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Analisys of the metal framework of the fixed prosthetic restoration with facing material – ceramics

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Abstract: Progress and achievements in the field of medical knowledge, technical sciences and materials engineering related to the broadly understood aspects of human health and life have intensively influenced the development of technologies used in the production of permanent prosthetic restorations. Ceramic materials and metal alloys with a wide range of applications in the manufacture of prosthetic restorations deserve special attention. The combination of the positive features of these two materials, with different chemical and physical properties, made it possible to obtain prosthetic structures that meet the strength and aesthetic requirements. Despite the dynamic development of more and more new techniques, devices and materials for the production of prosthetic restorations, metal-ceramic constructions are still a reliable and dominant method of making dental restorations of permanent crowns and bridges. Their quality and durability is largely influenced by the method of connecting the ceramic facing material with the metal base. There are three types of connections: physical, mechanical and chemical. The basis of the physical connection is the selection of appropriate thermal expansion coefficients of both materials. It is related to the compressive stresses occurring during the cooling of the fired ceramics.. The formation of depressions on the surface of the framework causes retention and microretention, thanks to which the surface of ceramic-metal adhesion increases. The chemical connection ensures the formation of a controlled oxide layer on the metal base due to the content of elements such as gallium, indium or iron.

***Keywords*:** metal, ceramics, metal substructure, metal-ceramic connection

1. Introduction

The growing interest in aesthetics and biocompatibility in dental prosthetics has resulted in the search for new materials for the production of permanent restorations.

Porcelain is commonly believed to be the best aesthetic material for permanent prosthetic restorations. This is due to many features, especially positive ones: indifference to the oral cavity environment, good aesthetic properties, low heat conductivity, resistance to body fluids, mechanical strength (hardness 7°on the Mohs scale).The glaze surface of the crowns meets the requirements of aesthetics, does not tarnish, does not change color and is resistant to plaque deposition. Currently, much attention is paid to ceramic materials used to make all-ceramic crowns. Bieniek and Spikermann divided the ceramics used today without a metal base.

Depending on the technique of production, they are divided into: systems with a hard foundation (Hi-Ceram, In - Ceram), layered ceramics (Mirage, Optec), pressed ceramics (Empress), cast ceramics (Dicor), ceramic systems made with computer support - CAD / CAM system.

Clinical evaluation of materials is based on parameters such as strength, marginal integrity, aesthetics, biocompatibility, abrasion, color stability and applicability. These materials are characterized by high mechanical strength. Metal-ceramic restorations are also characterized by high mechanical resistance, in which the metal part determines durability, and the fired porcelain ensures aesthetics. The use of the Finite Element Meteode (FEM) analysis allows for the design of safe structures and the preparation of effective manufacturing processes. Thanks to the MES package, it is possible to carry out complex analyzes and simulations of technological processes. An important material parameter is the breaking strength of the metal-ceramic connection, as well as the hardness of

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individual layers of dental ceramics. The characteristics of the mechanical properties are based on the research carried out by (Kowalczyk, 2001; Kowalczyk., Dobies,1999). However, the most interesting problem is the stress that occurs between the metal-fired porcelain and the metal. Therefore, the main emphasis in the study was placed on determining the effect of veneering with ceramics of a chromium-nickel alloy on the level of stresses arising in the ceramic-alloy system.I also consider the phenomenon of combining ceramics with a suitable metal alloy at high temperature, as well as the possibility of firing successive layers of porcelain on top of each other, to be an important problem. This issue was discussed on the basis of research conducted by (Kowalczyk , 2001).

2. Materials and methods

The Finite Element Method Package (FEM) was used to analyze the metal-ceramic connection.

2.1. The Finite Element Method package (FEM)

The finite element method (FEM) is now a commonly used engineering calculation tool. Computer programs in which the finite element method is used consist of three main parts:

1. preprocessor in which the task to be solved is built;
2. processor, i.e. the computing part;
3. postprocessor, used for the graphic presentation of the obtained results.

For users of these programs, the most laborious and time-consuming stage of solving a task is the division into finite elements in the preprocessor. It should be mentioned here that wrong division into finite elements causes wrong results.

