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# Assessment of the compressive strength of the metal-ceramic connections in fixed dental restorations

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## ABSTRACT

**Purpose:** The purpose of the work was to evaluate the compressive strength of metal-ceramic connections in the fixed dental restorations.

**Design/methodology/approach:** Restorations were made on a model of the natural patient's dentition which was developed specifically for this study. The study included 10 metal - porcelain crowns, for each group of teeth. Their production used Remanium 2000+ alloy and porcelain Vita VMK Master. A static compression test was carried out on the final crowns and Vicker's hardness test was performed. Visual observations were carried out on a scanning electron microscope.

**Findings:** On the basis of the research and the discussion it was possible to conclude that metal-porcelain crowns have a greater compressive strength than natural human teeth. Thus, they are more resistant to occlusal forces and the crowns for the first molars are the strongest restorations.

**Practical implications:** The metal-porcelain crowns are a very good option for teeth restoration and they can be used even in the areas of the mouth where the occlusal forces reach the maximum values.

**Originality/value:** The article focuses on testing of compressive strength of metal-ceramic crowns. The comparison with natural human occlusal forces shows the sufficient mechanical properties of metal-ceramic crowns for application in humans. The artificial tooth geometry allows applying prosthetic crowns in the patient's mouth without the risk of ceramic break down.

**Keywords:** Metal; Porcelain; Dentistry; Prosthetic crowns; Compressive strength; Hardness; Scanning electron microscopy

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BIOMEDICAL AND DENTAL MATERIALS AND ENGINEERING

## 1. Introduction

The interest in biomaterials and their application to medicine started as early as in the 19th century. Scientific discussion on the application of the materials for use in bone tissue environment is still taking place. The research and experiments conducted on animals whose main objective was the use of alloplastic materials replacing the bone has not come yet to any final conclusion. Today the biomaterials are classified to one of three groups: alloplastic materials - synthetic and biological, autogenous materials - from the same person, allogenous materials - from the same species and xenogenous - from other species [1]. Continuous progress of civilization and development of reconstructive techniques initiated the research and implementation of biomaterials in order to obtain good restorative results.

The most important findings are made in the field of bioengineering, and above all, biomaterials, which are manufactured to be used in dental technology. The knowledge of medicine and technology must be combined together. Medicine cannot do without the knowledge of engineering and vice versa, and the demand of the public continues to grow. Improvement of the standard of living is the incentive for new discoveries in the field of bioengineering and the introduction of new concepts in medicine [2].

### 1.1. Biomaterials

Over time, people have been looking for construction materials and tools that could be used in medicine. Medicine has a lot of challenges for exploration of the materials with very complex requirements for reconstructive techniques and treatment. Thanks to the reconstructive treatment it is possible to repair tissues and organs that have been damaged as a result of disease or injury. Nowadays it is possible to restore the original function and aesthetics of many organs [3,4].

The final result in the successful reconstruction are the best possible performance characteristics, qualitative, functional, mental and physical comfort of the patient. Very important features of the engineering products for different applications in medicine include the geometry of the element, the physical and chemical properties and the quality of manufacturing of the materials. The good material should meet a number of requirements that can be used in a living body without complications. The materials that can be used in medicine are called biomaterials [3,4].

### 1.2. Metals in dentistry

Among biomaterials, metals are a very wide group that has found applications in dental technology, and especially in prosthodontics. Metals are used less frequently in restorative dentistry and the example could be dental amalgam [5].

Surface treatment of metal biomaterials is of vital importance for biocompatibility to the tissues. For example, the surface of a dental implant can be porous to provide better osteointegration or covered with a layer of another material. Biomaterials used in prosthetic dentistry have specific properties, dictated by the terms of the anatomical and physiological requirements [5].

### 1.3. Dental porcelain

Dental porcelain is also known as dental ceramics. First of all, dental porcelain is used as a material for crowns and bridges. Some dental implants are also made of ceramics because of the highest possible biocompatibility. Dental porcelain is composed mainly of feldspar, kaolin and silica. Dental ceramics consists of three main components: 60-65% of silica ($SiO_2$), 5-10% of the feldspar ($K_2O/Al_2O_3/_6SiO_2$) and 15-20% of aluminum oxide ($Al_2O_3$) [6].

