Influence of veneering porcelain thickness on the residual stress developed within the veneering porcelain in the zirconia-ceramic and metal-ceramic systems – A novel testing method

Research Proposal

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Literature Review :

Fixed Prosthodontics has undergone a tremendous metamorphosis in the years since its inception. The conventional means of fabricating crowns and bridges involved casting a metal framework and then layering it with a veneering porcelain. This type of restoration demonstrated a high level of success and was the norm that came to be followed for a long time. Although these type of restorations demonstrated adequate strength and fracture toughness, an important problem associated with them has always been their esthetic inferiority.[1] Due to the inherent need to mask the metal underneath, opaquer had to be applied to the surface of the metal before porcelain layering. This opaquer in some instances gave the restoration a very lifeless and hence unesthetic appearance, especially in the hands of an unsophisticated ceramist.

Another problem associated with these restorations was that any amount of soft tissue recession would lead to exposure of the metal margin. In patients with thin gingival biotype and a high smile line; the conventional metal ceramic a restorations, in the esthetic zone, seemed to create a major compromise. [1] The veneering ceramic proved to be a decent match. The problem was mainly attributed to the metal that was an integral part of this type of restorations. Hence it was felt that restorations must be designed in such a way so as to be metal free.

Research took dentistry in the direction of ceramics.[2] An important consideration was that ceramics inherently being glass had a brittle nature overall. In addition ceramics demonstrated a poor tendency to withstand tensile forces, being adequately satisfactory in resisting compressive forces. The ceramics also have some manufacturing flaws which could be the region from which microcracks begin and propagate when the ceramic is placed under a tensile load.[3]In the continuous quest to find the most ideal all ceramic system for restorations, multiple systems have been proposed and tested. Some noteworthy attempts include spinell, alumina , zirconia , lithium disilicate, reinforced lithium disilicate etc. [4]

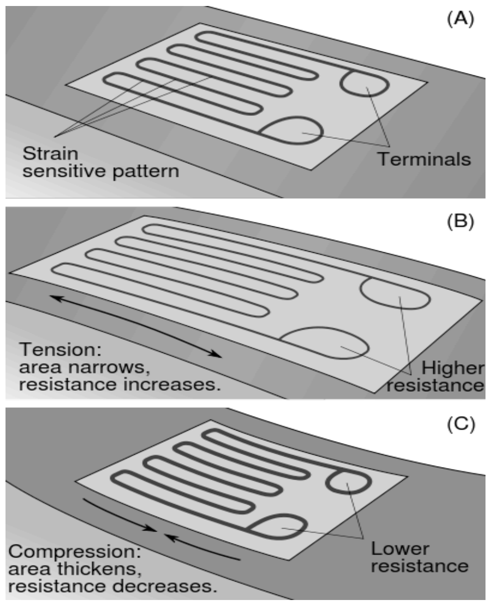
Zirconia is a name given to a crystalline form of zirconium dioxide. The observed advantages of zirconia include having shades that would more easily replicate teeth shades, while at the same time having it's mechanical properties in the range of metals.[5] Existing naturally in 3 different forms namely Monoclinic, Cubic and Tetragonal, oxides of other metals may be added to it to increase the stability of the crystalline structure. Examples of such metals would be Mg, Ca, Y etc. [3] Presently yttrium stabilized zirconia finds the most number of applications and has been most extensively tested. [6] Due to it's opaque nature zirconia finds more application in the dental field as a core material for crowns and bridges, replacing the conventional metal cores, to be layered with veneering porcelain for superior esthetics. [7] Multiple short term clinical studies have shown satisfactory results for FDPs in which zirconia has been used as a material for the core. [8] [9] [10] In most of the studies the zirconia ceramic FDPs have shown a higher technical complication rate than the metal ceramic system [11] Chipping of the veneering porcelain has been reported as the most commonly encountered technical complication. Numerically it was found to be in the region of 8-25 %. [7 8 9] In one study it was reported to be as high as 54% at the end of an observation period of just one year. [13] Chipping is not so commonly observed with the metal ceramic FDPs as it is with the zirconia ceramic system.[12]