2.2.1.The essence of the Finite Element method

The essence of the FEM method consists in dividing a complex area into simple sub-areas, which we call finite elements because they have a finite length. A finite element has four properties: shape - sub-areas can be in the form of a segment point, square, triangle, rhombus, trapezoid, solid; nodes - these are points where the sub-areas are interconnected and the vectors under consideration are related to, points of application of loads in the form of concentrated forces; quantities data and unknowns (analyzed quantities determined by specifying their values in nodes - known quantities, e.g. forces and moments loading structures and unknown displacement components), number of degrees of freedom of elements (LSSE).

The number of degrees of freedom of an element is the product of the number of nodes (Lw) and the degrees of freedom of a node (ss).

$$LSSE = L_w \cdot ss \tag{1}$$

and functions approximating Ni (shape functions):

- Function approximating degree "0"

$$T(x) = \frac{T_A + T_B}{2} = 0{,}5 \cdot T_A + 0{,}5 \cdot T_B \tag{2}$$

$$N_A = 0.5,\ N_B = 0.5 \tag{3}$$

- Function approximating degree „1”

$$\frac{T_A - T_B}{l} = \frac{T(x)}{x} \tag{4}$$

$$T(x) = \frac{x}{l} T_A + (\frac{x}{l} - 1) \cdot T_B \tag{5}$$

$$N_A = \frac{x}{l},\ N_B = \frac{x}{l} - 1 \tag{6}$$

where T_A - temperature at node A, N_A - shape function (constant), T_B- temperature at node B, N_B - shape function (constant).

2.3. Construction of the FEM model

2.3.1. Assumption of the task

The porcelain firing process takes place in a fully automatic, electronically controlled furnace under vacuum conditions. Cooling takes place gradually with air access, therefore the convection coefficient (thickness of the air layer) is taken into account Convection coefficient = 0.014 at 80 ° C

2.3.2. Geometric model

2.3.2.1. Introducing keypoints

2.3.2.2. Spreading continuous curves based on points

Individual points are connected with each other by lines. (Fig. 1)

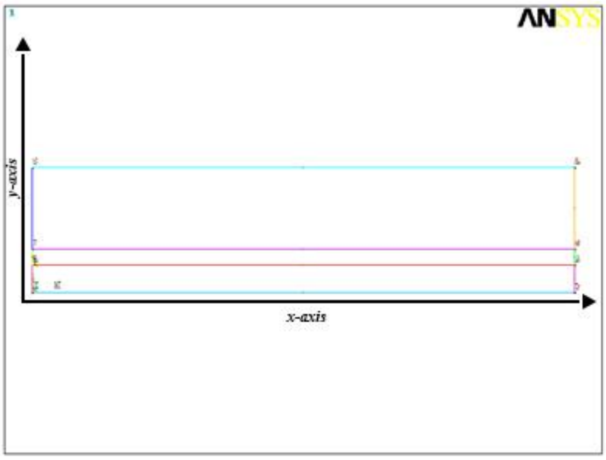

Fig. 1. Spread of continuous curves based on model points

2.3.2.3 Create and glue surfaces (Ai)

A1 - metal surface; A2 - opaque surface; A3 - porcelain surface (Fig. 2)

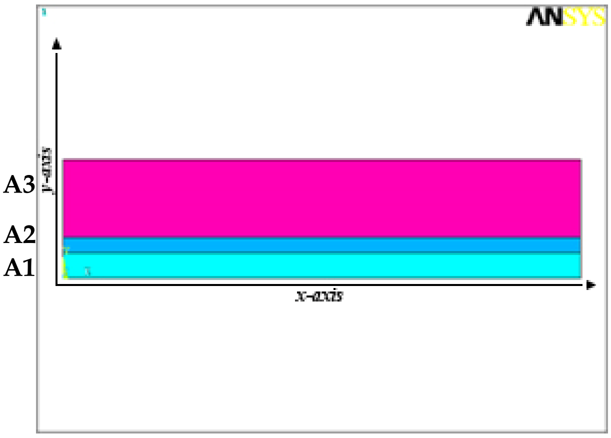

Fig. 2. Creation and gluing of the model surface

2.3.3. Differentiation of material parameters of individual layers

A1 (metal), A2 (opaque), A3 (dentin)

2.4 Boundary conditions of the task

The boundary conditions are defined by:

a. Initial temperature T_i = 900 ° C
b. Final temperature T_f= 36 ° C

These are the extreme temperatures in the cooling process of porcelain fired onto metal.