With the development of ceramic materials, prosthetics have started to grow the requirements of aesthetics, which is why it was decided to restrict the participation of natural kaolin and replace it with quartz that does not disperse light and provides excellent glassy character. Currently a typical feldspar, due to low mechanical properties, is used as finishing material applied to the surfaces of ceramic [6].

### 1.4. Metal-ceramic connection

Dental technology uses precious metals, non-precious metals and alloys. Precious metals, such as gold and platinum have been used for many years, however, due to the price, their use has been significantly reduced. Instead, dental practices started to use cobalt-based alloys, nickel and titanium [7].

Properties of metal alloys include relatively low thermal conductivity, whose size does not exceed 10-30% of the thermal conductivity of pure nickel or cobalt and is about 10% smaller than the thermal conductivity of the precious metals. Low thermal conductivity is caused by the influence of different metals, which result in the strengthening of the solution, but at the same time reduce the thermal conductivity. In dentistry it is advantageous, because metal prostheses do not heat up rapidly during the contact with a hot agent. Definitely, metallic materials show good characteristics in terms of thermal expansion. This property is particularly important in reconstructions made of ceramics and metal [7].

The core of the metal-ceramic connections is getting a sustainable, durable and aesthetic restoration. Nowadays, aesthetics in dentistry plays a very important role [7].

Mechanical connection occurs through micro grains of ceramics with minor inequalities resulting from blasting the metal surface. During the process of firing, metal oxides diffuse to ceramic and silicon oxides, there is also the diffusion of ceramics to metal surface layer which in turn gives the chemical connection. In addition, at the time of cooling followed by a contraction of both materials leading to stress and the effect of the difference in coefficients of thermal expansion [7].

### 1.5. The forces of mastication

Forces of mastication, or so-called occlusal forces, correspond to the reactions of contacts between the opposing teeth . The values of the forces that occur during the occlusion are a very common research problem within the scope of the biomechanics of the stomatognathic system. It is worth noting that measurements of occlusal forces are relatively easy to check and estimate, however, the obtained results differ significantly (Tab. 1) [8].

Table 1.
Summary of the distribution of the maximum occlusal forces in men and women [8]

| | Force on the teeth, N | | | | | | |
|---|---|---|---|---|---|---|---|
| | Incisors | | Canine | Premolars | | Molars | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Women | 215 | 213 | 301 | 321 | 413 | 433 | 450 |
| Men | 260 | 255 | 413 | 431 | 540 | 606 | 628 |

## 2. Materials and methods

Prosthetic crowns made of ceramics fused to metal substructure were prepared for further compression tests. Two crowns of each group of teeth were manufactured for tests. The material for metal substructure was cobalt alloy Remanium 2000+ (Tabs. 2,3). The veneering ceramics used was Vita VMK Master 95.

Table 2.
Chemical composition of the alloy Remanium 2000+

| Element | Co | Cr | Mo | W | Si | Mn | N |
|---|---|---|---|---|---|---|---|
| % | 61 | 25 | 7 | 5 | 1.5 | < 1 | < 1 |

Table 3.
Technical characteristics of Remanium 2000+ alloy

| Parameter | Value |
|---|---|
| Yield strength, Rp | 0.2-700 MPa |
| Tensile strength, Rm | 900 MPa |
| Hardness, HV | 10-340 HV |
| Elongation at rupture, A | 5-7 % |
| Young's modulus | 200 000 MPa |
| Density | 8.6 g/cm$^3$ |
| Vacuum 25-500°C | 14.0 x 10$^{-6}$ K$^{-1}$ |
| Initial melting point | 1325°C |
| Final melting point | 1415°C |

### 2.1. Static compression test

Auxiliary models have been necessary when performing a static compression tests because they served as the basis for the crowns. As the plaster models do not have the sufficient mechanical characteristics, it was necessary to print 3D models of dentition.

The samples were compressed on Zwick Roell Z020 machine equipped with a specially prepared mandrel (Fig. 1) so that a pressure point was not focused on a particular section of the dental cusp or the incisal edge. In these places there is the greatest concentration of the chewing forces. After exceeding the elastic limit of the sample, permanent deformation causing rupture of porcelain or damage to the metal framework could occur. During the test, each of the crown was separated from the compression element with a separator made of polypropylene. The purpose of this procedure was to eliminate direct contact of the crown against the compression element.

