1, 2 – incisors, 3 – canines, 4, 5 – premolars, 6, 7 – molars

	Occlusal forced on human teeth, N						
	1	2	3	4	5	6	7
Male	260	255	413	420	540	606	628
Female	215	213	301	312	413	433	450

2. Materials and methods

The study samples were prepared in the form of all-ceramic crowns. Substructure was made from zirconium dioxide (Renishaw). Then, by analyzing the coefficients of thermal expansion (WRC), the appropriate porcelain for manufacturing of crowns-ceramic VM9 company Vita was selected (Fig. 3).

2.1. Static compression test

Static Compression test is one of the main tests which are used to determine the mechanical properties of the materials. The aim of the compression test samples is to determine the characteristics by which it is possible to explore the values of mechanical parameters, the values of stresses that cause the destruction of the material and the value of strain [10].

The study used the machine Zwick/Roell Z020 (Fig. 4). A special head with a pin was installed, which enabled point pressure on a particular section of the nodule or the incisal edge. At the time of exceeding the limit of elasticity of the sample, permanent deformation and cracks in the porcelain occurred. For the performance of the test, a polypropylene spacer was used. It was placed between the crown and the tip of the tester tip.

A spacer eliminated direct contact of the tester with the crown and allowed uniform stress distribution on the mandrel, the compound with unusual surface nodule.

The samples were created for each group of teeth. There were two crowns of first incisors, two crowns of canines, three crowns of first premolars and three crowns of first molars.

VITA VM7 WRC (25-500°C) 6.9-7.3·10^4 K^{-1}	VITA In-Ceram ALUMNA, WRC (25-500°C) 7.2-7.6·10^4 K^{-1} VITA In-Ceram SPINELL, WRC (25-500°C) 7.5-7.9·10^4 K^{-1} VITA In-Ceram ZIRCONIA, WRC (25-500°C) 7.6-7.8·10^4 K^{-1} VITA In-Ceram AL, WRC (25-500°C) ca. 7.3·10^4 K^{-1}
VITA TITANKERAMIK WRC (25-500°C) 8.2-8.9·10^4 K^{-1}	TITAN WRC (25-500°C) ca. 9.6·10^4 K^{-1}
VITA VM9 WRC (25-500°C) 8.8-9.2·10^4 K^{-1}	VITA In-Ceram YZ WRC (25-500°C) ca. 10.5·10^4 K^{-1}
VITA VM13 WRC (25-500°C) 13.1-13.6·10^4 K^{-1}	WRC (25-500°C) 13.8-15.2·10^4 K^{-1}
VITA VM15 WRC (25-500°C) 15.5-15.7·10^4 K^{-1}	WRC (25-500°C) 16.0-17.3·10^4 K^{-1}

Fig. 3. Table of coefficients of thermal expansion (WRC) [9]

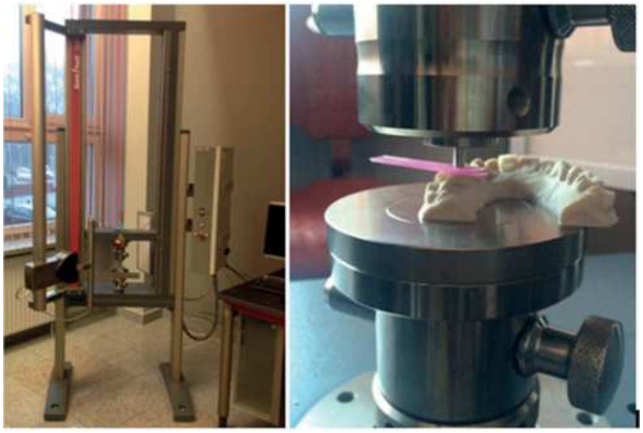

Fig. 4. The testing machine

To perform the static compression tests, it was necessary to create a very precise and firm base upon which the crown is placed during the test. The basis of this was achieved through the use of 3D printer with polylactide (PLA). The material was chosen specifically due to the proper mapping of individual's periodontium, to which the load is transferred by the crown and the core.

The following tests were performed for each sample:

- static test of compression,
- hardness test,
- survey breakthrough.

