Isı Bilimi ve Tekniği Dergisi, 34, 1, 1-7, 2014
J. of Thermal Science and Technology

ISSN 1300-3615

EFFECT OF MATERIAL THICKNESS ON RESIDUAL STRESSES ORIGINATED FROM COOLING PROCESS IN DENTAL RESTORATIONS

Mehmet DURANAY
Department of Mechanical Engineering, Firat University, 23119 Elazig, Turkey,
mduranay@firat.edu.tr

(Geliş Tarihi: 22.11.2011 Kabul Tarihi: 14.08.2012)

Abstract: The main aim of this investigation is to depict the effect of veneering and substrate material thicknesses on the residual stresses occurred on dental restoration after cooling process. The finite element method was used to determine residual stresses distribution on dental restoration. To this end, transient thermal stress analyses were carried out on two-dimensional finite element models during cooling time. It was used dental porcelain and Ni-Cr as veneering and substrate material, respectively. Firstly, cooling curve of dental restoration after firing process was obtained experimentally. Then, to compare experimental and numerical (obtained from the finite element program) cooling curves, an equivalent convection coefficients (Arman vd, 2009) depending on time were defined on the finite element program. The result of the minor revisions on the equivalent convection coefficients, the numerical cooling curve was closed up to experimental cooling curve. ANSYS finite element program was used in the finite element analyses. According to the finite element results, it was seen that residual stresses were significantly affected by the thickness of veneering porcelain and Ni-Cr substrate.
Keywords: Dental restoration, cooling curve, residual stress, finite element analysis.

DİŞ TAMİRLERİNDE MALZEME KALINLIĞININ SOĞUTMA İŞLEMİNDEN KAYNAKLANAN ARTIK GERİLMELER ÜZERİNDEKİ ETKİSİ

Özet: Bu araştırmanın amacı diş tamirinde soğutma işleminden sonra meydana gelen artık gerilmelerde kaplamanın ve alt malzeme kalınlığının etkisini göstermektir. Diş tamirinde artık gerilmelerin dağılımını belirlemek için sonlu eleman metodu kullanılmıştır. Bu amaçla, soğutma süresince iki boyutlu sonlu eleman modeller üzerinde geçici ısıl gerilme analizleri gerçekleştirilmiştir. Kaplama için diş porseleni ve alt malzeme için Ni-Cr kullanılmıştır. Öncelikle, fırınlama işleminden sonra diş tamiri soğutma eğrisi deneysel olarak elde edilmiştir. Daha sonra, deneysel ve sayısal (sonlu eleman programından elde edilmiştir) soğutma eğrilerini karşılaştırmak için, zamana bağlı olarak eşdeğer taşınım katsayıları (Arman vd, 2009) sonlu elemanlar programında tanımlanmıştır. Eşdeğer taşınım katsayıları üzerinde ufak değişikliklerin sonucu sayısal soğutma eğrisi deneysel eğri ile birbirine yaklaşmıştır. Sonlu eleman analizinde ANSYS sonlu eleman programı kullanılmıştır. Sonlu elemanların sonucuna göre, artık gerilmelerin porselen kaplama kalınlığı ve Ni-Cr alt malzemeden önemli ölçüde etkilendiği görülmüştür.
Anahtar Kelimeler: Diş tamiri, soğutma eğrisi, artık gerilmeler, sonlu elemanlar analizi.

NOMENCLATURE

Cp	Specific heat [J/kg°K]
E	Modulus of elasticity [GPa]
h	Thickness [mm]
h_{eq}	Convection coefficient [W/ m^{2}K]
k	Thermal conductivity [mW/mm°K]
t	Time [s]
T	Temperature [°K]
α	Thermal expansion coefficient [x10^{-6}/°K]
ρ	Density [gr/cm^3]
ν	Poisson ratio
σ_xx	Stresses [MPa]

INTRODUCTION

Nowadays, due to their superior aesthetics and biocompatibility properties, ceramic dental restorations have become a popular restoration preference for dental crown applications. Nevertheless, the mechanical properties of the ceramic cause some problems for a dental restoration's long life. In order to accomplish these problems, it is commonly used two layers of material such as a metal alloy and veneering porcelain in restorative treatments.

In dentistry, the thermal incompatibility between veneering porcelain and a metal substrate is often characterized by their difference in thermal expansion coefficient values (α) which is termed as mismatch (Isgró vd, 2004). Although 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 (Toparlı vd, 1999).

