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COUPLED THERMAL AND STRUCTURAL FINITE ELEMENT SOLUTION OF DENTAL CROWN STRUCTURES

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Abstract

The objective of this study is to calculate the temperature and thermal stress distributions related to time as a result of hot/cold liquid intake to the mouth utilizing finite element analysis (FEA). The crown models were developed and analyzed using ANSYS software. In the first step of the study, the temperature changes under thermal loading as a result of hot/cold liquid in the mouth were obtained depending on time. In the second step, the thermal stresses produced by temperature changes were calculated. The distributions of temperatures and thermal stresses were drawn for some critical nodes. The effect of different metal and ceramic substrates on thermal response was considered. In the research, Ni-Cr alloy (NC) substrate experienced the highest values of thermal stresses; comparatively the lowest stresses were calculated for Alumina core (AL) substrate. The values of the maximum thermal stresses for Zirconia core (ZrO_2) and IPS Empress 2 (IE 2) were very close, but the values of it used IE 2 was smaller that ZrO_2.

Keywords: All-ceramics; finite element analysis; stress distribution, thermal fatigue

1. Introduction

Due to their refractoriness, chemical inertia and mechanical properties at high temperature ceramics are widely used in high-temperature applications. However, ceramics are also easily broken and they have relatively lower thermal conductivity, higher thermal expansion coefficient and lower thermal shock resistance. For this reason, during sudden temperature changes ceramics can suffer damage or complete fracture [1]. Ceramics are brittle materials with varying tensile and compressive strengths. They can be both one-phase and multi-phase. Traditional ceramics are inorganic and nonmetallic materials. They have high melting points, high strengths in compression and at high temperatures. They also have excellent chemical resistance. Their disadvantageous characteristics include low strengths in tension and low resistance to impact loads and thermal shocks. Modern ceramics are usually composed of metallic and nonmetallic elements such as aluminum, silicon, titanium, magnesium, boron, oxygen, carbon and nitrogen [1-2]. Some of the ceramic materials are excellent insulators while some others act as semiconductors or conductors. Due to their characteristics ceramic materials are widely used in high temperature engineering applications. Thermal shock behavior of ceramics is studied to determine the durability and reliability of its products. The finite element analysis (FEA) is used in such studies. With its help it is possible to have thermal shock test simulations and determine stress and temperature fields generated during the cooling period [1]. Due to their brittle nature ceramics are often employed in combination with highly strength substrate material such as a strong ceramic core or metal alloys. These materials are bonded together at very high temperatures. Differences in thermal properties of ceramics and metals create a high thermal stress concentration at the margins of bonded interfaces [1-2]. Notwithstanding the extensive use of bonded ceramics, all-ceramic crowns are still appealing due to their biocompatibility, esthetics and solidness. However, high failure rates in high stress applications such as molar crowns limit the use of ceramic alone [3]. Systems attained by veneering of metal or alumina substructures with aesthetic porcelains are comprehensively used for the construction of high strength crown and bridge restorations [4]. Since, an important characteristic of the human face is the look of the upper front teeth a discontinuity or an interface in color generally gives a negative feeling of the person. There is no doubt that teeth are very significant in terms of human physical condition. While restoring a tooth, firstly, it must be guaranteed that the materials used in the tooth are appropriate both biologically and chemically. In addition to this, the main purpose is to achieve a crown that will be used without corrosion and failure, as long as possible; since it is a highly expensive procedure to replace these crowns. Besides these, factors such as strength, aesthetics, ease of manufacture and cost are taken into consideration. The beginning of all-ceramic crowns in the early 1980s has caused an interest in covering discoloration, staining and small accidental fractures with a minimum of tooth preparation and a good aesthetic result [5]**.** Today, it is generally accepted that ceramic restorations exhibit excellent aesthetic qualities. However, the mechanical shortcomings of such materials include their inherent brittleness and potential to abrade the opposing dentition. Recent developments have attempted to overcome such disadvantages by either the use of increasingly complex technology or by the simplification of existing techniques and/or materials. The diversity of dental ceramics continues to stimulate laboratory and clinical research [6].

During the imbibing of hot and cold liquids, the temperature in the oral cavity undergoes rapid changes. These changes create thermal stress on the ceramic restoration [7]. For the duration of cooling substantial stress formation may occur in layered structures with different thermal expansion coefficients. These stresses can cause immediate cracking of the porcelain, deformation of the restoration, or raise the probability of fracture during functional loading of the restoration. In these cases, the materials are considered to be thermally incompatible. In dentistry, the thermal incompatibility between veneering ceramic and a metal substrate is frequently characterized by their difference in thermal expansion coefficient values (α) which is termed as mismatch [8]. Even though many attempts have been carried out to improve dental restorative materials, there are still big differences, particularly in the mechanical and physical properties of tooth and restorative materials [9]. Residual tensile stresses in ceramic caused by thermal contraction mismatch between materials are significant contributing factors to failures of metal-ceramic and all-ceramic restorations. It is generally understood that the residual stress state in metal-ceramic and all-ceramics dental prostheses depends on many factors, including contraction mismatch, cooling rate, firing temperature, geometry, and fabrication technique [10].

During the last three decades, the finite element analysis (FEA) has been the prevalent technique used for analyzing physical characteristics of materials in the field of structural, solid and fluid mechanics. In biomedicine too, the FEA has been used with substantial advancements. Certain facts can be found out only by using the FEA [2]. Recently, the finite element analysis is also a popular numerical method in stress analysis [11]. FEA shows the internal stresses, and on that basis predictions can be made about failure [12]. Influence of veneer design, veneering and core materials is very important on dentinal stress distribution [13-15]. Finite element analyses have already been used to obtain thermal stress distribution on dental crown materials, successfully [16-17]. In the current study, a transient thermal stress analysis was conducted on crack-free, pinhole-free, homogenous and continuous dental ceramic crown using various ceramic and Ni-Cr alloy (NC) substrates. Notes were taken on the temperature changes and thermal stress distributions of crowned system due to the changes of hot/cold liquid in the mouth. In order to calculate thermal response of these crown systems the FEA was used.

2. Materials and Methods

A transient thermal stress analysis was carried out on dental ceramic crown on Ni-Cr alloy (NC) or ceramic substrates such as Zirconia core (ZrO_2), IPS Empress 2 (IE 2) and Alumina core (AL), numerically. The code and type data of above materials are given in Table 1. All materials were presumed elastic except NC alloy. Therefore, the solution was also performed as elastic-plastic, when NC alloy was used to as substrate material. Thermal and mechanical properties of dental ceramic (DC) and substrate materials are given in Table 2 [18-20].