Fig. 1. The testing machine Zwick Roell Z020 with the model of the dentition

## 2.2. Vickers hardness test

Samples for the hardness test were prepared in the form of flat specimens. Samples were subjected to twenty measures under load 500 mgf (5 · 0.9807 N ≈ 4.903 N) for 15 seconds with the hardness tester Future - Tech FM-700 (Fig. 2). 5 measurements were made at five different locations for each material.

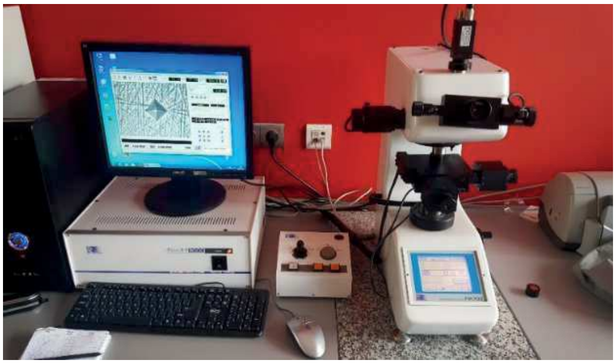

Fig. 2. Laboratory equipment for measuring the hardness of Vickers under low loading

## 2.3. Scanning electron microscopy

In order to carry out microscopic observation, it was necessary to stick the samples to the tables coated with conductive carbon tape (Fig. 3).

Fig. 3. Scanning electron microscope and the sample mounted on a stand in the chamber of the microscope

# 3. Results

## 3.1. The results of the static compression tests

Table 4 shows the results of compression test of the metal-porcelain crowns for each group of teeth. Table 4 includes a force at which there was a disconnection between porcelain and metal substructure, or porcelain has burst and crumble. In the case of incisors the average force at which the destruction of crowns took place is 694.0 MPa, canines reached 840.3 MPa, first premolars 1230.5 MPa and the highest compressive strength showed the first molars to give 1315.0 MPa. The results are illustrated in Figs. 4 and 5.

Table 4.
The results of compressive strength of metal-porcelain crowns for each group of teeth

| Tooth | Series nr | Compressive strength σ, MPa |
|---|---|---|
| Central incisors | 1 | 420 |
| | 2 | 968 |
| Average | | 694 |
| Canine | 1 | 1278 |
| | 2 | 576 |
| | 3 (affected) | 602 |
| | 4 (affected) | 905 |
| Average | | 840.3 |
| First premolars | 1 | 1302 |
| | 2 | 1159 |
| Average | | 1230.5 |
| First molars | 1 | 1324 |
| | 2 | 1306 |
| Average | | 1315 |

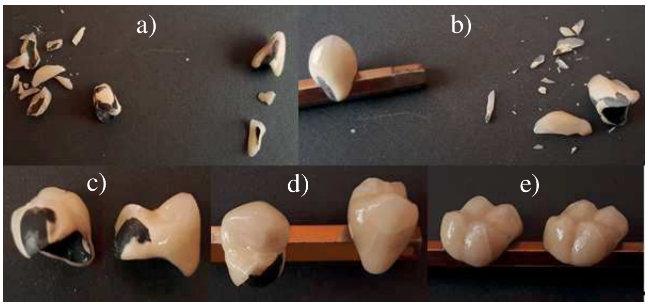


Fig. 4. Destroyed crowns after the compression test: a) medial incisors, b) canines, c) and d) the first premolars, e) the first molars

## 3.2. The results of the Vickers hardness test

The results of measurements of hardness of porcelain and metal frameworks are shown in Tables 5 and 6. On the basis of tests carried out, an arithmetic mean and standard deviation were calculated. The mean hardness of porcelain was 680.3 HV, and its standard deviation averaged 34.976 The hardness of metal was 432.7 HV and the standard deviation was 24.178.