While dental restoration cools after firing process of the veneering porcelain, differences between mechanical and thermal properties of the material pairs used in the crown constitute transient thermal stresses. At the end of the cooling process, these thermal stresses as mentioned remain as residual stresses in the restoration. If there is a major difference in thermal expansion behavior between the metal alloy and veneering porcelain, these residual stresses cause an unexpected failure in the dental crown.

Residual stresses in ceramic caused by thermal contraction mismatch between materials are important contributing factors to failures of metal–ceramic and all ceramic restorations. It is generally understood that the residual stress state in metal–ceramic and ceramic–ceramic dental prostheses depends on many factors, including contraction mismatch, cooling rate, firing temperature, geometry, and fabrication technique (DeHoff and Anusavice, 2004).

Some factors during cooling process such as high firing temperatures and thicknesses of metal alloy and veneering porcelain affect the distribution and amount of the residual stresses remained in the dental restoration. Also, determination of the effects and amounts of these factors by using experimental methods is difficult. Accordingly, in recently, it is required numerical solutions to solve such problems.

Finite element analysis (FEA) is also a popular numerical method in stress analysis (Ho vd, 1994). Several researchers have studied the mechanical aspects of endodontically treated tooth. Joshi et al. (Joshi vd, 2001) evaluated the mechanical performance of endodontically treated teeth using three-dimensional finite element methods. Holmes, Diaz-Arnold and Leary (Holmes vd, 1996) selected a computer simulation to predict the distribution of stresses in dentine of an endodontically treated tooth, restored with cast post and cores of various post dimensions. Toparlı (Toparlı, 2003) predicted the stress distribution in dentin of an endodontically treated tooth restored with cast post and cores of various metal alloys using the axisymmetric finite element method. Toparlı et al. (Toparlı vd, 2000, Toparlı vd, 2003) calculated thermal stress and temperature distribution of restored tooth and crowned tooth by using three dimensional finite element method.

DeHoff et al. (DeHoff vd, 2006) have calculated residual stresses in an all-ceramic, three-unit posterior fixed partial denture for four ceramic–ceramic combinations by using three-dimensional model and viscoelastic option of a finite element software program. Arman et al. (Arman vd, 2009) revealed that it is possible to determine transient and residual stress distribution occurring in crown and bridge restorations with adequate sensitivity by using elastic or elastic-plastic finite element solution methods.

In the present study, it was revealed that veneering and substrate material thicknesses affect residual stresses remained on dental crown after cooling process. For this aim, transient thermal stress analysis was performed on two-dimensional dental crown model using ANSYS finite element program. Firstly, cooling curve of dental crown used in transient thermal stress analyses was obtained experimentally. Then, equivalent convection coefficients (Arman vd, 2009) calculated from the cooling curve was defined on the finite element program depend on cooling time. Numerical cooling curve obtained from ANSYS was compared with experimental ones. The result of the minor revisions on the equivalent convection coefficients, the numerical cooling curve was closed up to experimental cooling curve. At the end of these analyses, residual stresses remained on porcelain and Ni-Cr alloy depending on cooling time were determined for different thicknesses of veneering porcelain and Ni-Cr alloy.

MATERIALS AND METHODS

Experimental Procedure

In this part of the study, cooling curve of a dental restoration was measured experimentally to calculate equivalent convection coefficient (h_{eq}) of cooling process. For this purpose, the standard firing process was applied on a dental restoration in the furnace. After the furnace cover had been opened at the maximum temperature value, at the cooling process, it was started temperature measurement on upper surface of the dental restoration. At the end of the cooling process, temperature of the dental restoration decreased to the room temperature (Fig. 1).

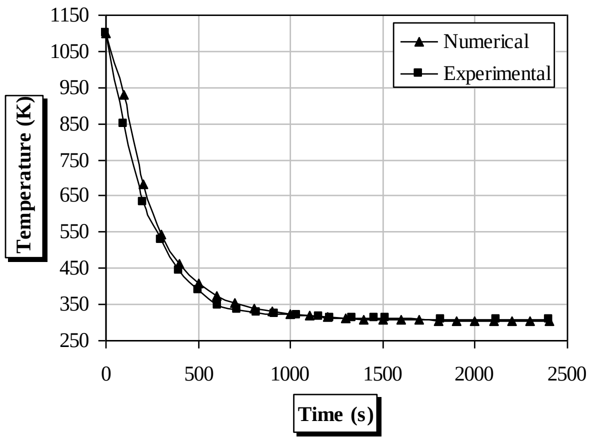

Figure 1. Comparison of experimental and numerical cooling curves

As seen in the cooling curve, temperature of the dental restoration decrease expeditiously, after the furnace cover was opened. The reason is that both convection and radiation affect on the dental restoration simultaneously. Therefore, h_{eq} including the convection and radiation effects together was calculated on the experimental cooling curve to use in the numerical analyses (Arman vd, 2009).