Table 1. Materials tested

Product	Code	Type
Zirconia core	ZrO_2	Sintered 5 wt % Y_2O_3 TZP
Alumina core	AL	Glass-infiltrated alumina
IPS Empress 2 core	IE 2	Lithium disilicate
IPS Empress 2 layering	IEL 2	Fluor-apatite
Ni-Cr alloy	NC	65.2 % Ni, 22.5 % Cr, 9.5 % Mo, < 2 % Fe-Si-Mn-Nb
Dental ceramic	DC	63.4 % SiO_2, 16.70 % Al_2O_3, 1.50 % CaO, 0.80 % MgO, 3.41 % Na_2O, 14.19 % K_2O

Table 2. Thermal and mechanical properties of materials

Properties	Material					
	Zirconia core (ZrO_2)	Alumina core* (AL)	IPS Empress 2 core* (IE 2)	IPS Empress 2 layering* (IEL 2)	Ni-Cr alloy (NC)	Dental ceramic (DC)
Thermal conductivity, k (W/mK)	2.2	33	3.5	3.5	91.8	1.11
Specific heat, C_p (J/kgK)	460.6	755	233	233	431	742
Thermal expansion coefficient, α ($K^{-1}\times10^{-6}$)	10.0	4.6	10.6	9.7	13.9	2.8
Elasticity modulus, E (GPa)	206	416	95	60	221	70
Poisson ratio, ν	0.29	0.23	0.25	0.25	0.33	0.20
Density, ρ (kg/m^3)	5900	3984	2400	2400	8902	2520
Tangent modulus (MPa)	-	-	-		1100	-
Yield Strength (MPa)	-	-	-		440	-

* The physical properties of these materials were supplied by the companies

The finite element model was created by utilizing ANSYS finite element software which is a known general purpose finite element program. It was assumed to be isotropic, homogeneous, axisymmetric and thermally solid. The axisymmetric view of crown structure is shown in Figure 1. Coupled thermal and structural finite element solution was carried out to solve thermal stress problem. The transversal cross-section of the crown was planned in a two-dimensional approach and a four-node, plane strain, and quadratic, thermal structure element, which is called as PLANE 13 in ANSYS, was used [21]. In addition, PLANE 13 has a 2-D magnetic, thermal, electrical, piezoelectric and structural field capability with limited coupling between the fields. PLANE 13 is defined by four nodes with up to four degrees of freedom per node as seen in Figure 2 [21-22].

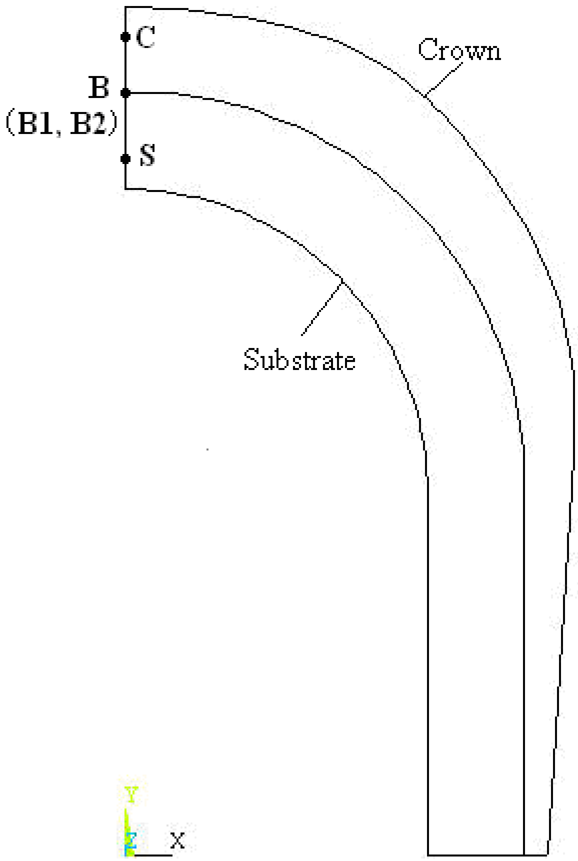


Fig. 1. The schematic geometry of model with considered nodes

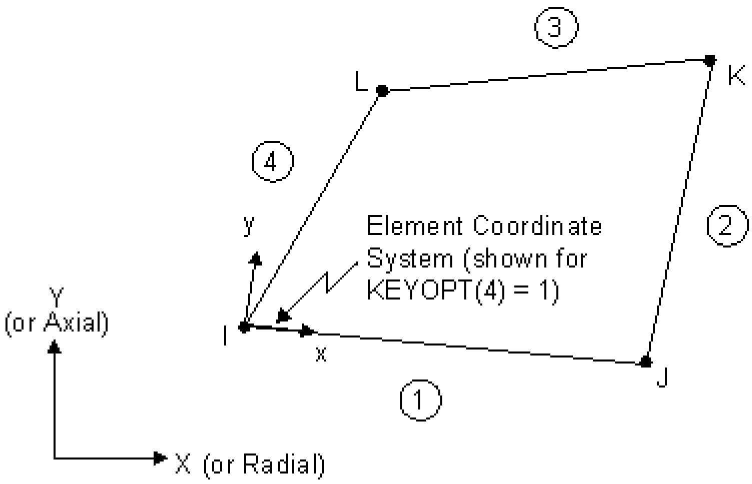


Fig. 2. Coupled-field solid element type (PLANE13)

Later than the mesh generation process, a superior mapped mesh was introduced to model both the ceramic crown and the substrate as seen in Figure 3. Using lower order triangular and tetrahedral elements in the analysis of structures was avoided as much as possible. Then again, mapped mesh shape uses all quadrilateral-area elements and all hexahedral-volume elements [21-22]. The whole model was divided into 1245 elements and 1344 nodes.

The crown structure was assumed to be initially at a uniform temperature of 36,5 ^{o}C. A transient finite element thermal analysis was performed using the program to establish the nodal point temperatures at each time step. These temperatures were next used as predefined input data to the finite element thermal stress solution at time steps for which the stress distributions in the crown structure was required. To model the influence of the sudden intake of hot and cold liquid the oral cavity temperature of the mouth was assumed to change from 36,5 to 60 ^{o}C and 0 to 36,5 ^{o}C, respectively. These temperatures were held constant for a period of 1 s., in other words hot and cold liquids were kept for 1 s in the mouth [7].

