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RESEARCH ARTICLE

Investigation of thermal stress in different metal-ceramic restorations by mathematical analysis

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A B S T R A C T

Objectives: The aim of this study was to investigate the effect of heat changes in oral environment producing thermal stresses (TS) in prosthetic restorations by a mathematical method.

Material and Methods: Three different metals, commercial pure titanium (cpTi), precious metal alloy (Minigold, Bego dental, Bremen, Germany), chrome-cobalt-molybdenum (Wirobond, Bego dental, Bremen, Germany) were chosen for the frameworks. Titankeramik, VM13, and Omega 900 ceramics (Vita, Bad Sackingen, Germany) were used in theoretical analysis. The physical properties of the materials were obtained from manufacturers and from the literatures reports. The calculation method was based on Boley's equation.

Results: In ceramics, the highest thermal stress was in titankeramik and the lowest was in VM13. Both commercial and theoretical samples were compared and at interface of the restoration, thermal stress accumulation was the highest in cpTi and titankeramik and the lowest was in precious metal alloy and VM13 respectively. In metallic frameworks CrCoMo had the highest and semiprecious metal alloy had the lowest thermal stress deposition in its structures.

Conclusions: Thermal stresses are not capable of breaking the metal-ceramic bond strength but shorten the life span of the prosthetics.

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INTRODUCTION

For prolonged period usage in oral environment, dental materials have to be in good conditions in terms of mechanical properties to resist chewing forces and must be biocompatable.[1] To meet these requirements new materials have been innovated to the present day. In this area, the important improvement was the first use of porcelain in 1774 by Alexis Duchateau and then there has been increasing attempt to get the best aesthetic result.[2]

Natural appearing of the ceramics made widespread usage.[3] In recent years, usage of the metal-free ceramics (MFC) have been increasing because of much aesthetics and much biocompatibility.[4] Unfortunately, brittleness and low tensile strength properties of ceramics do not allow MFC restorations for multiple-unit restorations in extensive oral rehabilitations.[5]

Metal ceramic fix partial dentures (MCFPD) have been shown to have a survival rate of 100%, 99% and 95% after 3, 5 and 11 years respectively.[6] Nevertheless, immunologic response to metals like allergic reaction and low corrosion resistance restrict the use of metals. To overcome these problems, titanium and gold alloys have begun to use for making FPD. However increase cost of precious alloys and special equipments required for casting titanium confined their usage.[7]

In a traditional MC crown, the preparation depth must be 2 mm at functional tubercule and 1.5 mm at non-functional tubercule.[8] The metal framework which provides strength and durability, must be at least 0.3 mm thickness.[9]

Dental materials are exposed to many factors in vivo that affect the lifespan.[10] In oral cavity thermal changes during nutrition vary between -5 to 76.5 ^{0}C and under these circumstances the differences in thermophysical properties between dental restorative materials facilitate the development of thermal stress especially in the vicinity of the different materials regardless of the material type.[11] This difference together with the stresses caused by mastication leads to impair mechanical compatibility of the material adhesion.[12,13]

Evaluating the thermal stresses, usually finite element method (FEM) which needs extra equipments like analyses programs (ANSYS, Hypermesh, Radioss, Nastran or MARC), special training for programs and much time to compose the finite element mesh of the sample for the tests has been used. However in our mathematical modeling, we calculated the thermal stress according to the Bruno Adrian Boley's equation. Boley is a mechanical, civil and aeronautical engineer and published a book titled Theory of Thermal Stresses. In his book, he mentioned the mathematical theories used in calculation of the thermal stresses in detail.

The purpose of this research is to determine the thermal stresses in different materials due to different temperatures by employing an alternative way; mathematical modeling. The null hypothesis was that the interface of the restoration has the highest thermal stresses in every material.

MATERIALS AND METHODS

In theoretical model, different framework metals and proper ceramic materials were chosen (Table 1). Physical properties of the materials that were used in the mathematical modeling were obtained from manufactures and the literature report values (Table 2). In the formula, the framework thickness was assumed as 0.5 mm meanwhile the total (metal-ceramic) thickness of the restoration was assumed as 1.5 mm.