This phenomenon of chipping may be interpreted as a cohesive failure within the layer of veneering ceramic. Many possible explanations have been suggested to understand the reason for this high chipping incidence. One of them has been the microscopic structural deformities present in the zirconia itself. [14] This hypothesis states that chipping occurs mainly in the veneering porcelain overlying the flawed zirconia surface. A lesser than adequate support of the layered porcelain by improper design of the underlying zirconia framework has also been suggested. [15] Another possible explanation has been the low fracture toughness of the veneering ceramic itself.[16] One of the most common reasons cited for chipping have been the mismatch in the thermal coefficient of the zirconia with the veneering ceramic. [17] It is known that the metals used for metal ceramic FDPs have a CTE that is slightly higher than the veneering ceramic. This puts most of the veneering ceramic under a compressive force rather than a tensile force. In the zirconia ceramic system the CTE being slightly lower could have a considerably different stress pattern. To add to this zirconia has a very low thermal conductivity.[18] A combination of these factors could lead to the development of residual

tensile stresses within the zirconia ceramic system. These stresses when combined with the stresses exerted on the system due to function and occlusion could be the reason for the early failure of the zirconia ceramic system due to chipping. Since the entire process involves multiple firing/cooling cycles, the thermal mismatch or gradient that is generated due to the CTE mismatch could be one of the most important factors[20]. The thermal behavior of any two-material system would depend on the properties of the materials (CTE , Thermal conductivity) , the rate at which the system is heated/cooled as also the ratio of the thickness of the two materials. Zarone et al have shown that altering the ratio between the zirconia and veneering ceramic could be a reason for the higher incidence of failures.[19] It is also important to study the stress versus depth to quantify how the stress patterns change at different depths within the system.
Mathematical models have demonstrated that if the cooling rate, thickness and CTE mismatch are considered together, the thickness of the materials would have the most significant effect on the stresses generated. [18] Some authors have utilized 3D finite element analysis to try and quantify these stresses developed [23] [24]

A study done by Kokubo demonstrated that increased thickness of the zirconia core along with a better support for the entire cuspal configuration would significantly improve the fracture load of the zirconia ceramic FDPs [21]. Yet no method has been able to quantify the residual stress so far.
A novel method to measure the residual stress patterns exists in industry. It involves the process of hole–drilling to release residual stresses, which could be measured by strain gauges.

The hole is drilled into the center of the sample in increments of constant depth. A strain gage rosette is applied around the hole to be drilled and dynamic strains are calculated throughout the drilling process. Hole diameter and depth are standardized. Strain data obtained is inserted into H-Drill, a software that computes residual stress from the observed strain data. This technique can give us a depth vs stress pattern as also can quantify the residual stress and give us it's nature (Compressive vs Tensile stress) .[22]



Application of this method to the dental setting could change our understanding of the residual stresses built up in the veneering porcelain.

A strain gauge consists of an [insulating](#) flexible backing which supports a metallic foil pattern. The gauge is attached to the object by a

Figure 1.

suitable adhesive, such as cyanoacrylate. As the object is deformed, the foil is deformed, causing its electrical resistance to change. [25] Depending on the type of deformation and the corresponding change in the resistance the nature of the strain (Compressive vs Tensile) can be computed.

A basic material sciences study was conducted on disks of metal ceramic and zirconia ceramic system using the hole drilling method.[22] This does not accurately replicate the clinical situation of having a crown. Another drawback was that the authors did not quantify the stresses and did not perform a statistical analysis to find out if there was a significant difference between the zirconia ceramic and metal ceramic system. Lastly this study utilized complex equipment for the process that is not readily available and is very expensive to use.

A cusped crown form would more closely if not completely replicate the clinical situation for which reason this study was designed. Also an attempt was made to apply the Hole Drilling design in a completely unique way by modifying and using the available research equipment, instead of relying on more sophisticated measures.

