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A Study of the Bond Strength of Dental Ceramic Masses and Stomet-1kz and Stomet-2kz Cast Alloys by Three-Point Bending Methods

K. D. Altynbekov[1], B. Zh. Nysanova[1], V. R. Dolgikh[1], L. P. Antonova[2], M. K. Shayakhmetova[1]

[1] *Department of Prosthetic dentistry, Asfendiyarov Kazakh National Medical University, Almaty - 050012, Almaty Region, Kazakhstan.*

[2] *Department of Stomatology, LLP "Educational and Medical Enterprise Daris-TTE", Almaty - 050016, Almaty Region, Kazakhstan.*

Abstract:

The issues of the bond strength of dental alloys and ceramics, such as mechanical retention, compressive stress and chemical effects, have been studied extensively. Despite this, the emergence of new innovative materials requires research on the subject of the physicomechanical characteristics of the bond strength of ceramic masses and alloys. The subject of research was the physicomechanical characteristics of the bond strength of ceramics and cast alloys based on nickel-free cobalt and chromium. To determine the bond strength of ceramics and metals, metal samples were used in the form of a plate made by casting "Stomet-1kz" and "Stomet-2kz" alloys based on nickel-free cobalt and chromium with dimensions of 25x3x0.5 mm. All samples were lined with a ceramic mass 1-1.5 mm thick. Such ceramic masses as "Vita 13", "Design" (Germany), "Noritake EX-3" (Japan), and "Duceram Plus" (Germany) were used as a ceramic coating. They were applied in accordance with the manufacturers' instructions. Each sample was subjected to a three-point bending of the metal part up to the separation of the ceramic layer from the metal alloy. Experimental studies have shown that dental alloys, according to GOST 31575-2012, are characterized by a sufficient amount of stress, at which the ceramic layer does not peel off from the metal sample (must be at least 25 MPa). Among the experimental samples studied, ceramic masses of synthetic origin have the following strength indices: "Noritake EX-3" – 45 ±6τ, MPa; "Design" – 32.8 ±4τ, MPa. In ceramic masses of natural origin, the values are as follows: "Duceram Plus" – 33.5 ±3τ, MPa, "Vita 13" – 26.2 ±2τ, MPa.

Keywords - glass ceramics, bond strength, alloys.

I. INTRODUCTION

Despite the increasing demand for the use of metal-free constructions in the clinic of orthopedic dentistry, metal-ceramic dentures occupy a leading place among other constructions [1, 2].

Meeting the aesthetic and functional requirements, metal-ceramic constructions of dentures have been widely used in clinical practice for over 60 years [3].

Among all metal alloys, the cheapest and, at the same time, one of the most reliable group from the point of view of bond strength with ceramics consists of alloys based on Co - Cr - Mo and Ni - Cr - Mo, which are distinguished by high strength, hardness and sufficient linear and bulk accuracy. The alloys of the Co-Cr system have the following chemical composition of the main components: cobalt - 40-60%, chromium - 20-30%; their main difference is the variation of alloying elements (Nb, Si, Mo, Zn, W). The main purpose of combining them is to ensure a strong adhesion of metal to porcelain. In the development of alloys of this system, a number of problems are solved, the main of which is ensuring a strong adhesion of metal to ceramics.

Ceramic masses during operation have two main characteristics: bending strength (a norm of 50 MPa) and adhesion of opaque masses to metals (a norm of 25 MPa) [4], which is provided by the properties of both the metal and the ceramic itself [5-7].

The bond between ceramics and metals is strong; however, ceramic fractures can occur due to many reasons: frequent stress and deformation during chewing, injuries, technical errors, and pathological occlusion [8].

According to the results of clinical studies on the causes and frequency of destruction of the ceramic lining of metal-ceramic dentures, it consists 0.5-10% of all manufactured [9-11].

The common causes of fractures of ceramic coatings in metal-ceramic dentures after orthopedic treatment include violations of the clinical and laboratory manufacturing stages, the careless attitude of patients to prosthetic constructions, and injuries [12].

In case of the difficult removal of metal-ceramic constructions with fractured ceramic coatings from the mouth and a large length of fractures, the intraoral repair of these defects offers patients an economic and alternative treatment, and can increase their clinical restoration [13].

Currently, the optimal solution to this problem is the restoration of such fractures directly in the patient's oral cavity using modern composite materials, which ensure sufficient durability and foreseeable results [14-17].