2.5. The finite element PLANE13

The PLANE 13 element is used for two-dimensional (2-D) analysis of coupled fields, i.e. the simultaneous analysis of the magnetic, thermal, electric, piezoelectric, structural fields, i.e. the field of stresses and strains. Used in structural analysis, PLANE 13 has the ability to analyze stresses and strains in the nonlinear ANSYS / Mechanical range. KEYOPT (1) option option is assumed to be 4. Then the item has degrees of freedom:

3. UX,
4. UY,
5. TEMP.

To sum up, the Plane 13 element is used for simultaneous thermal and strength analysis. It enables the determination of deformations occurring for systems of various materials characterized by different material factors under the influence of changing temperature conditions - cooling process.

2.6. Division into finite elements (mesh)

The division into finite elements of individual areas A1, A2, A3 is shown in Fig. 3.

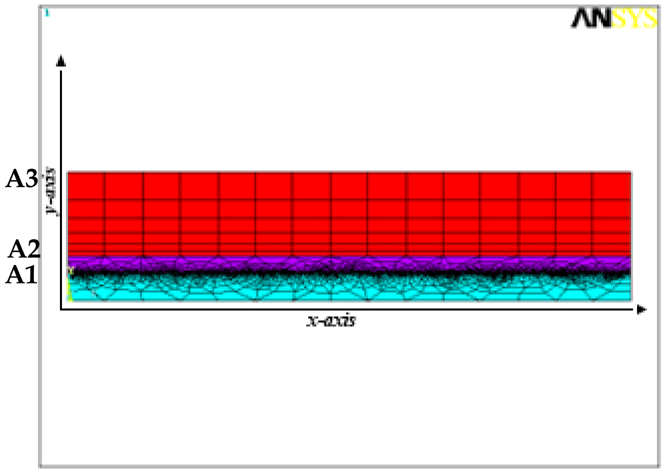

Fig. 3. Division of the model into finite elements

3. Results and discussion

3.1. The results of the analysis carried out

The analysis of the above-mentioned model was carried out during the cooling process from the firing temperature to room temperature. The tests were carried out for chrome-nickel alloys: Vicron S, Wirocer, Wiron 99, Wiron 88, Eversoft, Superbond, Supremcast and ceramics: Vita Omega 900, Vita VMK 95, Vita Response, Vita VM 13. (Table 1)

Table 1. List of types of ceramics and types of alloys used for analyzes

Analisys No	Layer No	Material	Thermal expansion coefficient $[10^{-6} K^{-1}]$	Young Modulus (E) [GPa]	Thermal conductivity (Axis X)
1	A3	Vita Omega 900 (dentyna)	13.6	91	1.1
	A2	Vita Omega 900 (opaker)	14.4	91	1.2
	A1	Vicron S	13.8	200	1.44
2	A3	Vita VMK 95 (dentyna)	13.5	91	1.1
	A2	Vita VMK 95 (opaker)	13.6	91	1.2
	A1	Vicron S	13.8	200	1.44
3	A3	Vita Response (dentyna)	15.3	91	1.1
	A2	Vita Response (opaker)	15.7	91	1.2
	A1	Vicron S	13.8	200	1.44
4	A3	Vita VM 13 (dentyna)	13.3	91	1.1
	A2	Vita VM 13 (opaker)	13.7	91	1.2
	A1	Vicron S	13.8	200	1.44