Numerical Procedure

In this study, the main aim is to investigate the effect of thickness. In some situations, different thicknesses can be seen in some regions of dental restoration. These differences affect the residual stresses remained on dental restoration, positive or negative. Hence, for different porcelain or Ni-Cr alloy thicknesses, transient thermal stress analyses were applied, and residual stresses remained on porcelain and Ni-Cr alloy were determined after from the cooling process.

In the numerical analyses, firstly, a two-dimensional finite element model, as seen in Fig. 2, was generated in ANSYS finite element program. In this finite element model, Plane 13, 2-D coupled-field solid element, was used as element type. It has a 2-D thermal and structural field capability with limited coupling between the fields, and is defined by four nodes with up to four degrees of freedom per node. It was used 1920 elements, and 2009 nodes in this finite element model.

Then, numerical cooling curve was compared with the experimental cooling curve by making transient thermal stress analyses on this model in order to define exactly cooling media in the furnace. The equivalent convection coefficients calculated from the experiment were used in these analyses and applied on upper surface of finite element model. At the end of the analyses, some mismatches between experimental and numerical cooling curves were observed. These analyses were repeated by doing minor revisions on h_{eq}, and these mismatches were revised. Finally, h_{eq} values provided the real cooling media were obtained from these analyses. The equivalent convection coefficients obtained were given in Table 1 depending upon time. Also, the harmony between experimental and numerical cooling curves was depicted in Fig. 1.

Afterwards, porcelain and Ni-Cr alloy thicknesses were changed individually so as to investigate the thickness effect and transient thermal stress analyses were performed on the two-dimensional finite element model. To investigate the thickness effect of porcelain, porcelain thickness was changed as 0.8, 1.2, 1.6 and 2.0 mm. On the contrary, Ni-Cr alloy thickness was considered as a constant value, 1.6 mm. Similarly, to investigate the thickness effect of Ni-Cr alloy, Ni-Cr thickness was changed as 0.8, 1.2, 1.6 and 2.0 mm, and porcelain thickness was taken into consideration as a constant value, 1.6 mm.

Mechanical and thermal properties of veneering porcelain and Ni-Cr alloy required in the finite element analyses were obtained in literature (Toparlı, 2003, Arman vd, 2009, Dai and Shaw, 2004, Lenz vd, 2002) and given in Table 2 and Table3, respectively.

RESULTS AND DISCUSSION

In this paper, a transient thermal analysis on 2-D finite element model was represented to investigate the residual stresses remained on dental restoration after the cooling process from 1100 ºK to room temperature (300 ºK), as seen in Fig.1. It was revealed the effect of different veneering porcelain and substrate metal thicknesses.

As depicted in Fig.2, four nodes were considered in the finite element results. Node A is on the bottom surface of substrate metal; Node B_1 and B_2 are situated on the side of substrate metal and porcelain on interface of veneering porcelain and substrate metal, respectively; Node C is on the upper surface of veneering porcelain. These nodes are special points on dental restoration.