In clinical practice, various composite materials have been proposed to restore the integrity of the ceramic coating of metal-ceramic dentures [18-21]. They are used depending on the localization of damage and the design features of dentures [22-25].

At the same time, the restoration of fractured ceramic coatings is considered as a temporary solution to this problem due to the insufficient adhesive bond strength of the restoration materials and the fractured surface of the ceramic lining, but it is more

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preferable than removing and replacing metal-ceramic dentures, which often lead to injury to the periodontium of abutment teeth and the manifestation of patients' negative reactions [26, 27].

The issues of metal bonding with ceramics, such as mechanical retention, the effect of compressive stresses and chemical interaction have been well studied. However, the emergence of new innovative materials requires research on the subject of the physicomechanical characteristics of the bond strength of ceramics and alloys [28-32].

The subject of the present research was the physicomechanical characteristics of the bond strength of ceramics and cast alloys based on nickel-free cobalt and chromium.

II. MATERIALS AND METHODS

In order to determine the bond strength of ceramics and metals, metal samples were used in the form of a plate made by casting "Stomet-1kz" and "Stomet-2kz" alloys based on nickel-free cobalt and chromium with dimensions of 25x3x0.5 mm. All samples were lined with a ceramic mass 1-1.5 mm thick.

Such ceramic masses as "Vita 13", "Design" (Germany), "Noritake EX-3" (Japan), and "Duceram Plus" (Germany) were used as a ceramic coating. They were applied in accordance with the manufacturers' instructions, and then the bond strength of ceramics and alloys was identified.

According to GOST 31575-2012 and ISO 9693 "Dental ceramic fused to metal restorative materials" [4], samples are subjected to a three-point bending of the metal part up to the separation of the ceramic layer from the metal alloy. Before testing, each sample was measured. A testing machine was set to determine the breaking force Ftimes.

The tests were carried out on an Instron 5982 universal testing machine designed for testing tensile, compression and three-point bending at room temperature. The maximum tensile/compression force is 100 kN. The longitudinal strain sensor makes it possible to measure the sample elongation with high accuracy. The equipment includes a camera that allows recording video tests and a furnace that allows heating the sample to 1100°C. The test results were processed with the help of Bluehill 3 software.

III. STATISTICAL ANALYSIS

When testing samples, the calculation of uncertainties was carried out according to the following method [8].

1. "Stomet-1 kz" alloy, "Vita 13" ceramics, thickness 1 mm

The first group of errors (for type A evaluation of uncertainty) includes errors associated with technological variations in the quantity and quality of production.

The second group of errors (for type B evaluation of uncertainty):

the permissible error of the Instron 5982 testing machine θ_1 = 0.5%

the permissible error of the micrometer θ_2 = 0.01%

the permissible error of the caliper θ_3 = 0.1%

The average value of the stress of separation of the ceramic layer from the metal alloy during bending (for n=10) is:

$$R = \frac{1}{10}\begin{pmatrix} 28,62 + 28,9 + 25 + 30,21 + 23,975 \\ +24,025 + 22,8 + 29,302 + 30,5 + 23,13 \end{pmatrix} = 26,34 \ MPa$$

The standard uncertainty $u_A(R)$ of measuring the stress of separation of the ceramic layer from the metal alloy during bending (standard type A uncertainty – standard deviation of the mean) is calculated as follows:

$$u_A(R) = \sqrt{\frac{(28,62-26,34)^2 + (28,9-26,34)^2 + (25-26,34)^2 + (30,21-26,34)^2 + (23,975-26,34)^2 + (24,025-26,34)^2 + (22,8-26,34)^2 + (29,302-26,34)^2 + (30,5-26,34)^2 + (23,13-26,34)^2}{10(10-1)}} = 0,99 MPa$$

In the considered case, to calculate type B uncertainties — uncertainties due to systematic sources — the error limits θ1, θ2, θ3 defined above are used

$$u_B(R) = \sqrt{\frac{(0.5)^2}{3} + \frac{(0.01)^2}{3} + \frac{(0.1)^2}{3}} = 0.294 \ MPa$$