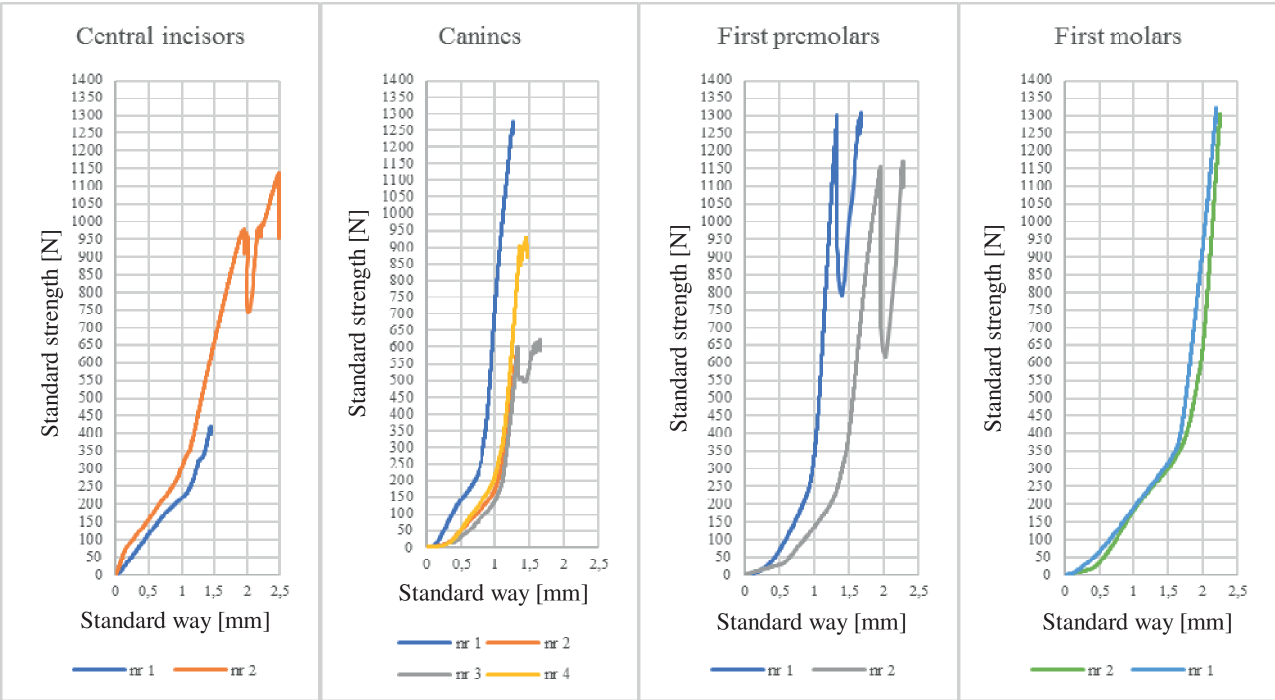


Fig. 5. Static compression tests performed on the medial incisors, canines, first premolars and first molar

Table 5.
The results of Vickers hardness during low load HV 0.5 porcelain Vita VMK Master

| Porcelain Hardness HV 0.5 | | | | |
|---|---|---|---|---|
| No measurement | Central incisors | Canines | First premolars | First molars |
| 1 | 645.8 | 621.6 | 697.9 | 687.2 |
| 2 | 608.8 | 680.4 | 652.2 | 726.3 |
| 3 | 612.5 | 719.2 | 687.4 | 780.4 |
| 4 | 720.4 | 708.1 | 636.8 | 734.0 |
| 5 | 688.8 | 677.3 | 613.1 | 708.1 |
| Average | 655.3 | 681.3 | 657.5 | 727.2 |
| +/- | 680.3 | | | |
| Stand. dev. | 43.466 | 33.868 | 31.461 | 31.109 |
| +/- | 34.976 | | | |

### 3.3. The results of the observations on a scanning electron microscope

Observations were carried out in broken down crowns, where the connection was lost between the material porcelain and the metal substructure (Figs. 6-8). Exceptions were the first molars (Fig. 9). On the borders of breakthroughs it was possible to observe any kind of structural details, such as cracks, microcracks, pores. Analyzing the place in which the rupture occurred could lead to different opinions. For each sample representing each group of teeth the images were taken at 500x magnification, 1000x and 3000x.