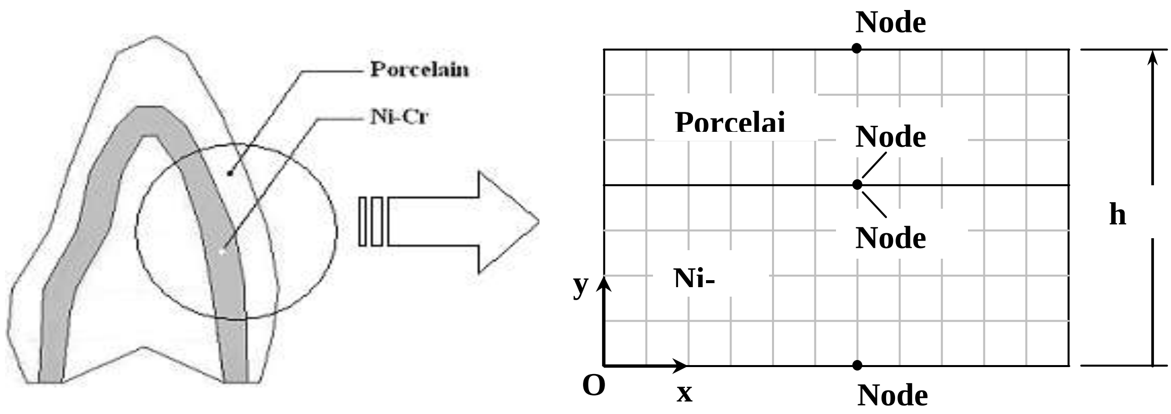

Figure 2. Schematic view of two-dimensional finite element model

Table 1. Equivalent convection coefficients (h_{eq}) used in FEA

Time (s)	0	20	60	120	240	720	1200	2400
h_{eq} (W/m^{2}K)	98	70	54	45	37	22	11	0,1

Because, in literature and so many clinical studies (Arman vd, 2009, Papazoglou and Brantley, 1998, Ozcan and Niedermeier, 2002, Ozcan vd, 2006), these places chosen are given the most critical regions having risk in terms of catastrophic failure. In result of the numerical analyses, σx, σy and τxy stress distributions were examined, and σx stress distributions were considered as the residual stress component, owing to the fact that it has the most critical values.

The sectional distribution of the residual stresses occurred in the dental restoration was given in Fig.3 and 4, depending on the thickness. In the graphics given in Fig.3 (a, b, c and d), the thickness of Ni-Cr alloy was given as a constant value (1.6 mm), but porcelain thickness was changed as 0.8, 1.2, 1.6 and 2.0 mm, respectively. For all of these porcelain thicknesses, it was observed that the residual stress distribution varies linearly. Also, at the interface of metal alloy and porcelain, the stress components have a discontinuity due to the different modulus of elasticity, and it was seen that the compressive stresses occur on the side of porcelain and the tensile stresses occur on the side of Ni-Cr alloy. The reason is that Ni-Cr substrate wants to shrinkage during the cooling process and applies a compressive force to porcelain. On account of the static equilibrium, veneering porcelain applies a tensile force to substrate. For instance, in Fig.3a, 9.39 MPa compressive and 20.3 MPa tensile stresses occurred on the side of porcelain and Ni-Cr alloy, respectively.

For 0.8 mm porcelain thickness (Fig.3a), it was seen that 5.5 MPa compressive stress remains on the upper surface on veneering porcelain. Since the thickness of porcelain was increased, for example 1.2 mm, the residual stresses decreased (-0.43 MPa), as seen in Fig.3b. However, when the porcelain thickness was increased to 1.6 and 2.0 mm, the residual stresses depicted increment and turned into tensile stresses (Fig.3c, d). On the other hand, it was seen that increment of the porcelain thickness does not much affect to the residual stresses occurred in Ni-Cr alloy. In the all of these figures, it was seen that the distribution of the residual stresses occurred in Ni-Cr alloy changes from the tensile to compression through the thickness of its.

In the graphics given in Fig.4 (a, b, c and d), the veneering porcelain thickness was given as a constant value (1.6 mm), but the thickness of Ni-Cr alloy was changed as 0.8, 1.2, 1.6 and 2.0 mm, respectively. For all of these thicknesses, it was observed the similar behaviors with the previous figures. For 0.8 mm Ni-Cr alloy thickness (Fig.4a), it was seen that 5.68 MPa tensile and 7.06 MPa compressive stresses remain on the upper (porcelain) and bottom (Ni-Cr) surface of the dental restoration, respectively. When the thickness of Ni-Cr was increased, it was seen that the residual stresses remained on the upper surface of porcelain decreased, as seen in Fig.4b, c and d. But, the values of the compressive residual stresses remained on the bottom surface of Ni-Cr increased. Similarly, it was seen that the variation of the residual stresses occurred in Ni-Cr alloy changes from the tensile to compression through the thickness.