Thermal stress calculation was accomplished according to the Boley

Table 1. Materials used for mathematical modeling

Brand name	Manufacture
Vita Titankeramik (Low-fusing ceramic)	Vita Zahnfabrik, Bad Säckingen, Germany
Vita VM13 (Feldspathic ceramic)	Vita Zahnfabrik, Bad Säckingen, Germany
Vita Omega 900 (Feldspathic ceramic)	Vita Zahnfabrik, Bad Säckingen, Germany
Wirobond (Co 63,3 - Cr 24,8 - W 5,3 - Mo 5,1)	Bego dental, Bremen, Germany
Midigold (Au 49,5 - Ag 35 - Cu 10 - Pd 3,4)	Bego dental, Bremen, Germany
Commercial pure titanium	Dentaurum J.P. Winkelstroeter KG, Pforzheim, Germany

Table 2. The physical properties of the materials[12-19]

Metals	Materials	E (Mpa)	α, x10^{-6} 1/°C	υ
CoCrMo based	Dentin Omega900 CoCrMo	90.000 91.000 198.000	13,7 14,4 14,2	0,28 0,28 0,33
Ti based	Dentin Ticeramic Ti	90.000 91.000 110.000	8,7 8,9 9,6	0,28 0,28 0,33
Au based	Dentin Vita VM13 Au	90.000 91.000 78.000	13,6 13,8 14,2	0,28 0,28 0,44

equation where elastic modulus of material was defined as 'E', thermal expansion coefficient as 'α', temperature change as 'T' and Poisson's ratio was defined as 'v'.[12,13,16-20]

The whole thickness of the restoration was 1.5 mm and expressed this thickness as 2 h in the formula. The structure of material was completely free of surface traction and stresses depended on the thickness only, that was T=T(z). Under these circumstances thermal stress components formed in the middle of the structure due to the temperature variation through the physical characteristic thickness will be of the following form.

$$\sigma_x = \sigma_y = f(z), \sigma_z = \tau_{xy} = \tau_{yz} = \tau_{zx} = 0 \qquad (1)$$

The equations can be used for stress components of this form.

$$\frac{d^2}{dz^2}\left[\frac{1-v}{E}f(z) + \alpha T\right] = 0 \qquad (2)$$

The solution of the Eq. 2 can be given as follows.

$$\sigma_x = \sigma_y = \frac{C_1 E}{1-v} + \frac{C_2 E}{1-v}z - \frac{E\alpha T}{1-v} \qquad (3)$$

C_1 and C_2 are the integral invariables determined by the zero force and moment on the sample.[9]

$$\int_{-h}^{h} \sigma_x dz = \int_{-h}^{h} \sigma_x z dz = \int_{-h}^{h} \sigma_y dz = \int_{-h}^{h} \sigma_y z dz = 0 \qquad (4)$$

Assuming that α, y and E are constant, Eq. 3 could be expressed in a better known form as follows.

$$\sigma_x = \sigma_y = \frac{\alpha E}{1-v}\left\{-T + \frac{1}{2h}\int_{-h}^{h} Tdz + \frac{3z}{2h^3}\int_{-h}^{h} Tzdz\right\} \quad (5)$$

Taking Eq. 3 into account and applying Eq. 4 for all cases it can be written as,

$$C_1\int_{-h}^{h}\frac{E}{1-v}dz + C_2\int_{-h}^{h}\frac{E}{1-v}zdz - \int_{-h}^{h}\frac{T\alpha E}{1-v}dz = 0 \quad (6)$$

Eq. 6 and Eq. 7 could be found from the underlain equation system,

$$C_1\int_{-h}^{h}\frac{E}{1-v}zdz + C_2\int_{-h}^{h}\frac{E}{1-v}z^2dz - \int_{-h}^{h}\frac{T\alpha E}{1-v}zdz = 0 \quad (7)$$

To calculate the thermal stresses under homogeneous temperature from surface to the bottom of the dental restoration Eq. 3 can be used for all cases, but in the first place to determine C_1 and C_2, Eq. 6 and Eq. 7 must be used.

RESULTS

As depicted in Table 3, the TS of the materials, increases parallel with the increment in the heat value. The stress values decrease from surface to the inner portions in all materials (ceramic and metal). TS formed in the vicinity of the contacts between ceramics and metals are the highest values.