2.2. Hardeness test

Hardness measurements were performed using a Vickers hardness tester, wherein the indenter is a diamond pyramid of 136° dihedral angle [11]. The broken samples were tested for hardness to enable examination of the porcelain and zirconia. On the crown of each group of teeth they were performed five measurements, wherein each lasting 15 seconds.

2.3. Testing of fracture lines

Fractures were examined on the SEM microscope Zeiss Supra 25. In order to perform the test, a broken crown was mounted on a tape of carbon that is bonded to a metal table. During the test, observations were made at the breakthroughs. At this point, it was possible to observe any kind of structural details, and material defects in the form of voids, pores and microcracks. In addition to the appearance of the breakthroughs, it was possible to make conclusions on the mechanism of cracking. For each group of teeth several pictures at different magnifications were taken.

3. Results

3.1. Static compression test

Table 2 shows the force at which the fracture occurred on various dental crowns. The force at which the bursting of the crown reached a value of from 400 to more than 1900 N was registered. The most robust crowns on the compressive force were premolars, which on average were fracturing with the strength of 1699.46 N. The crown of the canine fractured at the lowest value of the loading force, averaging around 405.68 N.

Table 2.
The results of the compressive strength on each zirconia crown prepared for each group of teeth

Teeth	Number of sample	Force, N
Incisor	1	1009.75
	2	677.67
Average		843.71
Canine	1	394.37
	2	416.98
Average		405.68
Premolar	1	1434.22
	2	1930.51
	3	1733.65
Average		1699.46
Molar	1	1429.83
	2	1260.66
	3	1046.95
Average		1245.81

Charts illustrating the process of the whole process of compression of incisors is given in Figure 5. As you can see on crowns of incisors (Fig. 6) – one element is broken on the neck from the palatal side. The second crown is broken at the incisal edge.

In the case of canines, one of the crowns broke on its neck. In the second restoration, a fracture line occurred at the incisal edge (Fig. 7). The crown of the canine 1 broke at a force 394.37 N, while the crown of the canine 2 at the load 416.98 N. Figure 8 provides graphs that depict the moment of rupture of both crowns of canines.

For all crowns of premolars the fracture occurred at the same place in the intertubercular groove (Fig. 9). Nevertheless, the amount of force with which the crowns brake down was from 1400 to 1900 N. The chart in Figure 10 shows the process of compression of individual crowns of premolars.

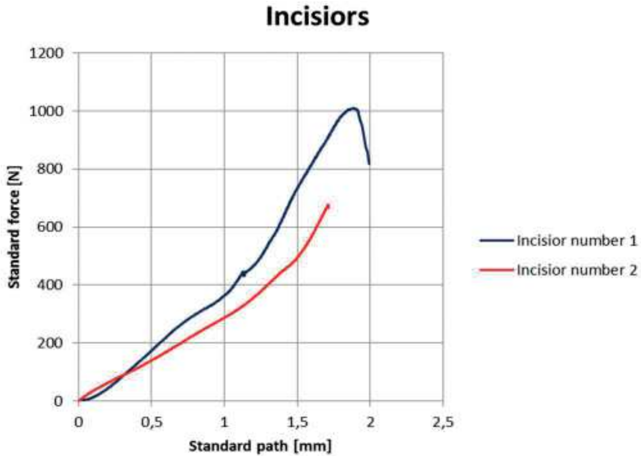

Fig. 5. Relationship between the standard force and the standard path of the occlusal load for incisors

Fig. 6. Crowns of incisors after destruction

Fig. 7. Crowns of canines after destruction

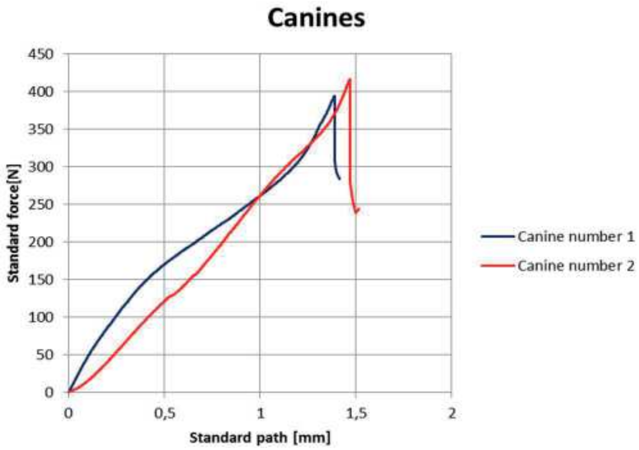

Fig. 8. Relationship between the standard force and the standard path of the occlusal load for canines