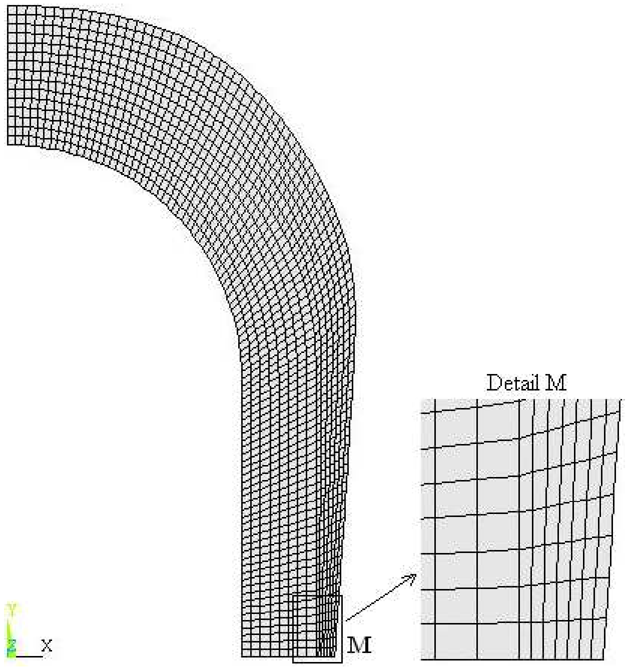


Fig. 3. The axisymmetric finite element model of the crown structure

The FEA was used to obtain the thermal stress distribution produced by temperature changes in both substrate and crown structures. Thermal stress distribution σ_x (the stress component in the x-direction) and temperature changes depending on time were obtained and drawn at some important nodes for consideration and evaluation. These nodes were named as C, B (B1 and B2) and S on the crown, interface and substrate, respectively (Figure 1). Furthermore, during the deformation of the metal-crown structure, NC alloy substrate is able to cause deformation plastically even though the fact that the dental ceramic crown stays elastic. Because, dental porcelain is a brittle material, therefore, it was assumed that ceramic crowns were elastic for the period of this analysis. The Von Mises yield criterion was carried out for determining the plastic deformation. The equivalent Mises stress is presented by the expression:

$$\sigma_m = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}} \quad (1)$$

where, σ_1, σ_2 and σ_3 are the three principal stresses. When σ_m reaches the yield strength, the material begins to be injuring plastically. The behavior of the NC alloy substrate material was assumed to be owing to bilinear kinematic hardening, which means that the real stress-strain curves can be approximated by a series of straight lines. This kind of hardening law allows the Baushinger effect to be represented [23].

3. Results

The temperature changes depending on time at Node B, interfaces substrate and crown, caused by hot liquids is shown in Figure 4. The magnitudes of temperatures at this node arise unexpectedly in 3 s and then decrease to the mouth temperature in 10 s. Besides, temperature changes are approximately the same during all time except between 2 and 4 s for all material combinations. When AL/DC combination is used, the temperature is reached the highest value as 54,55 ^{o}C at 3 s.

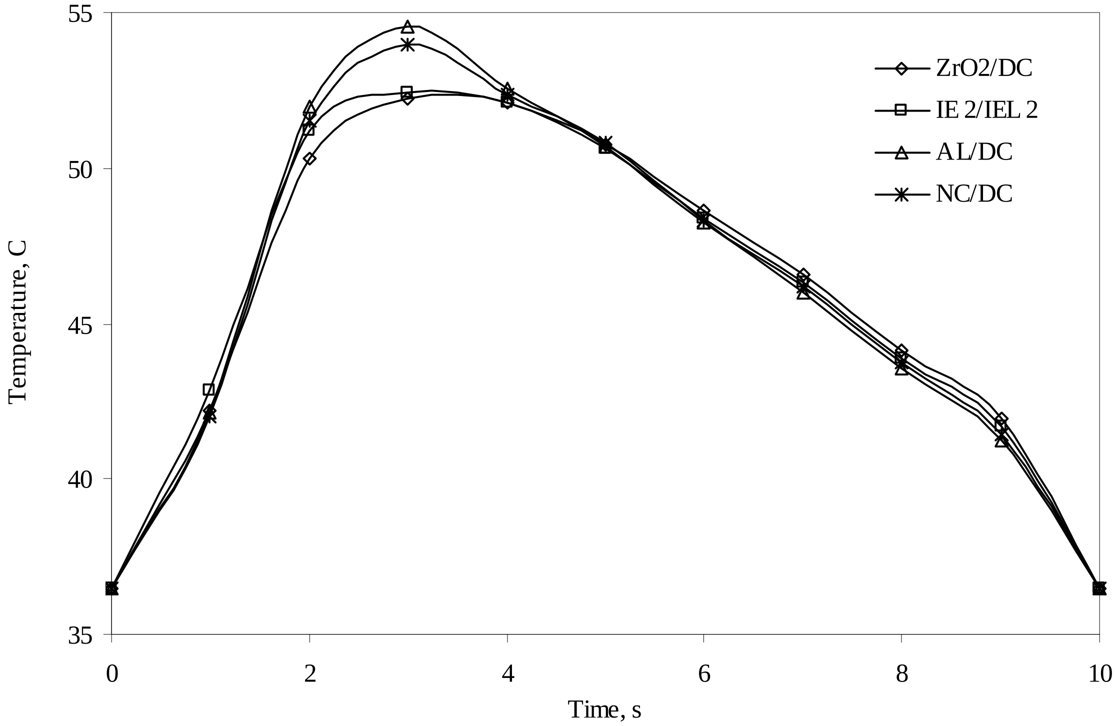


Fig. 4. Temperature changes depending on time at Node B caused by hot liquid

Figure 5 illustrates the changes in temperature depending on time at Node B, caused by cold liquid. The changing of temperatures is almost same for all materials after the 4 s. The differences are occurred during 2 and 4 s for IE 2/IEL 2, AL/DC and NC/DC material combinations. Besides the variations of temperature is clearly different for ZrO_2/DC combination from initial time to 3 s. In other words, when ZrO_2/DC is used, the temperature at Node B is decreased very faster than others. Nevertheless, the minimum value of temperature is calculated as 8,45 ^{o}C for AL/DC combination at 3 s. The decreasing of temperatures is continued from initial time to 3 s, after this time it is increased to the mouth temperature in 10 s. As mentioned previously, all thermal stress analysis was performed elastically, although an elasto-plastic thermal stress analysis was also carried out for NC/DC crown FEA model. Since NC can be failure as plastically. Besides, the Node B must be defined as Nodes B1 and B2, because temperatures and thermal stresses on the interfaces substrate and crown are calculated step by step using both substrate and crown material properties by ANSYS code. The results for Node B are presented for both substrate (Node B1) and crown (Node B2).