5	A3	Vita Omega 900 (dentyna)	13.6	91	1.1
	A2	Vita Omega 900 (opaker)	14.4	91	1.2
	A1	Wirocer	14.0	200	1.44
6	A3	Vita VMK 95 (dentyna)	13.5	91	1.1
	A2	Vita VMK 95 (opaker)	13.6	91	1.2
	A1	Wirocer	14.0	200	1.44
7	A3	Vita Response (dentyna)	15.3	91	1.1
	A2	Vita Response (opaker)	15.7	91	1.2
	A1	Wirocer	14.0	200	1.44
8	A3	Vita VM 13 (dentyna)	13.3	91	1.1
	A2	Vita VM 13 (opaker)	13.7	91	1.2
	A1	Wirocer	14.0	200	1.44
Analisys No	**Layer No**	**Material**	**Thermal expansion coefficient [10^{-6} K^{-1}]**	**Young's Modulus (E) [GPa]**	**Thermal conductivity (Axis X)**
9	A3	Vita Omega 900 (dentyna)	13.6	91	1.1
	A2	Vita Omega 900 (opaker)	14.4	91	1.2
	A1	Wiron 99	13.8	205	1.44
10	A3	Vita VMK 95 (dentyna)	13.5	91	1.1
	A2	Vita VMK 95 (opaker)	13.6	91	1.2
	A1	Wiron 99	13.8	205	1.44
11	A3	Vita Response (dentyna)	15.3	91	1.1
	A2	Vita Response (opaker)	15.7	91	1.2
	A1	Wiron 99	13.8	205	1.44
12	A3	Vita VM 13 (dentyna)	13.3	91	1.1
	A2	Vita VM 13 (opaker)	13.7	91	1.2
	A1	Wiron 99	13.8	205	1.44
13	A3	Vita Omega 900 (dentyna)	13.6	91	1.1
	A2	Vita Omega 900 (opaker)	14.4	91	1.2
	A1	Wiron 88	13.9	200	1.44
14	A3	Vita VMK 95 (dentyna)	13.5	91	1.1
	A2	Vita VMK 95 (opaker)	13.6	91	1.2
	A1	Wiron 88	13.9	200	1.44
15	A3	Vita Response (dentyna)	15.3	91	1.1
	A2	Vita Response (opaker)	15.7	91	1.2
	A1	Wiron 88	13.9	200	1.44
16	A3	Vita VM 13 (dentyna)	13.3	91	1.1
	A2	Vita VM 13 (opaker)	13.7	91	1.2
	A1	Wiron 88	13.9	200	1.44
17	A3	Vita Omega 900 (dentyna)	13.6	91	1.1
	A2	Vita Omega 900 (opaker)	14.4	91	1.2
	A1	Eversoft	12.83	200	1.44
18	A3	Vita VMK 95 (dentyna)	13.5	91	1.1
	A2	Vita VMK 95 (opaker)	13.6	91	1.2
	A1	Eversoft	12.83	200	1.44
19	A3	Vita Response (dentyna)	15.3	91	1.1
	A2	Vita Response (opaker)	15.7	91	1.2
	A1	Eversoft	12.83	200	1.44

Analisys No	Lajer No	Material	Thermal expansion coefficient [10^{-6} K^{-1}]	Young's modulus(E) [GPa]	Thermalconductivity (Axis X)
20	A3	Vita VM 13 (dentyna)	13.3	91	1.1
	A2	Vita VM 13 (opaker)	13.7	91	1.2
	A1	Eversoft	12.83	200	1.44
21	A3	Vita Omega 900 (dentyna)	13.6	91	1.1
	A2	Vita Omega 900 (opaker)	14.4	91	1.2
	A1	Superbond	14.07	200	1.44
22	A3	Vita VMK 95 (dentyna)	13.5	91	1.1
	A2	Vita VMK 95 (opaker)	13.6	91	1.2
	A1	Superbond	14.07	200	1.44
23	A3	Vita Response (dentyna)	15.3	91	1.1
	A2	Vita Response (opaker)	15.7	91	1.2
	A1	Superbond	14.07	200	1.44
24	A3	Vita VM 13 (dentyna)	13.3	91	1.1
	A2	Vita VM 13 (opaker)	13.7	91	1.2
	A1	Superbond	14.07	200	1.44
25	A3	Vita Omega 900 (dentyna)	13.6	91	1.1
	A2	Vita Omega 900 (opaker)	14.4	91	1.2
	A1	Supremcast	13.4	200	1.44
26	A3	Vita VMK 95 (dentyna)	13.5	91	1.1
	A2	Vita VMK 95 (opaker)	13.6	91	1.2
	A1	Supremcast	13.4	200	1.44
27	A3	Vita Response (dentyna)	15.3	91	1.1
	A2	Vita Response (opaker)	15.7	91	1.2
	A1	Supremcast	13.4	200	1.44
28	A3	Vita VM 13 (dentyna)	13.3	91	1.1
	A2	Vita VM 13 (opaker)	13.7	91	1.2
	A1	Supremcast	13.4	200	1.44