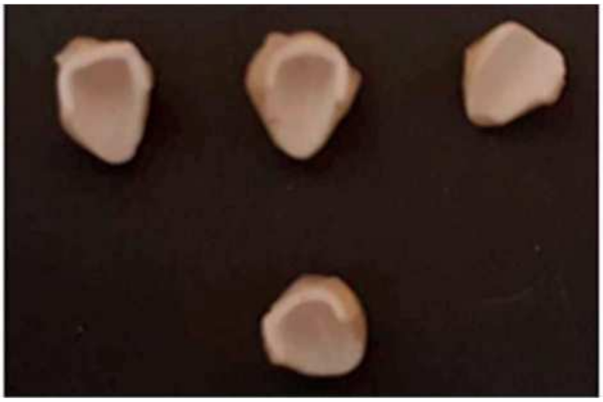

Fig. 9. Crowns of premolars after destruction

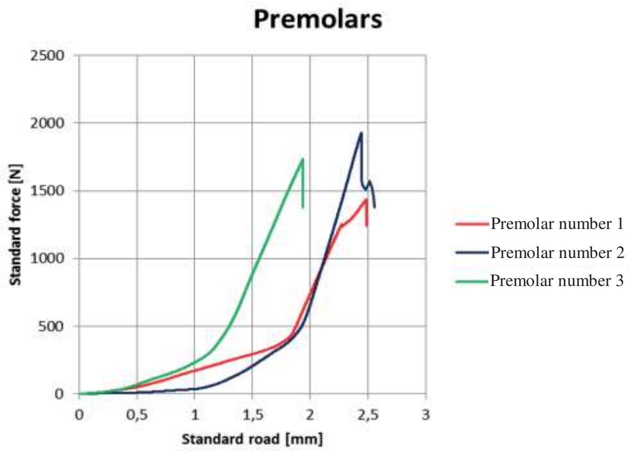

Fig. 10. Relationship between the standard force and the standard path of the occlusal load for premolars

All the crowns of molars were fracturing in the furrow between the buccal and palatal cusps (Fig. 11). The crown of molar 1 fractured at the highest load of 1429.83 N, while the crown of molar 3 broke as the first of the group of teeth with the load of 1046.95 N. The graph demonstrating the relationship between the strength and the path of the occlusal load is shown in Figure 12.

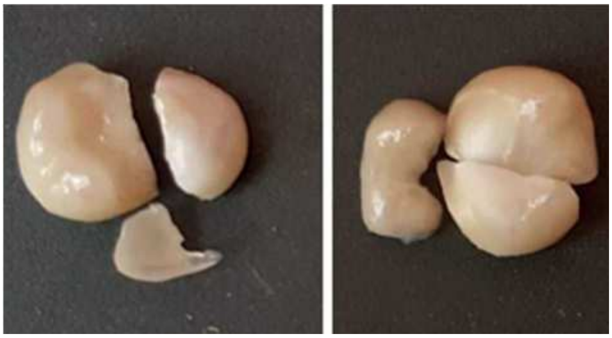

Fig. 11. Crowns of molars after destruction

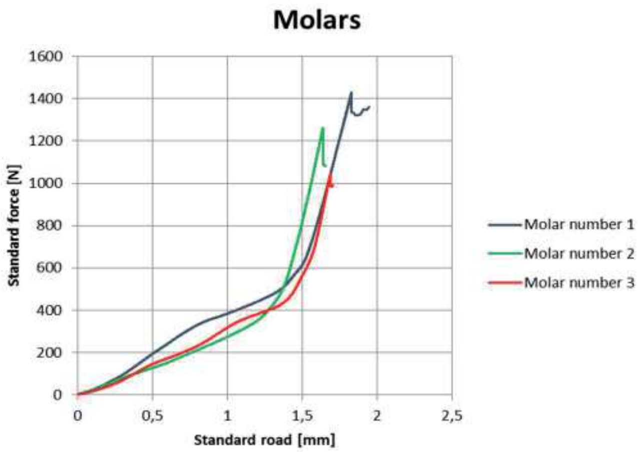

Fig. 12. Relationship between the standard force and the standard path of the occlusal load for molars

3.2. Hardness test

Table 3 shows the results of the hardness tests of porcelain and zirconium oxide. The average hardness of the porcelain was 562.24$HV_{0.5}$, and samples of ZrO_2 1369.52$HV_{0.5}$.