The total uncertainty u_C is calculated as the square root of the sum of the squares of the components of the uncertainties:

$$u_C(R) = \sqrt{(4,44)^2 + (0.294)^2} = 1,03 \ MPa$$

In the considered practical case, the normal law of distribution of possible values of this measurement variable is assumed. In this case, the coverage factor k = 2 at P ~ 0.95. Accordingly, the expanded uncertainty for the confidence level P = 0.95 is presented in the form:

$$u_{0,95} = 2 * 1,03 = \pm 2,07 \ MPa$$

The result of measuring the value of the stress of separation of the ceramic layer from the metal alloy during bending for the normal law of distribution can be represented as

$$R = (26,34 \pm 2,07) \ MPa, \ P \sim 0,95$$

Taking into account the rounding error, we get:

$$R = (26 \pm 2) \ MPa$$

2) "Stomet-1 kz" alloy, "Vita 13" ceramics, thickness 1.5 mm

The first group of errors (for type A evaluation of uncertainty) includes errors associated with technological variations in the quantity and quality of production.

The second group of errors (for type B evaluation of uncertainty):

the permissible error of the Instron 5982 testing machine θ_1 = 0.5%

the permissible error of the micrometer θ_2 = 0.01%

the permissible error of the caliper θ_3 = 0.1%

The average value of the stress of separation of the ceramic layer from the metal alloy during bending (for n=8) is:

$$R=\frac{1}{8}(22{,}18+26{,}265+28{,}152+25{,}33+27{,}45+28{,}545+25{,}984+25{,}21)=26{,}14\ MPa$$

The standard uncertainty $u_A(R)$ of measuring the stress of separation of the ceramic layer from the metal alloy during bending (standard type A uncertainty – standard deviation of the mean) is calculated as follows:

$$u_A(R)=\sqrt{\frac{(22{,}18-26{,}14)^2+(26{,}265-26{,}14)^2+(28{,}152-26{,}14)^2+(25{,}33-26{,}14)^2+(27{,}45-26{,}14)^2+(28{,}545-26{,}14)^2+(25{,}984-26{,}14)^2+(25{,}21-26{,}14)^2}{8(8-1)}}=0{,}73\ MPa$$

In the considered case, to calculate type B uncertainties — uncertainties due to systematic sources — the error limits θ1, θ2, θ3 defined above are used

$$u_B(R)=\sqrt{\frac{(0.5)^2}{3}+\frac{(0.01)^2}{3}+\frac{(0.1)^2}{3}}=0.294\ MPa$$

The total uncertainty u_C is calculated as the square root of the sum of the squares of the components of the uncertainties:

$$u_C(R)=\sqrt{(0{,}73)^2+(0.294)^2}=0{,}79\ MPa$$

In the considered practical case, the normal law of distribution of possible values of this measurement variable is assumed. In this case, the coverage factor k = 2 at P ~ 0.95. Accordingly, the expanded uncertainty for the confidence level P = 0.95 is presented in the form:

$$u_{0,95}=2*0{,}79=\pm 1{,}57\ MPa$$

The result of measuring the value of the stress of separation of the ceramic layer from the metal alloy during bending for the normal law of distribution can be represented as

$$R=(26{,}14\pm 1{,}57)\ MPa,\ P\sim 0{,}95$$

Taking into account the rounding error, we get:

$$R=(26{,}14\pm 1{,}6)\ MPa$$

3) "Stomet-1 kz" alloy, "Design" ceramics, thickness 1 mm

The first group of errors (for type A evaluation of uncertainty) includes errors associated with technological variations in the quantity and quality of production.

The second group of errors (for type B evaluation of uncertainty):

the permissible error of the Instron 5982 testing machine θ_1 = 0.5%

the permissible error of the micrometer θ_2 = 0.01%

the permissible error of the caliper θ_3 = 0.1%

The average value of the stress of separation of the ceramic layer from the metal alloy during bending (for n=8) is:

$$R=\frac{1}{8}(29{,}425+25{,}625+27{,}96+31{,}63+25{,}44+32{,}83+29{,}6+23{,}58)=28{,}26\ MPa$$

The standard uncertainty $u_A(R)$ of measuring the stress of separation of the ceramic layer from the metal alloy during bending (standard type A uncertainty – standard deviation of the mean) is calculated as follows:

$$u_A(R)=\sqrt{\frac{(29{,}425-28{,}26)^2+(25{,}625-28{,}26)^2+(27{,}96-28{,}26)^2+(31{,}63-28{,}26)^2+(25{,}44-28{,}26)^2+(32{,}83-28{,}26)^2+(29{,}6-28{,}26)^2+(23{,}58-28{,}26)^2}{8(8-1)}}=1{,}14$$