3.2. Results of the conducted analyzes

The results of the analyzes are illustrated in the drawings which show:
- stresses along the X axis fibers (SX);
- stresses running along the fibers of the Y axis (SY);
- stress intensity, material stress (SINT);
- reduced stresses (SEQV), equivalent stresses, which also speak
- about the effort of the material;
- model deformations along the X axis (UX);
- model deformations along the Y axis (UY).

In order to present the results of the analyzes, the most interesting models representing the above-mentioned stresses were selected.(Fig. 4 to Fig. 6)

3.3. Influence of the thermal expansion coefficient on the connection between porcelain and metal

The quality of the bond between metal and porcelain is influenced by the thermal expansion coefficient (TEC). In the absence of a combination of metal and porcelain (Fig. 8a), on cooling from the firing temperature to room temperature, the metal contracts more than porcelain because the TEC of the metal is greater than the TEC of porcelain. When metal and porcelain are joined (Fig. 8b), the shrinking metal part exerts compressive stresses in the porcelain, which prevents fractures. If the shrinkage of the metal is lower than that of porcelain, it will result in tensile stresses in the porcelain. Due to the brittleness of the ceramics, these stresses can damage it.

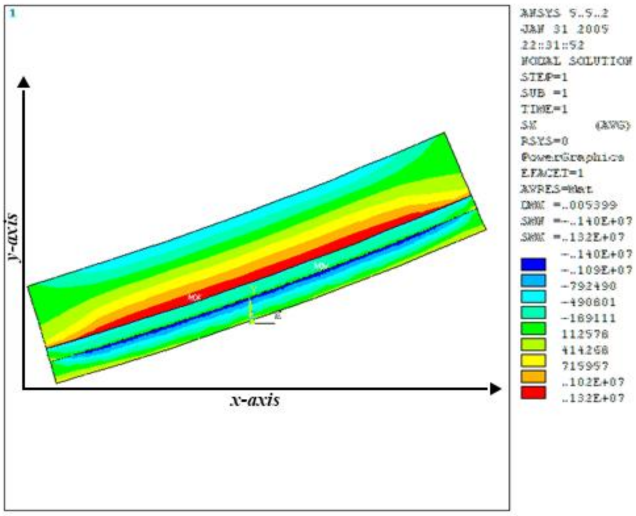

Fig . 4. Stresses UY forVita VM 13 and Vicron S

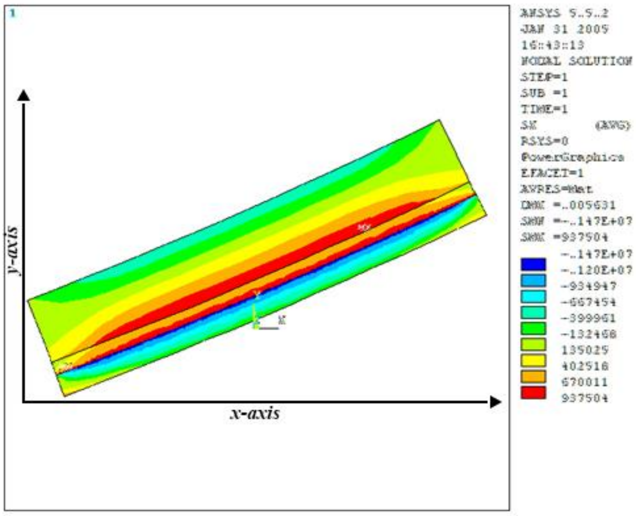