3.3. Results of the fracture line

During the test, for the crowns of each group of teeth images at the places where there has been a broken of all-ceramic crowns were taken with magnification of 500x, and 1000x. All the pictures (Figs. 13-16) show noticeable boundary between zirconia and porcelain. One does not see any transition phase. This demonstrates the mechanical connection between the substructure and the material veneering.

Table 3.
Results of Vickers hardness test for porcelain and zirconium oxide

Crown	Number of measurement	$HV_{0.5}$	
		Porcelain	Zirconia
Incisor	1	531.25	1315.32
	2	540.65	1374.18
	3	503.45	1326.68
	4	582.12	1280.97
	5	551.34	1269.41
Canine	1	596.33	1350.03
	2	601.76	1326.85
	3	543.21	1337.69
	4	567.91	1349.86
	5	533.44	1374.88
Premolar	1	587.11	1386.86
	2	553.23	1350.38
	3	571.63	1338.03
	4	603.43	1365.41
	5	533.46	1317.34
Molar	1	544.21	1329.42
	2	587.54	1391.41
	3	602.44	1374.33
	4	576.23	1350.42
	5	534.12	1369.52
Average		562.24	1369.52
Standard deviation		29.22	29.73

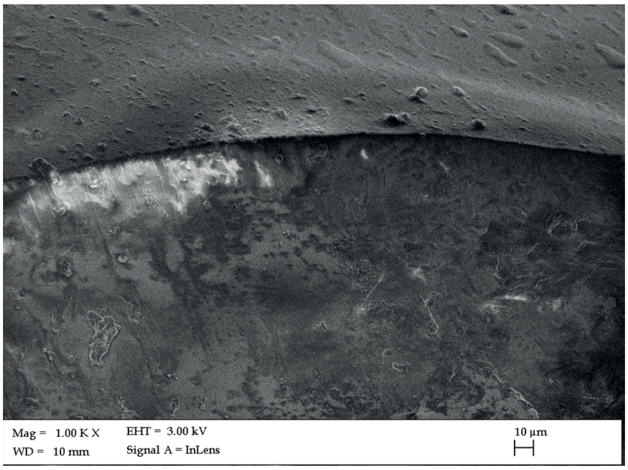

Fig. 13. Fracture line of a crown of an incisor at a magnification of 1000x

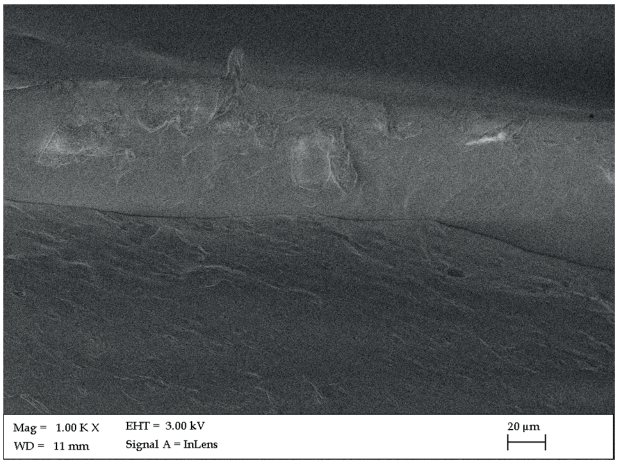

Fig. 14. Fracture line of a crown of a canine at a magnification of 1000x

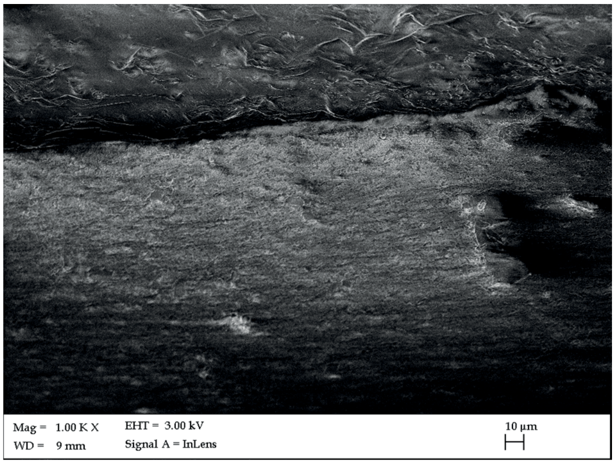

Fig. 15. Fracture line of a crown of a premolar at a magnification of 1000x

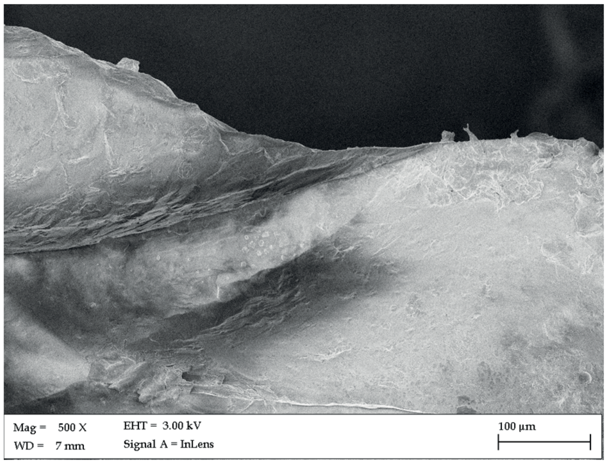

Fig. 16. Fracture line of a crown of a molar at a magnification of 1000x

4. Discussion

On the basis of studies it was found that the values of compressive forces which were obtained at the breakdown of all-ceramic dental crowns are higher than the maximal occlusal forces generated by man. This means that occlusal loads should not cause damage to the restorations of this type during the chewing function. In addition, it should be mentioned that during the normal chewing cycle the maximum bite force are not triggered [2,5,12].

Of all the groups of teeth, the lowest mechanical properties can be found in the crown of the canine, which broke with the lowest compressive load. This observation is also supported by clinical observations. Crowns of canines are destroyed because of their anatomy. They have a very prominent and sharp cusps of the incisive edge. Therefore, the strength of occlusal force causes their damage [4,10,13,14]. Probably, its gentle rounding, could be beneficial for reducing stress concentration in this area and the related increase in compressive strength. The crown of a premolar reached the highest resistance to compressive force.