MPa

In the considered case, to calculate type B uncertainties — uncertainties due to systematic sources — the error limits θ1, θ2, θ3 defined above are used

$$u_B(R)=\sqrt{\frac{(0.5)^2}{3}+\frac{(0.01)^2}{3}+\frac{(0.1)^2}{3}}=0.294\ MPa$$

The total uncertainty u_C is calculated as the square root of the sum of the squares of the components of the uncertainties:

$$u_C(R)=\sqrt{(1{,}14)^2+(0.294)^2}=1{,}17\ MPa$$

In the considered practical case, the normal law of distribution of possible values of this measurement variable is assumed. In this case, the coverage factor k = 2 at P ~ 0.95. Accordingly, the expanded uncertainty for the confidence level P = 0.95 is presented in the form:

$$u_{0,95}=2*1{,}17=\pm 2{,}35\ MPa$$

The result of measuring the value of the stress of separation of the ceramic layer from the metal alloy during bending for the normal law of distribution can be represented as

$$R=(28{,}26\pm 2{,}35)\ MPa,\ P\sim 0{,}95$$

Taking into account the rounding error, we get:

$$R=(28{,}26\pm 2{,}4)$$

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4) "Stomet-1 kz" alloy, "Design" ceramics, thickness 1.5 mm

The first group of errors (for type A evaluation of uncertainty) includes errors associated with technological variations in the quantity and quality of production.

The second group of errors (for type B evaluation of uncertainty):

the permissible error of the Instron 5982 testing machine θ_1 = 0.5%

the permissible error of the micrometer θ_2 = 0.01%

the permissible error of the caliper θ_3 = 0.1%

The average value of the stress of separation of the ceramic layer from the metal alloy during bending (for n=9) is:

$$R = \frac{1}{9}(28{,}143 + 32{,}85 + 26{,}04 + 29{,}23 + 26{,}08 + 32 + 29{,}8 + 30{,}4 + 27{,}7) = 29{,}14 \ MPa$$

The standard uncertainty $u_A(R)$ of measuring the stress of separation of the ceramic layer from the metal alloy during bending (standard type A uncertainty – standard deviation of the mean) is calculated as follows:

$$u_A(R) = \sqrt{\frac{(28{,}143-29{,}14)^2 + (32{,}85-29{,}14)^2 + (26{,}04-29{,}14)^2 + (29{,}23-29{,}14)^2 + (26{,}08-29{,}14)^2 + (32-29{,}14)^2 + (29{,}8-29{,}14)^2 + (30{,}4-29{,}14)^2 + (27{,}7-29{,}14)^2}{9(9-1)}} = 0{,}8 \ \text{MPa}$$

In the considered case, to calculate type B uncertainties — uncertainties due to systematic sources — the error limits θ1, θ2, θ3 defined above are used

$$u_B(R) = \sqrt{\frac{(0.5)^2}{3} + \frac{(0.01)^2}{3} + \frac{(0.1)^2}{3}} = 0.294 \ MPa$$

The total uncertainty u_C is calculated as the square root of the sum of the squares of the components of the uncertainties:

$$u_C(R) = \sqrt{(0{,}8)^2 + (0.294)^2} = 0{,}85 \ MPa$$

In the considered practical case, the normal law of distribution of possible values of this measurement variable is assumed. In this case, the coverage factor k = 2 at P ~ 0.95. Accordingly, the expanded uncertainty for the confidence level P = 0.95 is presented in the form:

$$u_{0,95} = 2 * 0{,}85 = \pm 1{,}7 \ MPa$$

The result of measuring the value of the stress of separation of the ceramic layer from the metal alloy during bending for the normal law of distribution can be represented as

$$R = (29{,}14 \pm 1{,}7) \ MPa, \ P \sim 0{,}95$$

Taking into account the rounding error, we get:

$$R = (29{,}14 \pm 2) \ \text{MPa}.$$

5) "Stomet-2 kz" alloy, "Noritake X3" ceramics, thickness 1.5 mm

The first group of errors (for type A evaluation of uncertainty) includes errors associated with technological variations in the quantity and quality of production.