Fig. 5. Stresses SX for Vita VMK 95 and Wiron 88

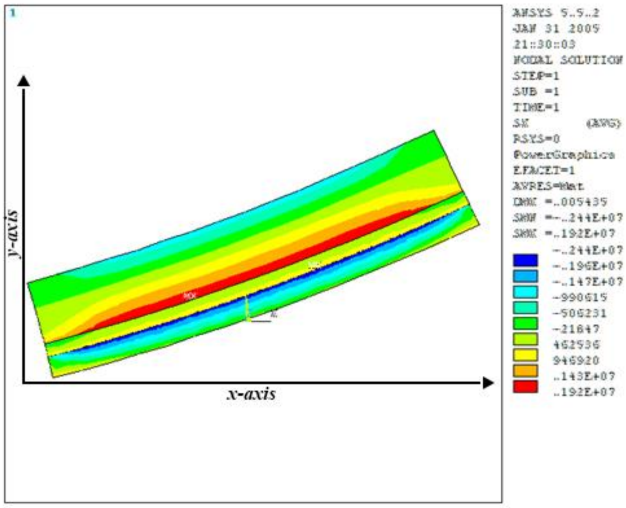

Fig. 6. Stresses SX for Vita VM 13 and Superbond

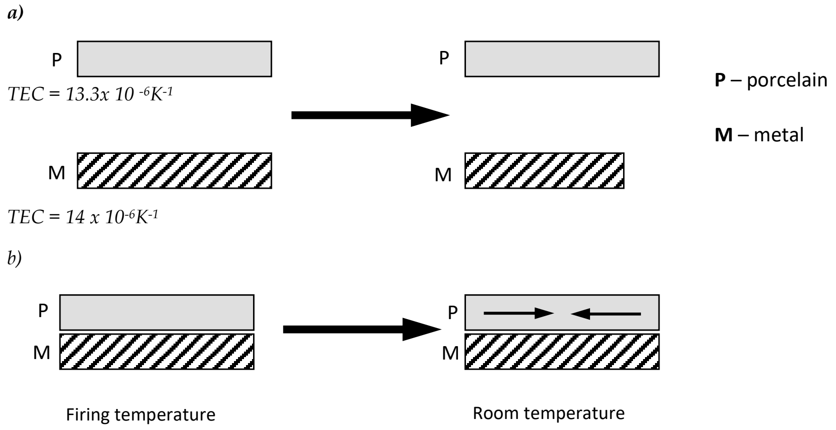

Fig. 8. The influence of the thermal expansion coefficient (TEC) of metal and porcelain on the quality of the connection between these components: (a) in the absence of a combination of metal and porcelain (b) when joining metal and porcelain

3.4. Results summary

The results are summarized in Table 2.

Tab. 2 Summary of the analysis results

Analisysy No	Type of Results	Smin	Smax
4	UX	-.005399	.001775
	UY	-.001452	.003727
	SX	-.140E+07	.132E+07
	SY	-542351	.108E+07
	SINT	.436E+08	.100E+09
	SEQV	.434E+08	.995E+08
14	UX	-.005626	.00179
	UY	-.001684	.004268
	SX	-.147E+07	937504
	SY	-785473	.138E+07
	SINT	.443E+08	.101E+09
	SEQV	.441E+08	.100E+09
24	UX	-.005435	.001794
	UY	-.001413	.003826
	SX	-.224E+07	.192E+07
	SY	-923609	.217E+07
	SINT	.436E+08	.103E+09
	SEQV	.433E+08	.102E+09

By analyzing the obtained results, it was found that there are differences in the values of compressive and tensile stresses. These differences result from different values of the thermal expansion coefficients (TEC). The greater the difference in the TEC values of metal and porcelain, the greater the stresses and deformations of the model. This dependence can be easily explained using the formula for stresses (σ):

$$\sigma = E \cdot \varepsilon \tag{7}$$

where: σ – stress, ε - deformation, E - Young's Modulus.