The impact of the heat changes in metal and ceramic interface is the highest in titanium and the lowest in Au at all temperatures.

In the frameworks, the gold alloy (Au) has the lowest and the Cr-Co-Mo has the highest TS. In ceramics, Titankeramik has the highest TS and the VitaVM13 has the lowest TS.

In comparison with metal and ceramics, metals have higher TS than that of the ceramics.

DISCUSSION

Aktas[21] mentioned that the shear bond strength between ceramics and metal was 45.7±8 Mpa and based on the results of the present study, thermal changes in oral environment that produces thermal stresses cannot cause prosthetic rehabilitation failure alone. However to gather with the stresses caused by mastication, thermal

Table 3. Thermal stresses of materials (0,75 to −0,25 is the ceramic portion, −0,25 to −0,75 is metal portion) versus distance in MPa

	Au			CrCoMo			Ti		
h (mm)	−5°C	37,5°C	76°C	−5°C	37,5°C	76°C	−5°C	37,5°C	76°C
0,75	0,085	−0,640	−1,281	0,111	−0,831	−1,662	0,152	−1,141	−2,283
0,25	−0,029	0,217	0,433	−0,045	0,335	0,670	−0,053	0,397	0,795
−0,25	−0,143	1,074	2,148	−0,200	1,501	3,001	−0,258	1,936	3,873
−0,25	0,121	−0,906	−1,812	0,271	−2,032	−4,065	0,239	−1,794	−3,589
−0,5	0,058	−0,433	−0,867	0,089	−0,670	−1,339	0,106	−0,795	−1,590
−0,75	−0,005	0,039	0,078	−0,092	0,693	1,387	−0,027	0,204	0,409

*Use absolute values for negative units

stresses can reduce the life span of the restorations.

Different methods may be used to calculate the thermal stresses. In literature, FEM analysis is widely used. Toparlı used FEM analysis in his study to calculate the thermal stress of post-restored tooth.[22] Similarly, Hsueh et al. used FEM for the calculation of the effect of layer thickness on thermal stresses.[23] In addition, Benetti used FEM in his study to investigate the effect of fast and slow cooling in porcelain-zirconia restorations. He used Comsol software (Version 3.5, COMSOL Inc, Burlington, MA, USA) for FEM analysis.[24] As a result, a researcher needs to use an additional program (ANSYS, Hypermesh, Radioss, Comsol, Nastran or MARC FEM softwares) for this analysis, which increase the cost of the study and requires additional time. Nevertheless, using mathematical method there is no need for any instrument, which makes easily affordable in terms of coast and time.

Using titanium as a prosthetic material is more biocompatible and its weight is lighter than the other materials which are used as a framework.[25,26] Vasquez compared the bond strength of low fusing ceramic to cpTi and feldspathic ceramic to gold alloy after thermal-cycling by using FEM and found the bond strength of cpTi decreased more than gold alloy.[27] Our results show similarities, not as a unit, with that of Vasquez. In our research, thermal changes which decrease the bond strength were highest between cpTi and titankeramik. Although, these two researches on the same subject employed different methods, the results support each other. However to find the accurate and precise evolution between FEM and mathematical analysis further studies on the same subject must be done simultaneously.

Ferhan used FEM analysis to detect the effect of thermal stress on different post materials. She determined the temperature change in oral cavity within the range of 0 C^0 to 67 C^0.[28] In another research investigating the effect of thermal stress on dental pain, Iman used FEM analyze and assumed the lowest and the highest temperature in oral cavity as 0 and 60 C^0 respectively.[29] We formed our mathematical modeling at 76.5 C^0 which was calculated from lower incisors during consumption of hot beverage.

The main aim of our research is put into practice the mathematical analysis. Furthermore from the point of the results as depicted in Table 2, Au has the lowest thermal stress and on the contrary Cr-Co-Mo has the highest. It can be explained by the difference of thermal stresses caused by elastic modulus of the materials' dissimilarities.

CONCLUSION

The results obtained from mathematical analysis showed the effect of thermal stresses is not capable of breaking the metal-ceramic bond strength alone. The use of mathematical analysis is pretty simple and predictable method than FEM. However, more studies must be performed to test the accuracy of this method.

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