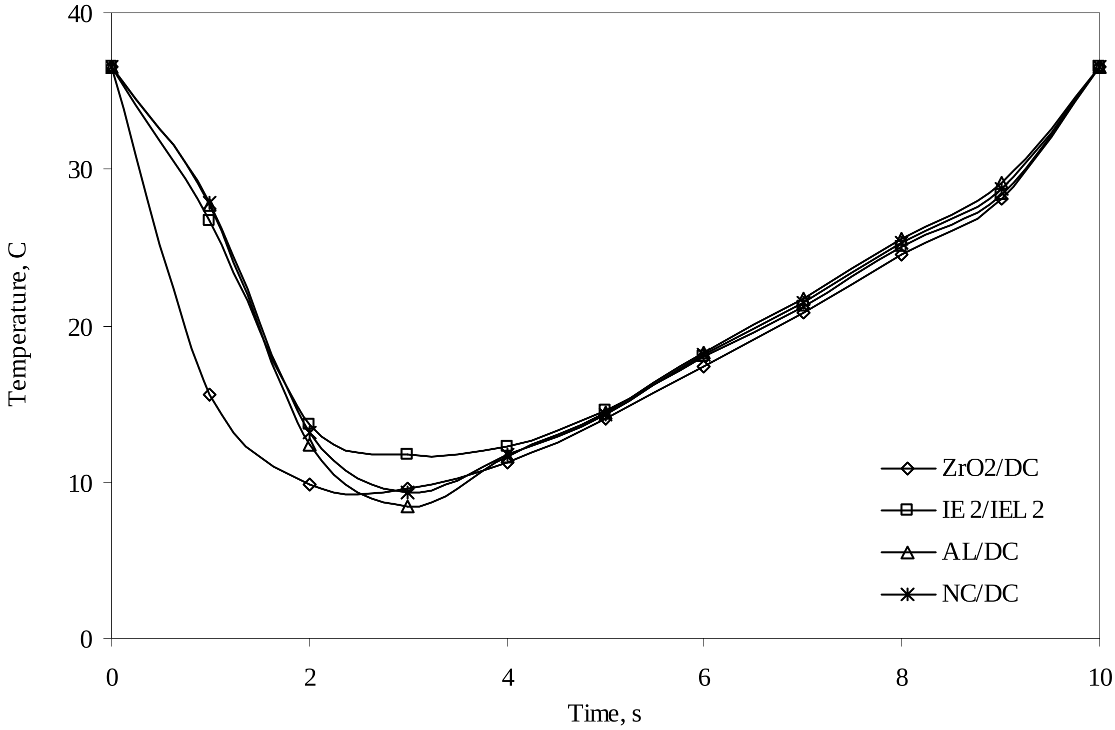
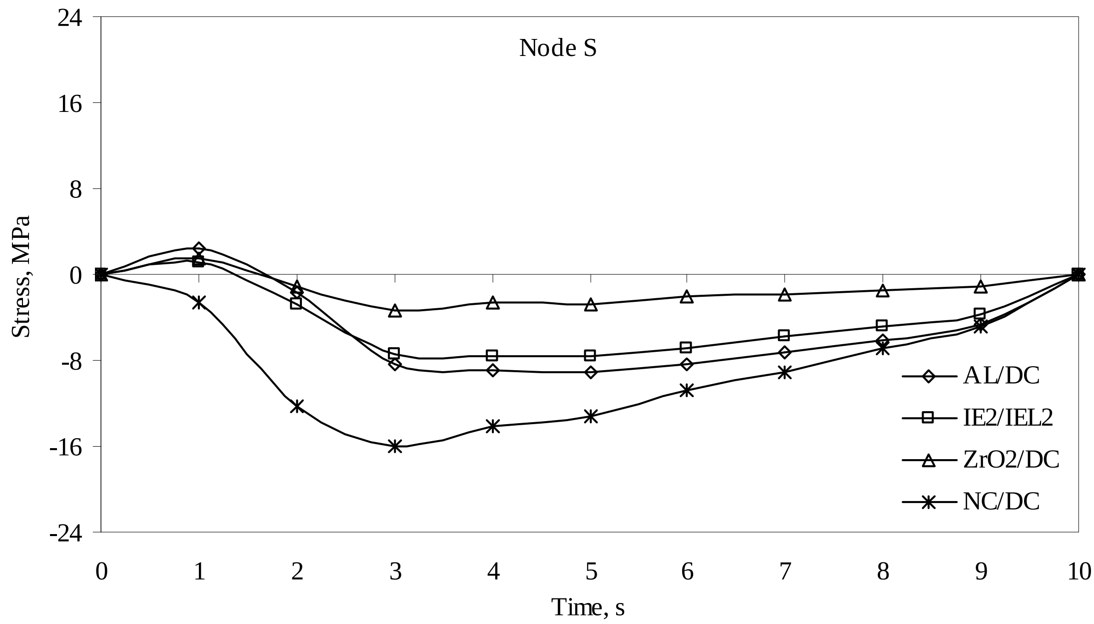