The second group of errors (for type B evaluation of uncertainty):

the permissible error of the Instron 5982 testing machine θ_1 = 0.5%

the permissible error of the micrometer θ_2 = 0.01%

the permissible error of the caliper θ_3 = 0.1%

The average value of the stress of separation of the Noritake X3 ceramic layer from the metal alloy during bending (for n=7) is:

$$R = \frac{1}{4}(52{,}67 + 55 + 38.48 + 50.4 + 33{,}19 + 42{,}7 + 42.8) = 78{,}8 \ \text{МПа} \ MPa$$

The standard uncertainty $u_A(R)$ of measuring the stress of separation of the ceramic layer from the metal alloy during bending (standard type A uncertainty – standard deviation of the mean) is calculated as follows:

$$u_A(R) = \sqrt{\frac{(52{,}67-45)^2+(55-45)^2+(38{,}48-45)^2+(50{,}4-45)^2+(33{,}19-45)^2+(42{,}7-45)^2+(42{,}8-45)^2}{7(7-1)}} = 3 \ \text{MPa}$$

In the considered case, to calculate type B uncertainties — uncertainties due to systematic sources — the error limits θ1, θ2, θ3 defined above are used

$$u_B(R) = \sqrt{\frac{(0.5)^2}{3} + \frac{(0.01)^2}{3} + \frac{(0.1)^2}{3}} = 0.294 \ MPa$$

The total uncertainty u_C is calculated as the square root of the sum of the squares of the components of the uncertainties:

$$u_C(R) = \sqrt{(3)^2 + (0{,}294)^2} = 3 \ \text{МПа} \ MPa$$

In the considered practical case, the normal law of distribution of possible values of this measurement variable is assumed. In this case, the coverage factor k = 2 at P ~ 0.95. Accordingly, the expanded uncertainty for the confidence level P = 0.95 is presented in the form:

$$u_{0,95} = 2 * 3 = \pm 6 \ \text{МПа} \ MPa$$

The result of measuring the value of the stress of separation of the ceramic layer from the metal alloy during bending for the normal law of distribution can be represented as

$$R = (45 \pm 6)\text{MPa}, \ P \sim 0{,}95$$

6) "Stomet-2 kz" alloy, "Duceram Plus" ceramics, thickness 1.5 mm

The average value of the stress of separation of the Duceram Plus ceramic layer from the metal alloy during bending (for n=7) is:

$$R = \frac{1}{4}(36{,}36 + 33{,}62 + 40{,}68 + 29{,}55 + 31{,}43 + 30{,}96 + 31{,}64) = 58{,}81 \ MPa$$

The standard uncertainty $u_A(R)$ of measuring the stress of separation of the ceramic layer from the metal alloy during bending (standard type A uncertainty – standard deviation of the mean) is calculated as follows:

$$u_A(R) = \sqrt{\frac{(36{,}36-33{,}46)^2+(33{,}62-33{,}46)^2+(40{,}68-33{,}46)^2+(29{,}55-33{,}46)^2+(31{,}43-33{,}46)^2+(30{,}96-33{,}46)^2+(31{,}64-33{,}46)^2}{7(7-1)}}$$

=1,46 MPa

In the considered case, to calculate type B uncertainties — uncertainties due to systematic sources — the error limits θ1, θ2, θ3 defined above are used

$$u_B(R) = \sqrt{\frac{(0.5)^2}{3} + \frac{(0.01)^2}{3} + \frac{(0.1)^2}{3}} = 0.294 \ MPa$$

The total uncertainty u_C is calculated as the square root of the sum of the squares of the components of the uncertainties:

$$u_C(R) = \sqrt{(1{,}46)^2 + (0{,}294)^2} = 1{,}49 \ MPa$$

In the considered practical case, the normal law of distribution of possible values of this measurement variable is assumed. In this case, the coverage factor k = 2 at P ~ 0.95. Accordingly, the expanded uncertainty for the confidence level P = 0.95 is presented in the form:

$$u_{0{,}95} = 2 * 1{,}49 = \pm 2{,}98 \ MPa$$

The result of measuring the value of the stress of separation of the ceramic layer from the metal alloy during bending for the normal law of distribution can be represented as

$R = (33{,}46 \pm 2{,}98)$ MPa, P ~ 0,95

III. RESULTS

According to the paragraph 4.1.3.2 of GOST 31575-2012, the stress value at which the ceramic layer peels off from the metal sample (τ) should be at least 25 MPa.

Tables 1 and 2 show data on the evaluation of the bond strength of "Vita 13" ceramic masses and "Stomet-1kz" alloy.