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Purpose of the study :

The objectives of this study are

1- Apply the hole drilling method to measure residual stresses at different depths in crown samples made of zirconia ceramic and metal ceramic restorations and to find out the influence that different thicknesses of the veneering porcelain have on these stresses
2- Quantify stress at various depths
3- Demonstrate if the metal ceramic and zirconia ceramic system show different stress patterns
4- Develop a unique way of applying hole drilling by modifying and using available research equipment

Null Hypothesis

Veneering porcelain thickness does not have an influence on the residual stresses developed within the zirconia ceramic system

There is no difference between the behavior of the zirconia ceramic and the metal ceramic system

Alternate Hypothesis

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Veneering porcelain thickness has a significant influence on the residual stresses developed within the zirconia ceramic system

There is a significant difference between the behavior of the zirconia ceramic and the metal ceramic system

Materials and Methods

1) Sample Size Calculation

Previous studies on the subject do not mention means or standard deviations

Hence a sample size cannot be directly calculated

The way to go would be to conduct a pilot study to find the efficacy of the measurement system and find out errors

The pilot study would also give us means and standard deviations

A sample size would then be calculated

2) Sample Production

A second molar typodont tooth was prepared to receive a full contour crown. Uniform reduction of 2.0 mm all around was maintained. The tooth preparation was performed by one operator and inspected by another operator to avoid bias.

Preparation was standardized to have a uniform 2.0 mm deep chamfer margin all around the tooth. A wax pattern was made of the prepared tooth and cast in D.Sign 30 alloy to fabricate a Master Die. The die was checked for casting defects, finished and polished. Two flat surfaces were maintained on the mesial and distal side of the root extension of the die in order to be clamped firmly in the hole drilling assembly.

Two full contour crowns were waxed up on the master die, one to simulate a veneering porcelain thickness of 2.0 mm and one to simulate a veneering porcelain thickness of 3.0 mm. On both the wax ups a 2.0 mm diameter area on the occlusal was left flat for ease of subsequent strain gage application. A split mold index was made of each of these wax ups to be used at a later stage to ensure proper porcelain application and proper dimension of the final crowns. Thus we obtained a split mold simulating 2.0 mm veneering porcelain thickness and a split mold simulating 3.0 mm of veneering porcelain thickness.

10 frameworks each of metal Ivoclar D.Sign 59 alloy and zirconia (NobelProcera) were made for the master die. In order to produce the metal frameworks, the full contoured crown wax ups were cut back to get a waxed up framework of 1.0 mm thickness. A split mold index was made at this stage to standardize all the metal frameworks. The frameworks were waxed up on the master die, checked with the split mold to ensure thickness of the metal framework and then invested in gypsum based investment material (Cristobalite, Whip Mix). After wax elimination, they were cast in Ivoclar D.Sign 59 alloy. All metal frameworks were finished and inspected for casting errors and accuracy of thickness.

In order to produce zirconia frameworks, the master die was scanned to fabricate Nobel Procera Zirconia frameworks of standardized 1.0 mm thickness by CAD/CAM milling. A dual scan was done to ensure accuracy and each coping was inspected for milling errors and accuracy of thickness.

Compatible veneering porcelain, Ivoclar D.Sign and Ivoclar Emax Ceram was applied to metal and zirconia frameworks respectively. Veneering porcelain was applied to a uniform thickness of 2.0 mm for 5 metal frameworks and 5 zirconia frameworks using the previously designed split mold. Veneering porcelain was applied to a uniform thickness of 3.0 mm on 5 metal and 5 zirconia frameworks using the second split mold designed.

Thus four different groups of samples were formed –

MN (Metal Narrow) : Metal framework with 2.0 mm veneering porcelain

ZN (Zirconia Narrow): Zirconia framework with 2.0 mm veneering porcelain

MW (Metal Wide) : Metal framework with 3.0 mm veneering porcelain

ZW (Zirconia Wide) : Zirconia framework with 3.0 mm veneering porcelain

Porcelain was applied by a layering technique according to manufacture instructions by one operator. Veneering porcelain was applied in 3 different layers – opaque, body and enamel. All the samples were checked with the split mold before and after the final firing to ensure no post firing adjustments.