Fig. 5. Temperature changes depending on time at Node B caused by cold liquid

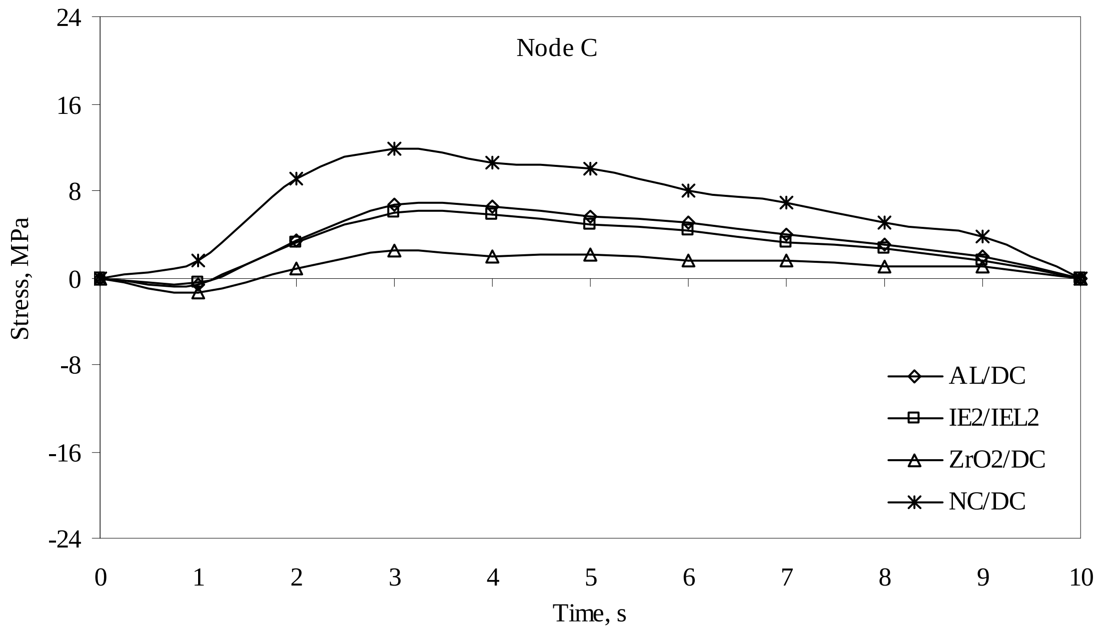
Thermal stress distributions depending on time at selected nodes caused hot liquid are shown in Figure 6. As seen in this figure, compressive and tensile thermal stresses are obtained on the Nodes S (substrate) and C (crown), respectively. Besides, thermal stresses are also calculated as compressive and tensile forms on Nodes B1 (used substrate material properties during the solution) and B2 (used crown material properties) selected on the interface, respectively. Additionally, thermal stresses are observed as tensile form beginning of the process to 1 s after this time it is decreased and its form is changed as compressive on Node S except NC substrate. Besides, this changing is observed from compressive form to tensile form for Node C for same period. The magnitudes of thermal stresses calculated using NC substrate are higher than other substrate materials for all nodes. The highest values of stresses are obtained during 3 s, generally. The maximum values of thermal stresses at this moment are calculated as -16.00 and 11.92 MPa for Node S and C, respectively. Furthermore, its highest values are obtained for NC substrate as -13,16 and 13,11 MPa for Nodes B1 and B2 at 3 s, respectively.
Thermal stress distributions depending on time at selected nodes caused cold liquid are illustrated in Figure 7. Thermal stresses are created as compressive and tensile forms for Nodes S and C, respectively. The changing of compressive form to tensile form on Node S and tensile form to compressive form are observed like as hot liquid intake the mouth illustrated in Figure 6. Furthermore, when NC substrate is used, thermal stresses are also higher than using other materials as substrate. The highest values of thermal stresses are also calculated at 3 s for all materials and nodes except Node B1 using ZrO_2 and IE 2 as substrate materials. In other words, the highest values on Node B1 for ZrO_2 and IE 2 substrate are calculated at 2 s. The maximum thermal stresses caused cold liquid are computed for NC substrate as 23,85 tensile form and -20,37 MPa compressive form on Nodes S and B2, respectively. It is understand that the maximum compressive stress is occurred on the interface. Figures 6 and 7 point out that thermal stresses caused both hot and cold liquids for

AL substrate are lower than using other substrate materials. Additionally, it is computed very close for each other using ZrO_2 and IE 2 substrates.

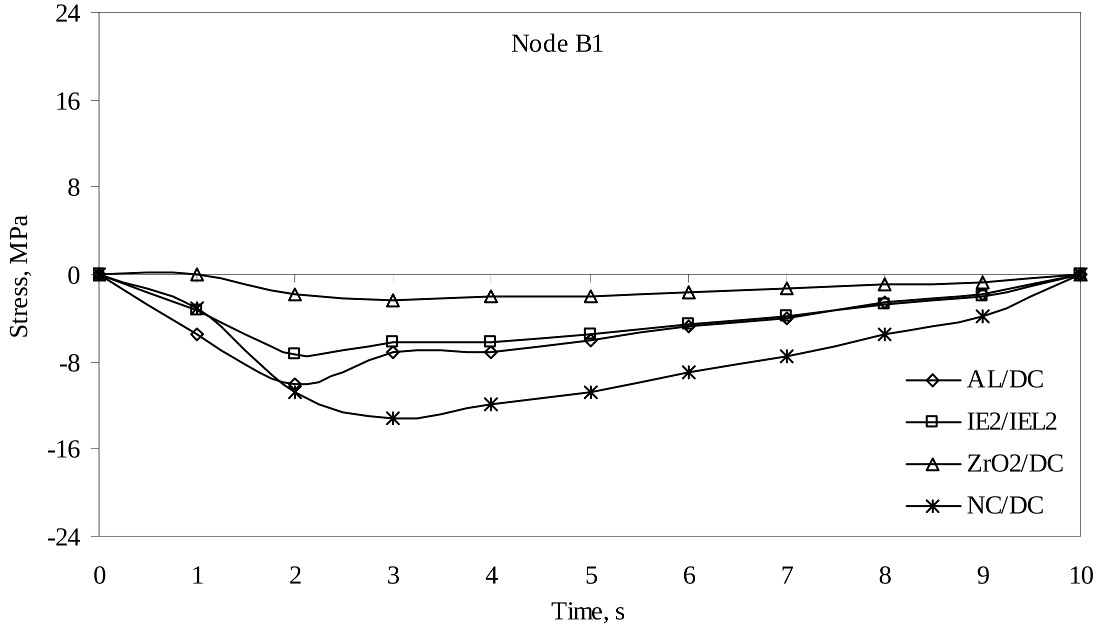
The maximum values of thermal stresses at selected nodes caused hot and cold liquid are presented in Figures 8 and 9, respectively. According to these figures, the magnitudes of thermal stresses caused cold liquid are higher than hot liquid. It is seen that the highest values of thermal stresses are calculated used NC substrate, whereas the lowest stresses are computed for AL substrate. The maximum thermal stresses for ZrO_2 and IE 2 are very close, but the values of it used IE 2 smaller than ZrO_2.



(a)



(b)