Table 1. "Stomet-1 kz" alloy, "Vita 13" ceramics, thickness 1 mm

Width, mm	Thickness, mm	k	F_{times}, N	τ, MPa
3	0,5	2,65	10,8	28,62
3	0,5	2,8	10,32	28,9
3	0,5	2,55	9,8	25
3	0,5	2,65	11,4	30,21
3	0,5	2,5	9,59	23,975
3	0,5	2,5	9,61	24,025
3	0,5	2,5	9,12	22,8
3	0,5	2,45	11,96	29,302
3	0,5	2,5	12,2	30,5
3	0,5	2,65	8,73	23,13
			Average value	26,64

Table 2. "Stomet-1 kz" alloy, "Vita 13" ceramics, thickness 1.5 mm

Width, mm	Thickness, mm	k	F_{times}, N	τ, MPa
3	0,5	2,65	8,37	22,18
3	0,5	2,55	10,3	26,265
3	0,5	2,55	11,04	28,152
3	0,5	2,75	9,21	25,33
3	0,5	2,5	10,98	27,45
3	0,5	2,75	10,38	28,545
3	0,5	2,8	9,28	25,984
3	0,5	2,55	9,89	25,21
			Average value	26,14

As can be seen from Fig. 1, when the breaking force F_{times} = 11.77 N, the ceramic layer is torn off from the metal plate. Then with the help of the diagram the coefficient K is determined, and the stress at which the ceramic layer peels off from the metal plate is found according to the formula $\tau = kF_{times}$.

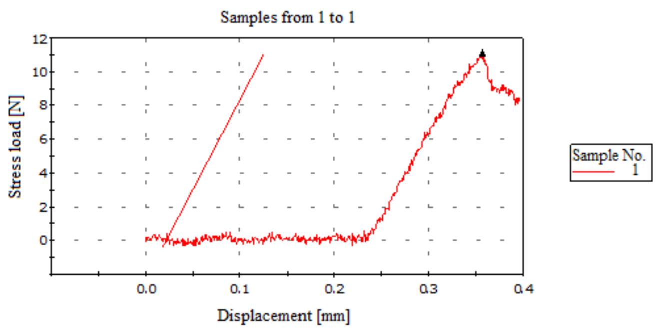

Fig. 1. The diagram obtained by bending the metal plate and "Vita 13" ceramic mass

Tables 3 and 4 show data on the evaluation of the bond strength of “Design” ceramic masses and “Stomet-1kz” alloy.

Table 3. "Stomet-1 kz" alloy, "Design" ceramics, thickness 1 mm

Width, mm	**Thickness, mm**	**k**	**F_{times}, N**	**τ, MPa**
3	0,5	2,5	11,77	29,425
3	0,5	2,5	10,25	25,625
3	0,5	2,65	10,55	27,96
3	0,5	2,45	12,91	31,63
3	0,5	2,65	9,6	25,44
3	0,5	2,45	13,4	32,83
3	0,5	2,5	11,84	29,6
3	0,5	2,8	8,42	23,58
			Average value	28,24

Table 4. "Stomet-1 kz" alloy, "Design" ceramics, thickness 1.5 mm

Width, mm	**Thickness, mm**	**k**	**F_{times}, N**	**τ, MPa**
3	0,5	2,65	10,62	28,143
3	0,5	2,45	13,41	32,85
3	0,5	2,8	9,3	26,04
3	0,5	2,75	10,63	29,23
3	0,5	2,55	10,23	26,08
3	0,5	2,4	13,33	32
3	0,5	2,7	11,04	29,8
3	0,5	2,82	10,78	30,4
3	0,5	2,55	10,88	27,7
			Average value	29,14

Fig. 2 shows the diagram obtained by bending "Stomet 1kz" metal alloy and "Design" ceramic layer.

As can be seen from Figure 2, when the breaking force F_{times} = 11.04 N, the ceramic layer is torn off from the metal plate. Then with the help of the diagram the coefficient K is determined, and the stress at which the ceramic layer peels off from the metal plate is found according to the formula $\tau = kF_{times}$.