Cracks that have arisen in this group are the result of compressive force that was loaded centrally on the occlusal surfaces. It should also be noted that the authors of many publications on the biomechanics of the mastication reflect the gentle slope of the teeth during biting [15-18]. Good mechanical properties obtained by zirconia allow for using it for manufacturing of substructures with a smaller wall thickness. It allows for less invasive preparation is on the core [3,6-12].

A very important property of ceramic materials is their hardness, which can be defined as the resistance of a material to permanent penetration of the second material on its surface. In addition, for prosthetic purposes it is an important factor to prevent abrasion of the natural teeth or restorations which are in opposing dental arch.

The study showed an average hardness of porcelain 562.24 $HV_{0.5}$. This result is similar to the hardness of the enamel [4,15,16]. The patient's own teeth should not rub off on contact with the restorations. For zirconia, the hardness values were twice as high as the hardness of the veneering porcelain. The large difference in hardness between the substructure and the veneering material can cause stress, resulting in braking of restorations. In addition, based on tests carried out on a scanning electron microscope, we found a very good adhesion of materials.

Each material is shown as a separate layer, which may indicate an adhesive connection. In terms of aesthetics the use of crowns made on the foundation of zirconia allows to produce fully acceptable prosthetic reconstruction, in contrast to the crowns with the substructure made of metal alloy.

Prosthetic treatment with restorations made of metal may cause discoloration in the area of both the gingival margin and the tooth tissue. In addition, the use of such amendment will not ensure the achievement of transparency of light similar to natural teeth [15-18].

5. Conclusions

On the basis of research found the following conclusions:

1. Compressive forces, at which ceramic crowns are broken down, are in the range of maximal occlusal loads exerted by a man.
2. There is a mechanical connection between zirconia and porcelain. All-ceramic crowns of premolars showed the highest resistance to compressive forces, while the crowns of canines are characterized by the lowest resistance to the biting forces.
3. Full porcelain crowns under static compressive loads are broken down. There is a difference of stresses between the materials, causing a fracture of the restoration which runs along the whole thickness of the crown.

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