Processing temperatures, cooling rates and handling of all materials were standardized. A thermocouple was installed to ensure that the cooling rates and temperature gradients are identical for all samples. The cooling rate employed was the conventional cooling as suggested by the manufacturer. After the specimens reached the glazing temperature, the furnace was turned off and the samples were left in the oven with the door shut till the temperature cooled down to 100^{o}C. At this point the furnace door was opened to allow the samples to slowly reach room temperature.[26]

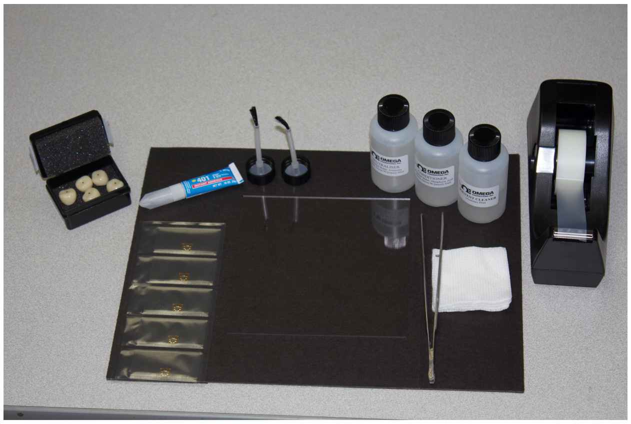
3) Assembly in MTS machine :

A new method was devised to perform the hole drilling with a standard Universal Testing Machine. In order to orient the drill and the sample on the master die the upper and lower members of the MTS machine were used. A specialized holder was made to attach the lab hand piece to the upper member of the MTS machine. A holder was designed to clamp the master die in the lower member of the MTS machine. A bowl was designed around the sample in the lower holder to contain coolant that will be used during drilling. In order to compensate for the slight rotation of the lower member relative to the upper member as the two progress towards each other, a standard rod was designed on the lower holder with a corresponding recess in the upper holder. This ensured that as the lower member rose towards the upper member, the sample and the hand piece would be automatically oriented to each other as soon as the rod engaged the recess.

Each sample was placed on the master die once all the individual parts were assembled. A bur (1mm diameter flat ended was inserted into the hand piece. A piece of articulating paper was placed on the occlusal surface of the sample and the two members of the MTS machine were moved closer to each other until the bur slightly touched the sample. In this way a spot was marked on every sample so that the strain gage could be oriented at the exact same location on every sample. Once the samples were marked each sample was numbered. (MN1-MN5, MW1-MW5, ZN1-ZN5, ZW1-ZW5)

Strain gage EA-13-031RE-120 with three individual strain gages arranged in a rosette pattern was chosen for the study. The selection of the strain gage was based on the diameter of the rosette that would fit on the occlusal surface area of the samples and the maximum allowable hole diameter.

4) Sample Preparation :



The surface of each sample was prepared for bonding of the strain gage in 3 steps -

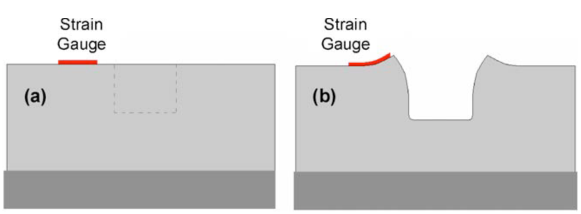
1) In the first step the surface of the sample was cleaned using Solvent Cleaner (Acetone).

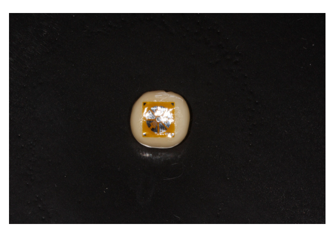
2) As a second step; Conditioner [Distilled water, Phosphoric acid (trace) and Decon 90 (trace)] was applied to the sample surface, left for 10 seconds and the sample was dried using a clean piece of gauze.

3) The last step involved application of Neutraliser [Distilled water, Ammonia (trace) and Decon 90 (trace)]

At the end of the 3 step sample preparation process, the sample was considered ready for strain gage application.

<u>5) Application of Strain Gauge:</u>





Strain gage cyanoacrylate glue (Omega engineering) was applied to the bonding surface of the strain gage and to the surface of the sample. One operator applied strain gages to all samples ensuring that the space for the hole drilling at the center of the rosette corresponded exactly with the previously marked spot. All samples were checked at this stage to ensure adequate bonding of strain gages to the samples.