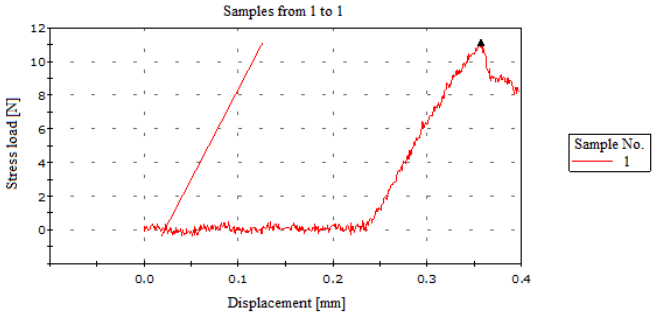

Fig. 2. The diagram obtained by bending "Stomet 1kz" metal alloy and "Design" ceramic layer 1 mm thick

Table 5 shows data on the evaluation of the bond strength of “Noritake X3” ceramic masses and “Stomet-2kz” alloy.

Table 5. "Stomet-2 kz" metal alloy and "Noritake X3"

Width, mm	**Thickness of the metal alloy, mm**	**k**	**F_{times}, N**	**τ, MPa**
3	0,5	3,6	14,63	52,67
3	0,5	3,6	15,29	55
3	0,5	3,6	10,69	38,48
3	0,5	3,6	14,0	50,4
3	0,5	3,6	9,22	33,19
3	0,5	3,6	11,86	42,7
3	0,5	3,6	11,89	42,8
			Average value	45±6

As can be seen from Figure 3, when the breaking force F_{times} = 15.29 N, the ceramic layer is torn off from the metal plate. Then with the help of the diagram, shown in Figure 2, the coefficient k is determined, and the stress at which the ceramic layer peels off from the metal plate is found according to the formula $\tau = kF_{times}$.

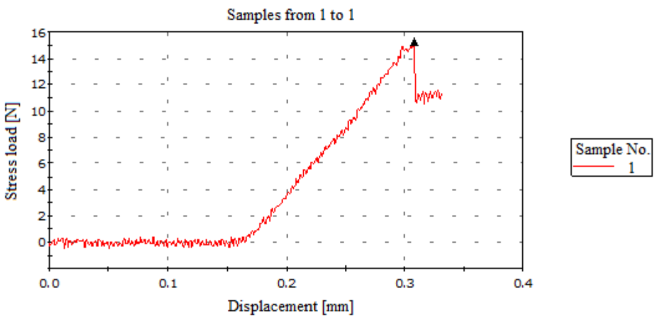

Fig. 3. The diagram obtained by bending "Stomet-2kz" metal alloy and "Noritake X3" ceramic mass

Table 6 shows data on the evaluation of the bond strength of "Duceram Plus" ceramic masses and "Stomet-2kz" alloy.

Table 6. "Stomet-2 kz" metal alloy and "Duceram Plus"

Width, mm	Thickness, mm	k	F_{times}, N	τ, MPa
3	0,5	3,6	10,1	36,36
3	0,5	3,6	9,34	33,62
3	0,5	3,6	11,3	40,68
3	0,5	3,6	8,21	29,55
3	0,5	3,6	8,73	31,43
3	0,5	3,6	8,6	30,96
3	0,5	3,6	8,79	31,64
			Average value	33,5±3

As can be seen from Figure 4, when the breaking force F_{times} = 8.75 N, the ceramic layer is torn off from the metal plate. Then with the help of the diagram the coefficient K is determined, and the stress at which the ceramic layer peels off from the metal plate is found according to the formula $\tau = kF_{times}$.

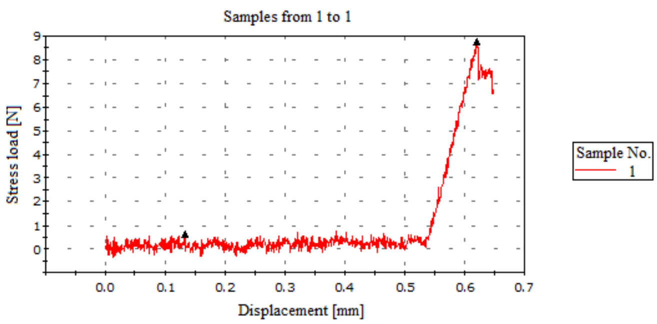

Fig. 4. The diagram obtained by bending the metal plate and "Duceram Plus" ceramic mass

IV. DISCUSSION

The quality of metal-ceramic constructions largely depends on the properties of the alloys used and the strength of their adhesion to the ceramic coating, since during the chewing process dentures are deteriorated and deformed.

According to the theory of combining metals and ceramics, several types of fusing of the ceramic lining with the metal denture part are known: mechanical retention, compressive forces, van der Waals forces and chemical compounds [33].