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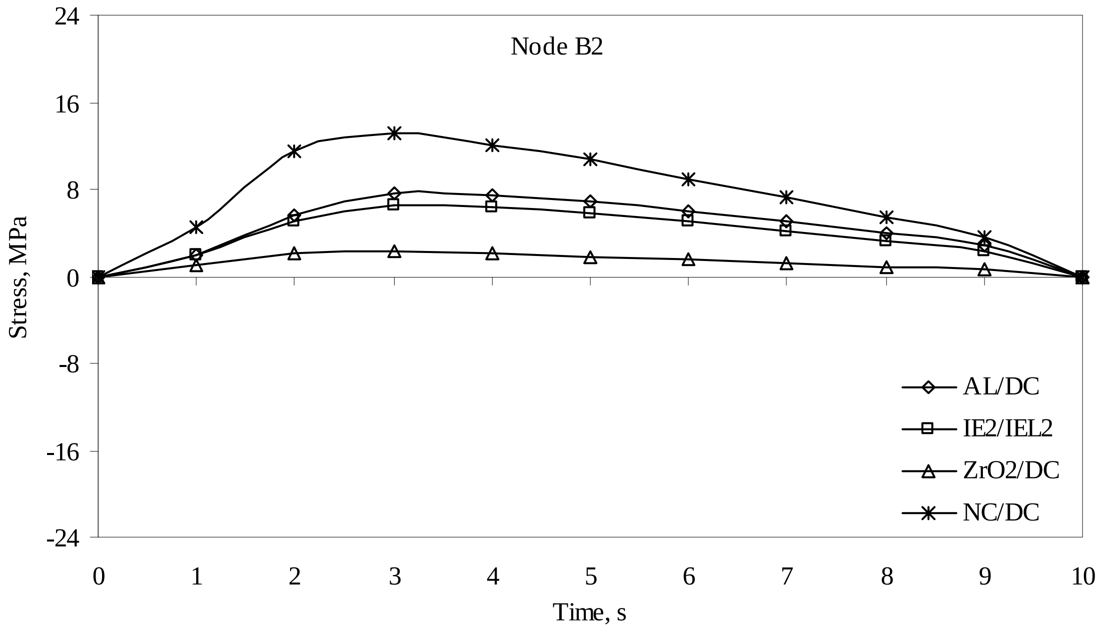
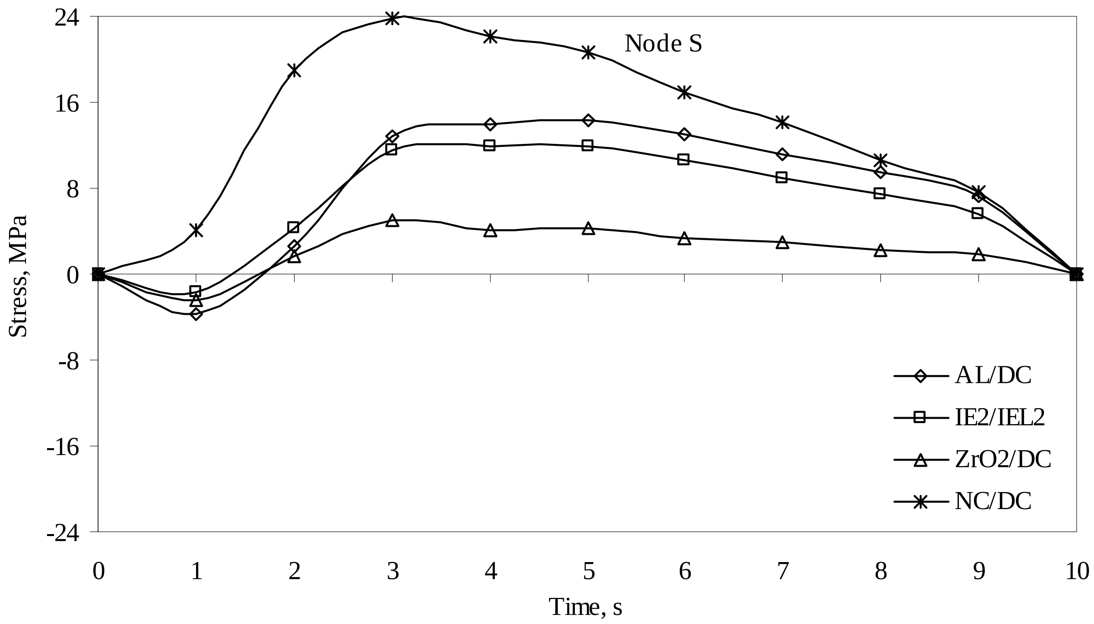
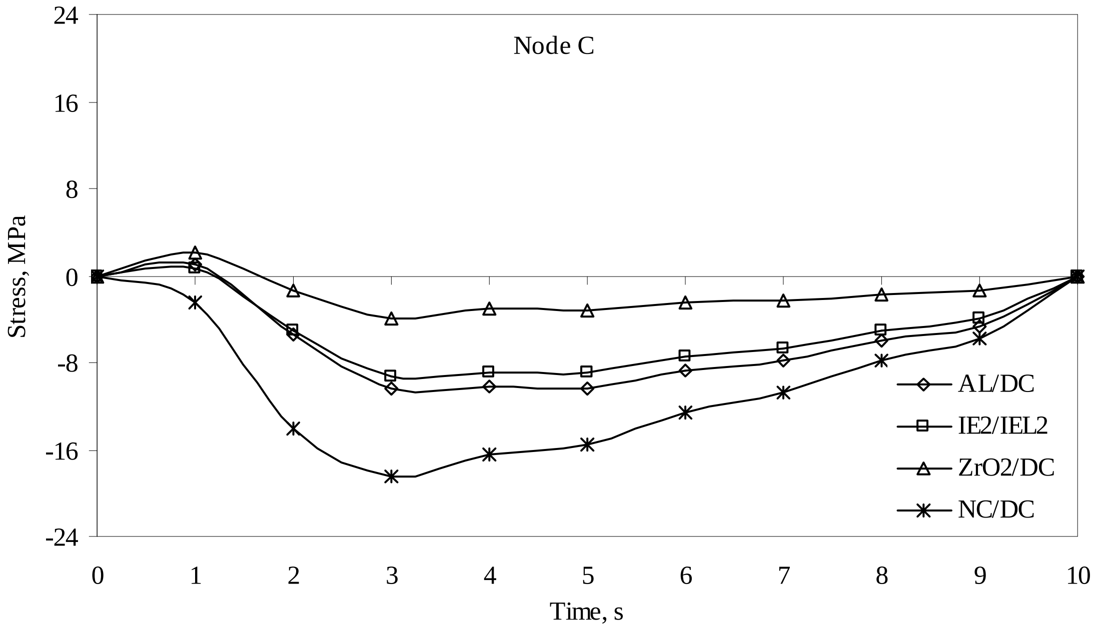


(d)

Fig. 6. Thermal stress distributions for x-direction at selected nodes by hot liquid


Node S
Stress, MPa
Time, s
AL/DC
IE2/IEL2
ZrO2/DC
NC/DC
24
16
8
0
-8
-16
-24
0
1
2
3
4
5
6
7
8
9
10

(a)