The formula shows that the stresses are directly proportional to the strains. The deformationsare as follows:

$$\varepsilon = \frac{\Delta l}{l} \tag{8}$$

where: l - sample length, Δl - increase in length, while the thermal expansion coefficient is equal to:

$$\alpha = \frac{\Delta l}{l \cdot \Delta t}. \tag{9}$$

where: α - thermal expansions coefficients, Δt - temperature change

After the transformations and substitutions, we have:

$$\alpha = \varepsilon \cdot \Delta t \tag{10}$$

$$\varepsilon = \frac{\alpha}{\Delta t} \tag{11}$$

$$\delta = \frac{\alpha}{\Delta t} \cdot E \tag{12}$$

Thus, the formula shows that the stresses are directly proportional to the coefficient of thermal expansion. The greater the coefficient of thermal expansion, the greater the stress.

3.5. Discussion of the results

28 analyzes were performed and the presence of compressive and tensile stresses was found in individual layers of the model (metal, opaque, dentin).The presence of compressive stresses in the dentin layer is a result of greater metal shrinkage during the cooling process. These stresses are desirable for the ceramic-alloy system, as they have a positive effect on the quality of the porcelain-metal bond. Due to the compressive stresses, the connection is permanent. The occurrence of compressive stresses is present in models where the thermal expansion coefficient of the metal is greater than the thermal expansion coefficient of porcelain. The presence of tensile stresses in the dentin layer was also found. They appear when the metal has a lower thermal expansion coefficient than porcelain. These stresses are the result of less shrinkage of the metal layer than of the ceramic layer. They are unfavorable for the porcelain-metal system as they can damage the ceramics. Cracks or chipping of the dentine layer are not the desired effect in the performance of prosthetic restorations. Tensile stresses indicate a poor connection between porcelain and metal. For a high-quality joint between metal and porcelain, compressive stresses must be present in the dentin layer. The greater the stress, the more durable and stronger the connection. The amount of stress is influenced by the size of the metal's thermal expansion coefficient. It must be greater than the TECof the porcelain for compressive stresses to occur.

4. Conclusions

Conclusions regarding the conducted analyzes:

1. The use of FEM analysis allows for the design of safe structures and the preparation of effective manufacturing processes;
2. FEM is characterized by the possibility of easy use both by process analysts (statisticians) and by designers;
3. The FEM method allows you to perform the analysis through computer simulations that immediately show the end result. The analyst immediately concludes whether the analysis required will be applicable in reality;
4. MES does not require complicated equipment for conducting research and engineering analyzes, which is associated with high costs; -makes it possible to significantly reduce the number of experimental tests
5. Compressive and tensile stresses were found in the conducted analyzes;
6. Compressive stress has a positive effect on the joint between porcelain and metal;
7. The value of compressive stress is directly related to the value of the thermal expansion coefficient (TEC) of the metal;
8. The compressive stress in the dentin layer TEC of the metal implies a greater value than the TEC of porcelain;

9. The greater the difference in the assumption in point 8 of the conclusions between the thermal expansion coefficients of metal and porcelain, the greater the compressive stress will be;
10. The greater the compressive stress, the greater the deformation of the model is also;TEC the metal must not be smaller than the TEC of porcelain because then tensile stresses arise in the dentine layer;
11. Tensile stresses have a destructive effect on the metal connection with ceramics;
12. When firing porcelain on metal, it is very important that the thermal expansion coefficients of metal and porcelain are properly selected (the difference between the TEC of metal and porcelain must be approx. 0.5 - 1.0□10-6K-1).

References

ANUSAVICE K., 1992. *Postęp w technologii i właściwościach porcelany i metal – ceramiki.* Magazyn stomatologiczny nr 10/1993. 30 – 31.

BEHAM G., *IPS EMPRESS, 1992. Nowa technologia ceramiczna cz. II.* Magazyn stomatologiczny nr 6/1992. 30 – 31.