Compressive forces inside the metal-ceramic construction are developed due to the precisely manufactured frame and a slightly higher thermal expansion coefficient of the metal than the covering porcelain. This slight difference makes porcelain "stretch" towards the metal frame when the denture is cooled after firing.

A chemical compound is formed due to the development of an oxide layer on the metal and the strength of the compound, which is increased by firing in an oxygen-rich atmosphere. It is known that metal alloys easily form chromium oxides, which are firmly bonded to porcelain without any other substances.

To improve the connection between ceramics and metals, various technologies and materials are used. It was found that when using 4% hydrofluoric acid, the bond strength was 25.278 MPa [34].

The data of a number of studies indicate an increase in the concentration of metal elements, in particular, chromium, in the opaque layer after sintering, which may cause an increase in the adhesive force of materials [35].

A comparative analysis of the adhesive retention of various lining coatings on non-noble alloys using plasma compounding mechanisms showed high adhesive strength (28–35 MPa) [36].

Based on the study of the adhesive strength of the Co-Cr alloy and ceramic coatings, it was shown that in Duceram Plus it amounted to 45-47 MPa and in Duceram Love – to 43-44 MPa [37].

It is known that dental porcelain and the metal frame used for the manufacture of a denture must have compatible melting points and thermal coefficient of linear expansion. The thermal coefficient of linear expansion of the studied alloys Stomet-1kz and Stomet-2kz in the temperature range of 20-50^{0}C is within 14.2 – 16,1*10^{-6}K^{-1}. The thermal expansion coefficient of Noritake EX-3 is 12,4 × 10^{-6}/°C (25°C ~ 450°C). Accordingly, the values of the thermal expansion coefficients of alloys suitable for the application of Noritake EX-3 ceramics range from 13,3 × 10^{-6}/°C to 14,3 × 10^{-6}/°C. A distinctive feature of Noritake EX-3 porcelain is its high strength [38].

The high rate of oxidation between Noritake EX-3 porcelain and the alloy can be explained by the fact that Noritake EX-3 allows repeated firing. With this technology, the risk of spalling is almost zero.

Duceram Plus is well fused with all dental alloys. This is due to the selective solubility of chromium oxides. The thermal expansion coefficient of alloys can be between 25-600°C=13,8 and 15,2 mkm/m [39].

The results of our studies have shown that dental alloys, according to GOST 31575-2012, are characterized by a sufficient amount of stress at which the ceramic layer does not peel off from the metal sample (must be at least 25 MPa). The chemical composition of the studied alloys Stomet-1kz and Stomet-2kz with an increase in the Si content by 1% significantly increases the strength of adhesion of metal to ceramics.

Among the experimental samples studied, ceramic masses of synthetic origin have the following strength indices: "Noritake EX-3" – 45 ±6 τ MPa; "Design" – 32,8 ±4τ MPa. In ceramic masses of natural origin, these values are as follows: "Duceram Plus" – 33.5 ±3 τ MPa; "Vita 13" – 26.2 ±2τ MPa.

As a result of the experimental studies, new data were added on the bond strength of ceramics and metals, which can be further applied in scientific research. It is established that the proposed chemical composition of the developed alloys provides adequate adhesion of ceramics and metals in the manufacture of metal-ceramic dentures. This allows the manufacture of extended metal-ceramic dentures.

V. CONCLUSIONS

As a result of the research, the mathematical model of the three-motor asynchronous electric drive of synchronous rotation with the frequency converter of belt conveyor was developed, which takes into account feedbacks on the mismatch of motor speeds, as well as the relationship of conveyor drive drums through a conveyor belt with a certain tension value. The resulting model ensures the synchronous rotation of the electric motors of the system, thereby ensuring the service life of the belt conveyor. The optimal control law as a function of time is determined, ensuring smooth start and braking, reducing the cost of electricity during the transition of the conveyor from one mode to another. To implement the tasks of optimal control of a multi-motor electric belt conveyor, the Pontryagin L.S. principle method is applied. The algorithm and program for calculating the optimal control of the multi-motor asynchronous electric drive of synchronous rotation with the frequency converter of belt conveyor were compiled and the “S” shaped optimal control curve was determined. The functionality of modern industrial frequency converters makes it possible to successfully implement the obtained optimum acceleration curve of a three-motor asynchronous electric drive of belt conveyor.

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