Node C
Stress, MPa
Time, s
AL/DC
IE2/IEL2
ZrO2/DC
NC/DC
24
16
8
0
-8
-16
-24
0
1
2
3
4
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9
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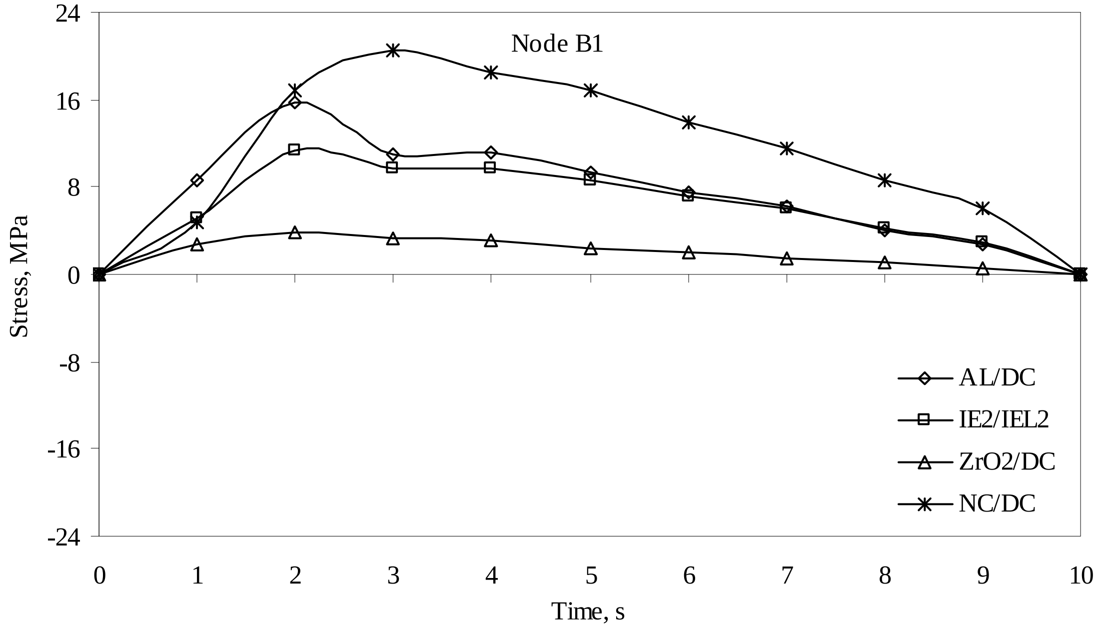
(b)



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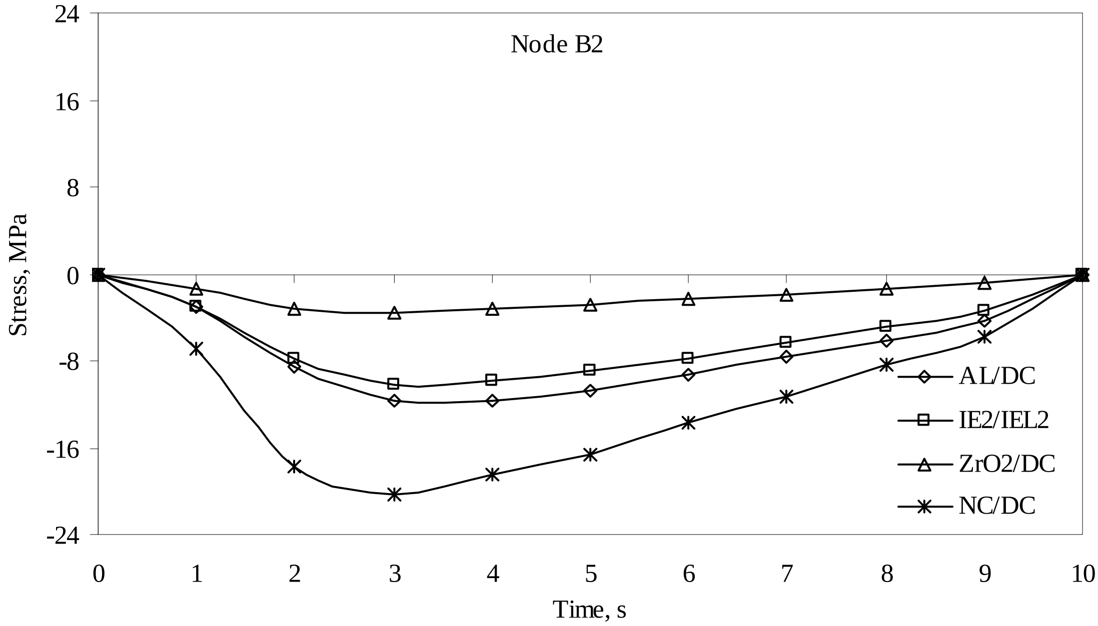

(d)

Fig. 7. Thermal stress distributions for x-direction at selected nodes by cold liquid

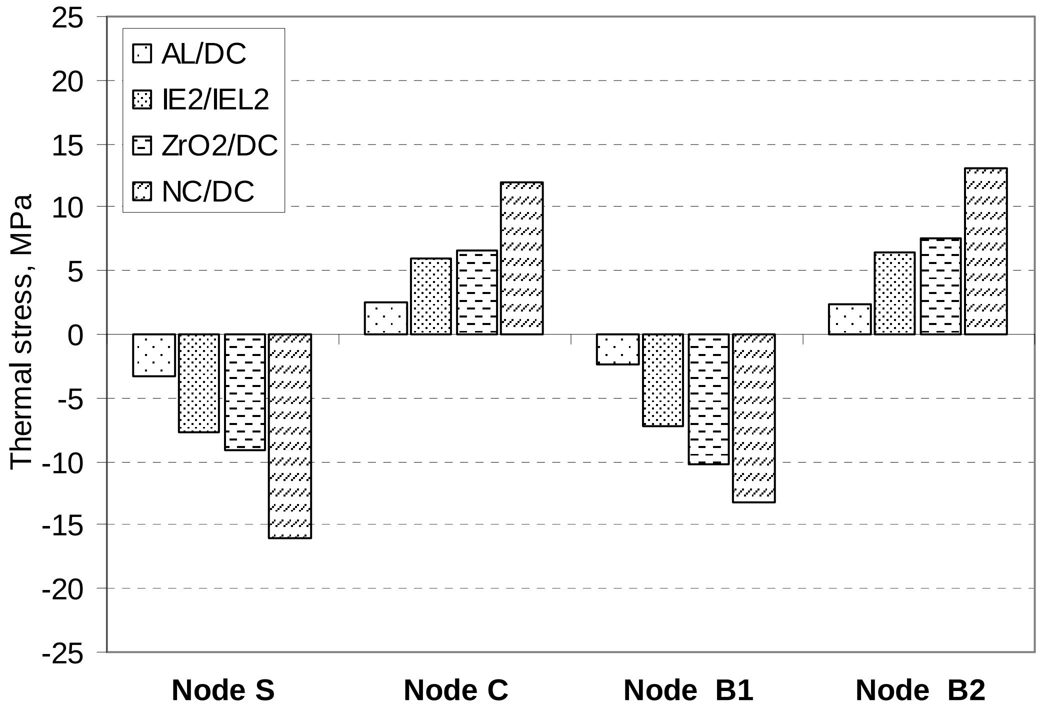

Fig. 8. The maximum values of thermal stresses at selected nodes caused hot liquid