The nodal distribution of the residual stresses occurred in the dental restoration was given in Fig.5 and 6. In Fig.5, the substrate thickness was considered as a constant value (1.6 mm) and the residual stress distributions occurred at the critical nodes of dental restorations was depicted depending on the porcelain thickness. As seen in Fig.5, for constant Ni-Cr alloy thickness, when the veneering porcelain thickness was increased, the residual stresses occurred at the A, B1

Table 2. Mechanical and thermal properties of veneering porcelain (Toparlı, 2003, Arman vd, 2009, Dai and Shaw, 2004, Lenz vd, 2002)

Temperature	T (ºK)	293	473	573	673	773	893	993	1100
Modulus of elasticity	E (GPa)	70	67,52	66,15	64,77	63,39	61,64	100	0,2
Poisson ratio	ν	0,193	0,196	0,189	0,188	0,187	0,182	0,180	0,179
Thermal expansion coeff.	α ($x10^{-6}$/ºK)	13,5	13,6	13,6	13,7	13,7	13,6	17,5	16,9
Thermal conductivity	k (mW/mmºK)	1,10	1,31	1,45	1,62	1,81	2,05	2,32	2,60
Specific heat	C_p (J/kgºK)	730	973	1081	1160	1233	1305	1360	1410
Density	ρ (gr/cm^3)	2,497							
Maximum Strength	σ_{max} (MPa)	69							

Table 3. Mechanical and thermal properties of Ni-Cr alloy (Toparlı, 2003, Arman vd, 2009, Dai and Shaw, 2004, Lenz vd, 2002)

Temperature	T (ºK)	293	473	573	673	773	893	993	1100
Modulus of elasticity	E (GPa)	200	195	192	185	158	124	100	73
Poisson ratio	ν	0,252	0,251	0,251	0,250	0,250	0,249	0,247	0,246
Thermal expansion coeff.	α ($x10^{-6}$/ºK)	13,80	13,88	13,92	13,98	14,07	14,25	14,73	15,48
Thermal conductivity	k (mW/mmºK)	9,8	12,5	13,9	15,3	16,9	18,5	20,0	21,9
Specific heat	C_p (J/kgºK)	422	489	540	505	506	518	531	546
Density	ρ (gr/cm^3)	8,2							
Maximum Strength	σ_{max} (MPa)	515							

and B2 nodes were not more affected, but the residual stresses at Node C changed from the compression to tensile. Accordingly, it was determined that the most proper porcelain thickness in terms of the residual stress occur at the upper surface of porcelain (Node C) is 1.2 mm for 1.6 mm Ni-Cr alloy thickness.

Similarly, the thickness of the veneering porcelain was taken into consideration as a constant value (1.6 mm) in Fig.6. At the critical nodes of dental restorations, the residual stress distributions occurred was shown depending on the substrate thickness. For constant veneering porcelain thickness, since the substrate thickness was increased, the residual stresses occurred at the nodes A and B1 were seen increases, at nodes B2 and C were seen decreases. Also, it was determined that the most compatible thickness with 1.6 mm veneering porcelain thickness is 2.0 mm Ni-Cr alloy, in terms of the residual stress occurred at the upper surface of porcelain (Node C).