Table 6.
The results of the Vickers hardness during low load for Remanium HV 0.5 2000+

| Substructure Hardness HV 0.5 | | | | |
|---|---|---|---|---|
| No measurement | Central incisors | Canines | First premolars | First molars |
| 1 | 398.0 | 424.7 | 407.0 | 488.3 |
| 2 | 403.9 | 396.6 | 478.3 | 402.6 |
| 3 | 414.6 | 438.1 | 438.1 | 421.2 |
| 4 | 457.6 | 408.7 | 423.0 | 434.0 |
| 5 | 412.6 | 404.6 | 389.3 | 441.4 |
| Average | 415.5 | 414.5 | 427.1 | 437.5 |
| +/- | 423.7 | | | |
| Stand. dev. | 22.864 | 14.932 | 30.307 | 28.608 |
| +/- | 24.178 | | | |

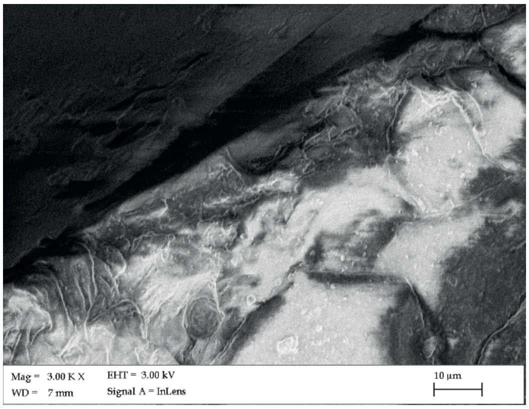


Fig. 6. SEM image of the connection between porcelain and the metal substructure for a central incisor crown at a magnification of 3000x

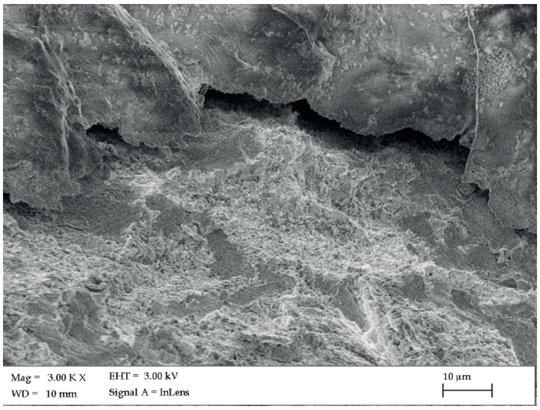


Fig. 7. SEM image of the connection between porcelain and metal substructure of the canine crown at a magnification of 3000x

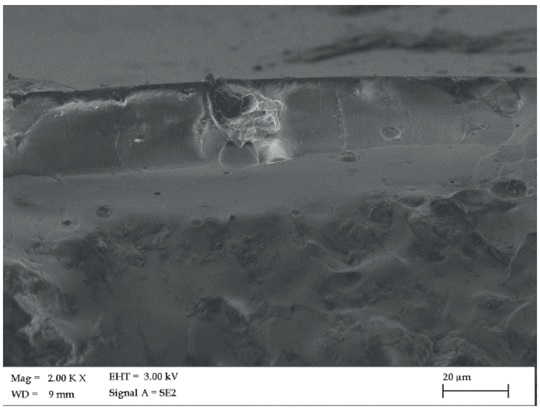


Fig. 8. SEM image of the connection between porcelain and metal substructure for the first premolar crown at a magnification of 500x

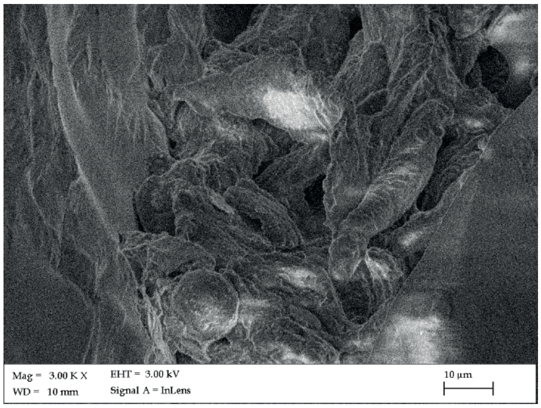


Fig. 9. SEM image for the metal-ceramics connection for the crown of the first molar at a magnification of 100x

## 4. Discussion

Estimation of the compressive strength of connections in metal-ceramic fixed restorations can be made on the basis of the static compression tests and observations under a scanning electron microscope. Additionally, measurements of the hardness of the metal framework and the veneering porcelain can be carried out. As a result of the study it is possible to establish the point at which the metal substructure or the veneering porcelain break down.

When conducting the static compression tests, we selected those parts of teeth that are most likely to be loaded with the biggest chewing forces. It appears to take place in the central incisor, especially at the distal incisal edge, in the canine the area of the incisal cusp, palatal cusp of the first premolars and mesial palatal cusp of the first molars.