Single conductor wire 136- AWP (Micromeasurements Group) was cut, uncoated at the ends by scraping and then soldered to the solder tabs corresponding to each strain gage. Thus each sample had 6 solder connections (2 for every gage). Adequacy of the solder connection was ensured by measuring a resistance of a minimum of 120 ohms across the strain gage with the help of a 46 Range Professional Multimeter (Radioshack).

A 6 channel strain conditioner was connected to a computer and software Strain Smart 5000 was used for all the readings. Alligator clips were attached to wires coming from Channels 1,2 and 3 of the strain conditioner. The surface of the bowl on the lower holder was insulated by applying insulating tape and the alligator clips were attached to the bowl. The insulation ensured that false current readings will not be recorded.

6) Assembly of the sample :

Each sample was seated on the master die with TempBond clear cement. One drop of cement was placed on the buccal and lingual margin of every sample and the crown was seated on the master die and held with uniform finger pressure for 5 minutes to ensure complete seating of the crown. Every crown was visually inspected and seating was confirmed by one operator. Cementation of the crown to the master die ensured that there would not be any error due to the vibration of the crown, once the drilling process was initiated. Upon completion of the drilling for one crown the crown was unseated using a Milltex forcep and the die was cleaned using hand scalers and visually inspected for no residual cement before another sample was cemented.

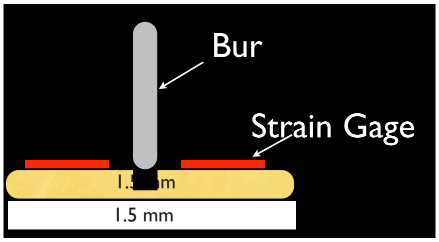
Once the sample was cemented in place the alligator clips were attached to the 6 wires, thus connecting the strain gages to the conditioner. The connection was reconfirmed at this stage using online monitors in Strain Smart 5000 to make sure that none of the strain gages were off scale at the start of the experiment.

7) Drilling procedure :

The handpiece speed was set at 19000 RPM. A program was set on the MTS machine to move with a crosshead speed of 0.1 mm / min for a total of 15 mins, thus ensuring a constant depth of 1.5 mm drilling for every sample. At the beginning of each drilling procedure the MTS machine was set using load control until the bur very slightly touched the surface of the sample as shown by the change in the load on the display. The machine was now changed to displacement control before the program was initiated. The onscreen display ensured that the movement was at uniform speed and had no irregularities. Mineral oil was squirted onto the sample at intervals of 1 mins. The mineral oil acted like thermal insulation, electrical insulation and lubricant through out the drilling process.

The strain gages were monitored with an online display right throughout the procedure and continuous readings were made.

Sample Demonstration



Data analysis :

The strain data available from the experiment will be put into the H-Drill Software to calculate residual stress at different depths. At this point graphs will be plotted of stress vs depth to show the exact behavior of the porcelain. Also the stress values for the wide and narrow Zirconia groups will be compared to wide and narrow metal groups in the attempt to show a difference.

Statistical Analysis

t - test to compare within the group to find the influence of thickness of the framework

ANOVA to compare within the groups to see if the results are similar for zirconia and metal

Clinical Significane :

Understanding the stress behavior of zirconia ceramic with different thicknesses of veneering porcelain and comparing it to metal will possibly show us the reason for the observed excessive chipping in the zirconia ceramic system. These findings will also show us why the metal ceramic system seems to work better. Finally the authors wish to advocate design recommendations that would possibly limit the incidence of chipped veneering porcelain in layered zirconia restorations.