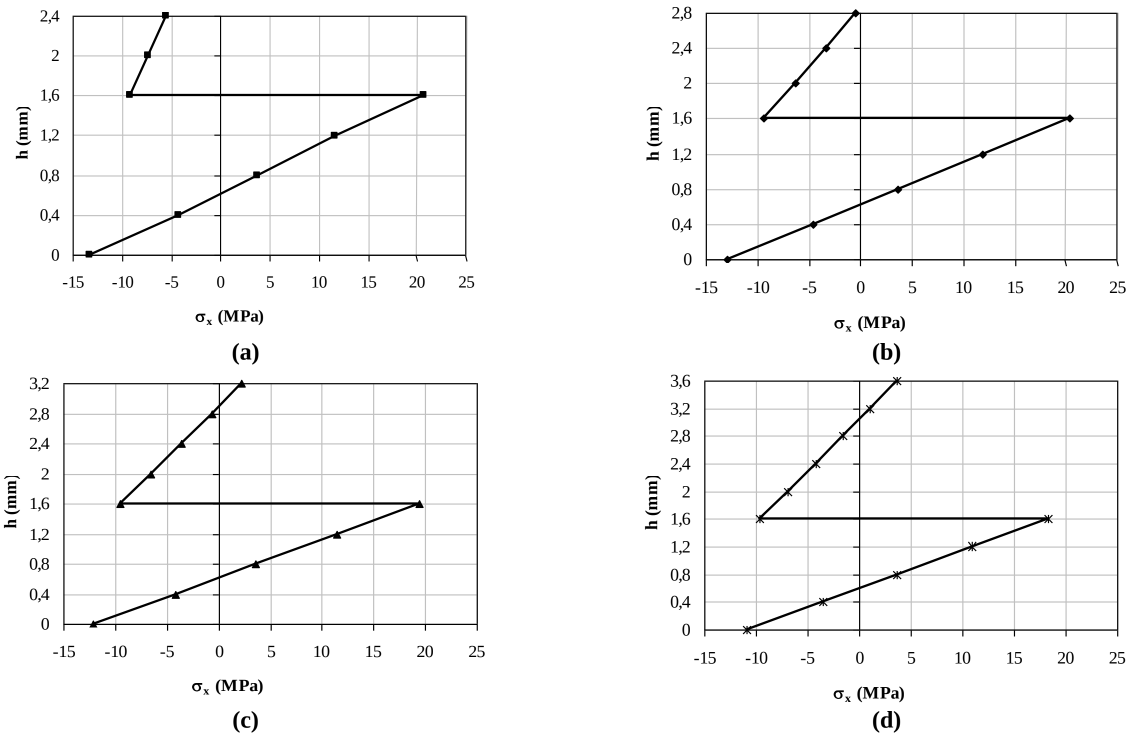

Figure 3. The distribution of the residual stresses according to the porcelain thickness; **(a)** 0.8, **(b)** 1.2, **(c)** 1.6 and **(d)** 2.0 mm

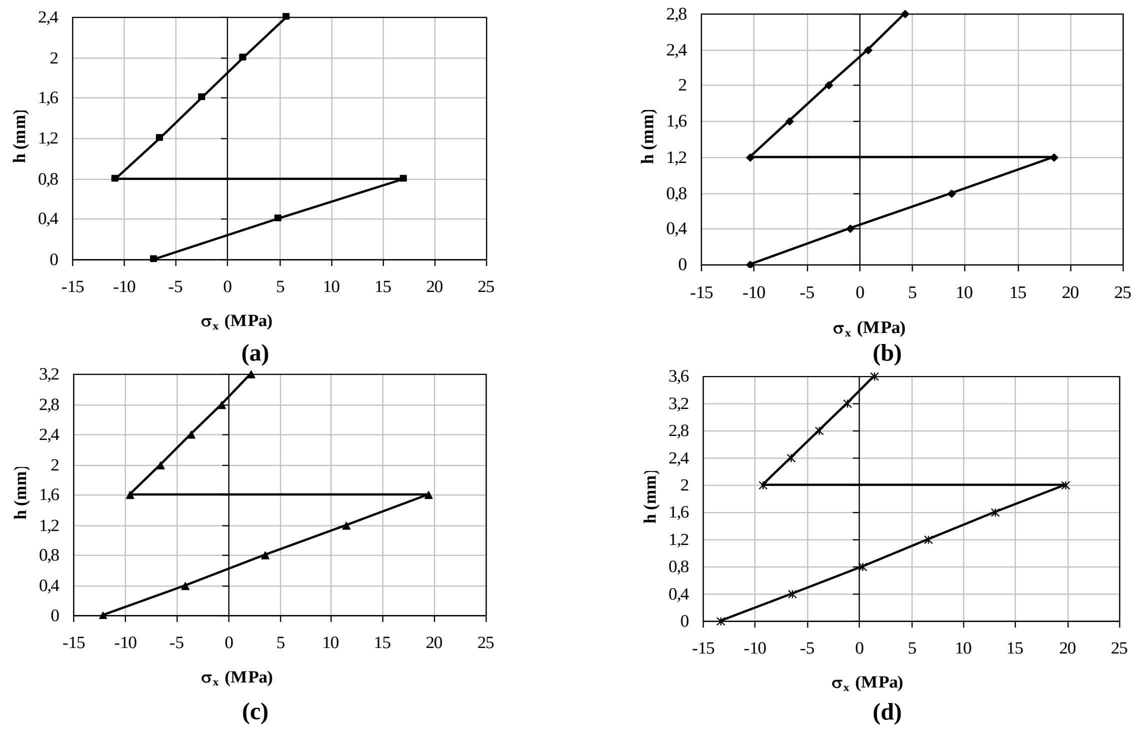

Figure 4. The distribution of the residual stresses according to the Ni-Cr alloy thickness; **(a)** 0.8, **(b)** 1.2, **(c)** 1.6 and **(d)** 2.0 mm