BEHAM G., *IPS EMPRESS, 1992. Nowa technologia ceramiczna cz. IV.* M stomatologiczny nr 8 – 9/1992. 30 – 32.

CASTELINI D., BACETTI T., CLAUSER C., BERNARDINI V., 1994. *Rozszerzalność termiczna różnych materiałów używanych do konstruowania koron.* The jal of ProstheticDentistry. Nr 7/1994. 360 – 367.

Century Supplement.

COMBE E.C., 1997. *Wstęp do materiałoznawstwa stomatologicznego*. Podręcznik. Sanmedica. Warszawa. 56, 121-126.

CRAIG R., POWERS J., WATAHA J., 2000. *Materiały stomatologiczne. Podręcznik*. Wydawnictwo Medyczne Urban i Partner. Wrocław. 227-243, 248, 287-297. Dentistry in 21 st Century Supplement. /www.ada.org:JADA dentistry in 21 th

FISHER C., 1994. *Omega 900 – ceramika w najlepszym wydaniu.* Quintessence Tom V nr 4/200. 173 – 187.i krakowskiego oddziału Polskiego Towarzystwa Stomatologicznego.: Stomatologia kliniczna. Tom XV. Kraków. 102-103

JURASZEK J., BABIŃSKI L., THORPE J., 1998. *Metoda Elementów Skończonych.* Wydawnictwo Politechniki Łódzkiej Filii w Bielsku – Białej. Bielsko – Biała. 12-13.

KARASIŃSKI A., MARCZAK – PROŚNIAK I., 2001. *Nowa porcelana Finesse.* Magazyn stomatologiczny nr 12/2000. 46 – 49.KOWALCZYK W. *Wytrzymałość na zrywanie połączenia metal – ceramika w różnych systemach ceramiki napalanej na metal.* Magazyn stomatologiczny nr 11/2001. 16 – 19.

KOWALCZYK W., DOBIES K., 1999. *Twardość poszczególnych warstw w różnych systemach ceramiki stomatologicznej napalanej na metal.* Protetyka stomatologiczna 3/1999 Tom XLIX. 168 – 173.KOWALCZYK W.: Struktura ceramiki czterech różnych systemów napalania porcelany na metal w mikroskopie optycznym. Magazyn stomatologiczny nr

MAJEWSKI S., 2000. *Podstawy protetyki w praktyce lekarskiej i technice dentystycznej.* Podręcznik. Wydawnictwo stomatologiczne SZS – W. Kraków. 394-395

NIEWIADOMSKI K., *Materiały ceramiczne stosowane w technice porcelany napalanej na metalu.* Magazyn stomatologiczny nr 9/1993. 45 – 51.

Podstawy Metody Elementów Skończonych. 1984. Praca zbiorowa, Mały poradnik mechanika Tom I – Nauki matematyczno-fizyczne, materiałoznawstwo. WNT Warszawa, 157-158

TRYLIŃSKI, W., Praca Zbiorowa, *Poradnik Konstruktora przyrządów precyzyjnych i drobnych.* WNT Warszawa 1970. 57

RAY N.: *Dental materials Lecture Notes.* 2001. Podręcznik. /www.freebooks4doctors.com/

Spiechowicz E.: *Współczesne postępowanie laboratoryjne w protetyce stomatologicznej.* 1980. Podręcznik. Państwowy Zakład Wydawnictw Lekarskich. Warszawa. 101-103, 121-132.

SZCZYREK P.: *Możliwość zastosowania systemu ceramicznego In – ceram firmy Vita w wykonawstwie uzupełnień stałych – część I.* Protetyka stomatologiczna. Tom L nr

WIERZYŃSKI E., 1978. *Całkowite korony kosmetyczne*. Podręcznik. Państwowy Zakład Wydawnictw Lekarskich. Warszawa. 76-84.

WILSON H., MCLEAN OBE J., BROWN D., 1995. *Materiały stomatologiczne i ich kliniczne zastosowanie.* Podręcznik. Sanmedica. Warszawa. 26-4. Zeszyt naukowy Akademii Medycznej im. Mikołaja Kopernika w Krakowie