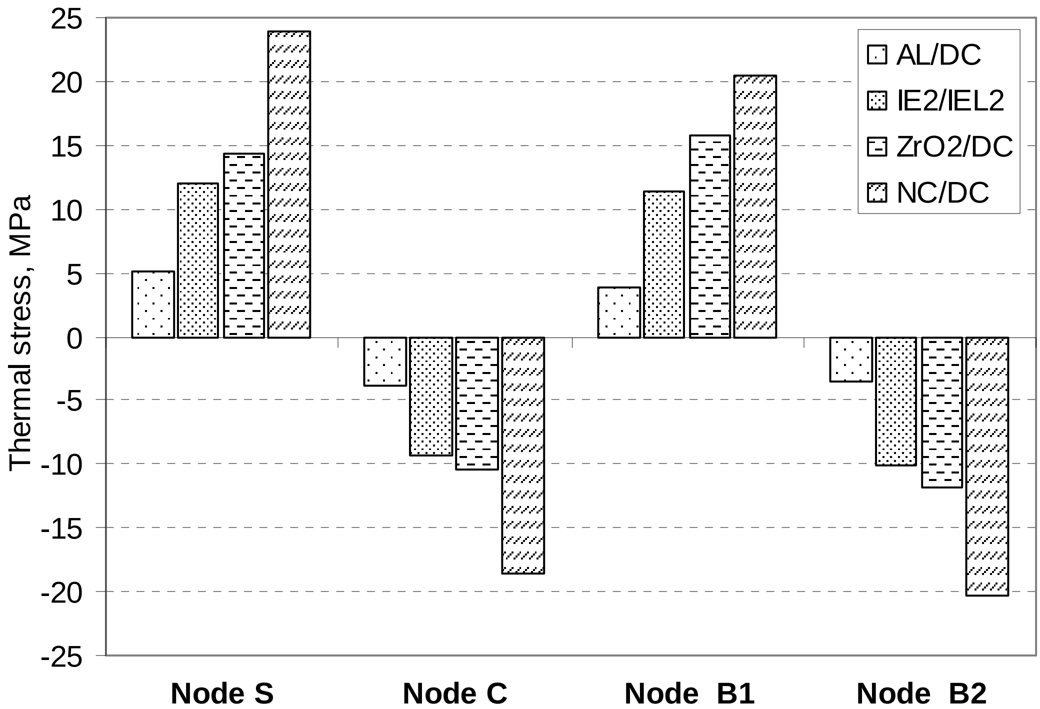

Fig. 9. The maximum values of thermal stresses at selected nodes caused cold liquid

4. Discussion

Thermal diffusivity is a significant factor in transient heat transport problems [24]. Hot and cold liquid drinks in the mouth cause a temperature gradient that result in thermal stresses due to the different thermal and mechanical properties of different materials in the restored tooth. The thermal stresses which occur in the restored tooth are dependent on many factors such as the properties of restorative materials, preparation design and adhesive resistance between tooth and restorative materials [25]. Thermal stress concentrations occur on biomaterial interfaces. Thus, investigation of the temperature and thermal stress distribution is obtained some critical points [17]. Farah and Craig [26] identified only the loading conditions. On the other hand, the dimensions of the crown design and details of their finite element model not clearly described. The factors which may account for the differences in stress levels contain; crown geometry, boundary conditions, type, size and number of elements and loading condition. In this study, a transient coupled thermal and structural analysis caused hot and cold liquids intake the mouth of crack-free, pinhole-free and continuous various all ceramic and metal/ceramic crowns was carried out numerically. The finite element analysis was applied for the duration of the nonlinear solution of the structure. Thermal loads were also considered since the teeth are subjected to different temperatures of ingested foods and drinks. Thermal records in the oral environment range between 0 and 67 ^{o}C. Since enamel and dentine show signs of slightly different coefficient of thermal expansion, thermal loads may even create stresses in the intact natural tooth [27]. The problem is amplified for the crowned tooth.

In this study, thermal stresses for using AL substrate are smaller than using other substrate materials, while its values for NC substrate higher than others. Since the highest and lowest thermal expansion coefficients are the NC (α=13.9 $K^{-1}\times10^{-6}$) and AL (α=4.6 $K^{-1}\times10^{-6}$) substrate, respectively. In other words, the magnitudes of thermal stresses are strictly affected the differences of thermal expansion coefficients between substrate materials and DC crown (α=2.8 $K^{-1}\times10^{-6}$). Besides, thermal stresses are obtained very close for ZrO_2 and IE 2 substrates as mentioned previously. Indeed, the difference of thermal expansion coefficients between ZrO_2 and IE 2 is very small and it can be neglected. Consequently, thermal convenience for all-ceramic crown system is very suitable in comparison with metal-ceramic crown systems. It can be said that thermal fatigue and/or crack formation might be created where if the crown structure is having high thermal stresses. For the parameters explained above, for cold liquids the thermal loadings were considered as 0 ^{o}C and for hot liquids 60 ^{o}C. Since heat is transferred by convection of the outer surface, the heat on the outer surface of the crown can be lower or higher than the temperature of the oral environment. Both among the substrate and crown materials the heat transfer occurs by conduction. Thermal stresses caused the cold liquid (0 ^{o}C) intake the mouth is more dangerous than hot liquid. Because, thermal stresses for cold liquid are higher than hot liquid. The main reason of this, the temperature differences between drinkable materials and oral environment. In a next study, if porosity is created in the both substrate and dental ceramic crown structure or occur as a result of service period, a raise in thermal stresses may result due to the irregular distribution. This might have an undesirable effect on the strength of the materials.

5. Conclusions

The temperature of the oral cavity varies due to the daily intake of foods and drinks at different temperatures. Temperature changes in the oral cavity interfere with the strength of the used material and may shorten its service period. In coping with thermal stresses, changing the amount of the materials used in the production of all-ceramic and metal-ceramic crowns is important. This condition must be evaluated for thermal fatigue as well. This research concludes that in comparison with metal-ceramic crown systems all-ceramic crown systems are more convenient thermally. High thermal stresses can cause thermal fatigue and/or crack formation in the crown structures. Lastly, compared to hot liquid, cold liquid cause thermal stresses of higher magnitude. In the research, NC substrate experienced the highest values of thermal stresses; comparatively the lowest stresses are calculated for AL substrate. The values of the maximum thermal stresses for ZrO_2 and IE 2 were very close, but the values of it used IE 2 was smaller that ZrO_2.

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