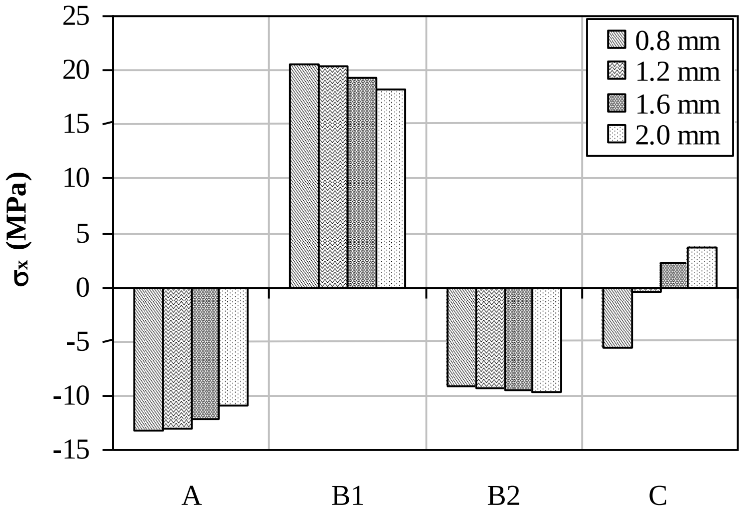

Figure 5. Nodal distribution of the residual stresses depending on the porcelain thickness

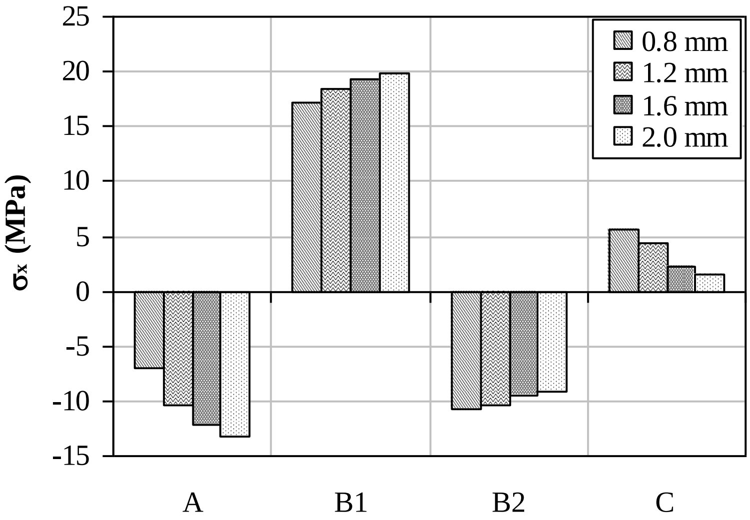

Figure 6. Nodal distribution of the residual stresses depending on Ni-Cr alloy thickness

CONCLUSIONS

A transient thermal stress analyses on 2-D finite element model were applied to investigate the effect of the thickness of veneering porcelain and substrate material on the residual stresses remained on dental restoration after the cooling process. The equivalent convection coefficients provided the real cooling media in the furnace and determined from the experimental and numerical studies were used in these analyses. Since these coefficients include both heat transfer and radiation during cooling process of the dental restoration, the results from these analyses were obtained as very realistic.

From the all of these analyses, it was revealed that the thicknesses of veneering porcelain and substrate material affect on the residual stresses remained on the dental restoration. It was observed that porcelain crown was influenced from the difference of the thickness between substrate material and porcelain. While the thickness of the porcelain was changed, it was seen that the residual stresses remained on the porcelain returned from the compression to tensile. As seen in the clinical studies, it was concluded that porcelain thickness must be chosen compatible with substrate material.

Also, it was determined that the residual stresses occurred at the interface of porcelain and substrate material arisen from the differences of modulus of elasticity and thermal expansion coefficient of porcelain and substrate material. Therefore, veneering porcelain used must be compatible with substrate material in terms of the mechanical properties, as mentioned above.

Additionally, the experimental and 2-D finite element method used in this study can be a reference for subsequent investigations of numerical analyses relevant to dental restoration applications.

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Mehmet DURANAY, he was born in Elazig in 1957. He graduated from the Mechanical Engineering Department of Firat University in 1980 and he received MSc degree from the same university in 1984. He gained Ph.D. degree from Firat University in 1998. He became assistant professor in year 2000 at Firat University Mechanical Engineering Department. He is interested in heat transfer, solar energy.