The results of the static compression tests of the metal-ceramic crowns were compared to the results of normal occlusal forces which are able to exert by a man [9-12]. It turned out that the values from the static compression tests showed nearly three times higher resistance of the crowns to the compressive forces than the forces exerted by human teeth. It should be noted that the results were obtained from the study protocol using a symmetrical dental arch. It is the indisputable fact that the static compression test uses the force that is applied perpendicular to the long axis of the tooth. As the distribution of natural occlusal forces is never perpendicular, and the resultant force acts at an angle as a result of anatomy and construction of the stomatognathic system, therefore it can be said that the forces exerted during the test are considerably higher than those exerted by own teeth under the influence of the force of the muscles [13-15]. Slightly different matter is when the dental arches are set asymmetrically. Then the occlusal force exerted on the opposing teeth on one side will always be higher than on the opposite side. Then the role of the dentist is a thorough analysis and thoughtful design of the future restoration. During the discussion, it is necessary to draw attention to the fact that occlusal forces depend largely on biostatics, anatomy and the health status of the patient. Therefore, it cannot be clearly defined, that crowns are indestructible in the patient's mouth, because everything depends on the factors mentioned earlier, as well as oral hygiene, which did not fall within the scope of this work. A dentist in the team with a dental technician, despite the large amount of work and effort in the implementation of the ideal crown, are not always able to create the ideal conditions.

Among the examined groups of teeth the best results of static compression tests are characterized by molars, followed by premolars, canines and incisors. These results in comparison with the literature data [9] can be treated reliably, because in the literature the highest bite loads are exerted on molars and force values are falling along the arch. The fact that the molars can withstand the largest compressive forces can be justified by the anatomy of the tooth, its size, area and possibilities of transferring forces and compressive stresses to the adjacent tissues. Premolars that are slightly smaller than the molars but have a much higher surface area than the incisors or canines are also capable of carrying heavy loads, but not as big as molars. More difficult is the interpretation of the results obtained for incisors and canines. The case concerns their anatomy. The teeth are very hard structures and their incisal edges which are the most exposed to compressive forces are subjected to high occlusal forces. Confirmation of the above assumptions illustrate Fig. 5, which shows the destruction caused by the compression. At first glance, you will notice that the greatest damage was on incisors and canines, since porcelain was completely crushed and dropped out of the metal frame. In the case of the premolars porcelain crumbled at the place where the pressure was applied, while the molars lost porcelain without chipping at the point of force application. The analysis of the sites where porcelain cracks or crumbles are repetitive, but you cannot draw firm conclusions by analyzing the study results of two crowns. The best solution would be to conduct studies on a larger number of samples or conduct of clinical trials which would be the most reliable in terms of clinical applications.

According to the literature the ceramic is resistant to compressive forces, in contrast to tensile or shear forces [9,15,16]. In the case where it is possible to control occlusal forces and stresses acting on the crown, materials can be appropriately selected to create the best conditions for the restoration. McLaren [9] suggests that in any prosthetic reconstruction the shape should be designed to change the tensile or shear forces to compressive forces.

Analysis of the damaged metal frameworks of the canines showed that the lack of metal framework underneath the porcelain in the area of the incisal cusp does not significantly affect the change of the fracture line.

Observations by the scanning electron microscopy reveal that the connection between the metal framework and the porcelain coating is chemical. Confirmation of this claim show Fig. 6-8.

The images even at 500 x magnification show the fractures resulting from compression. These gaps were created under the influence of loads applied to the cusps and the incisal edges of the incisors. A layer of porcelain began to detach from the substructure and formed a gap between the two materials, creating additional environment to break the connection. Only on the molars, there has been no gap between metal and ceramics, but the cracks of the porcelain is still visible in Figure 9.

## 5. Conclusions

1. The static compression test proved that the metal - porcelain crowns are destroyed in the range of maximum occlusal loads which can be exerted by a man.
2. The link between the metal and ceramics in the prosthetic crowns has mechanical and chemical nature. The highest compressive strength is seen on the crown of the first molars and the lowest on the mesial incisor crowns due to the geometry of the tooth crowns.
3. The fractures in the metal-ceramic dental crowns occur only in the layer of porcelain and metal framework is not destroyed.

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