References

(1) Mclaren EA, All ceramic alternatives to conventional metal ceramic restorations. Compend Continuing Education in Dentistry 1998. 19(3): p307-8,310,312

(2) Mclaren J, Dental Ceramics. Proceedings of first international symposium on ceramics. Chicago (IL) Quintessence International 1983

(3) Seghi RR, Denry IL, Rosenstiel SF. Relative fracture toughness
and hardness of new dental ceramics. J Prosthet Dent. 1995;74:145–150

(4)Raigrodski AJ. Contemporary materials and technologies for all-ceramic fixed partial dentures: a review of the literature. Journal of Prosthetic Dentistry 2004;92:557–62

(5) Piconi C, Maccauro G. Zirconia as a ceramic biomaterial. Biomaterials 1999;20:1–25

(6) Gupta TK, Bechtold JH, Kuznickie RC, Cadoff LH, Rossing BR. Stabilization of tetragonal phase in polycrystalline zirconia. Journal of Materials Science 1978;13:1464

(7) Raigrodski, A. J. and Chiche, G. J. (2002), ALL-CERAMIC FIXED PARTIAL DENTURES, PART I: IN VITRO STUDIES. Journal of Esthetic and Restorative Dentistry, 14: 188–191

(8) Five-year clinical results of zirconia frameworks for posterior fixed partial dentures.

Sailer I, Fehér A, Filser F, Gauckler LJ, Lüthy H, Hämmerle CH, Int J Prosthodont. 2007 Jul-Aug;20(4):383-8.

(9) Clinical behavior of zirconia-based fixed partial dentures made of DC-Zirkon: 3-year results.
Tinschert J, Schulze KA, Natt G, Latzke P, Heussen N, Spiekermann H.
Int J Prosthodont. 2008 May-Jun;21(3):217-22

(10) Five-year clinical prospective evaluation of zirconia-based Denzir 3-unit FPDs.

Molin MK, Karlsson SL , Int J Prosthodont. 2008 May-Jun;21(3):223-7

(11) Randomized controlled clinical trial of zirconia-ceramic and metal-ceramic posterior fixed dental prostheses: a 3-year follow-up Sailer I, Gottnerb J, Kanelb S, Hammerle CH, Int J Prosthodont. 2009 Nov-Dec;22(6):553-60

(12) Tan, K., Pjetursson, B. E., Lang, N. P. and Chan, E. S.Y. (2004), A systematic review of the survival and complication rates of fixed partial dentures (FPDs) after an observation period of at least 5 years. Clinical Oral Implants Research, 15: 654–666

(13) Larsson C, Vult von Steyern P, Sunzel B, Nilner K. All-ceramic
two- to five-unit implant-supported reconstructions. A randomized, prospective clinical trial. Swed Dent J. 2006;30: 45–53

(14) Ohlmann B, Rammelsberg P, Schmitter M, Schwarz S, Gabbert O. All-ceramic inlay-retained fixed partial dentures: preliminary results from a clinical study. J Dent. 2008;36: 692–696

(15) Marchack BW, Futatsuki Y, Marchack CB, White SN. Customization of milled zirconia copings for all-ceramic crowns: a clinical report. J Prosthet Dent. 2008;99:169–173

(16) Beuer F, Schweiger J, Eichberger M, Kappert HF, Gernet W, Edelhoff D. High-strength CAD / CAM-fabricated veneering material sintered to zirconia copings–a new fabrication mode for all-ceramic restorations. Dent Mater. 2009;25:121–128

(17) Fischer J, Stawarzcyk B, Trottmann A, Hammerle CH. Impact of thermal misfit on shear strength of veneering ceramic / zirconia composites. Dent Mater. 2009;25:419–423

(18) Swain MV. Unstable cracking (chipping) of veneering porcelain on all-ceramic dental crowns and fixed partial dentures. Acta Biomater. 2009;5:1668–1677

(19) Zarone F, Russo S, Sorrentino R. From porcelain-fused-to-metal to zirconia: clinical and experimental considerations. Dent Mater 2010;20:20 [November 20]

(20) Gostemeyer G, Jendras M, Dittmer MP, Bach FW, Stiesch M, Kohorst P. Influence of cooling rate on zirconia/veneer interfacial adhesion. Acta Biomater 2010;6(December (12)):4532–8.

(21) The influence of zirconia coping designs on the fracture load of all-ceramic molar crowns
Yuji KOKUBO[1) 2)], Mitsuyoshi TSUMITA[1)], Takamitsu KANO[1)], Shunji FUKUSHIMA[1)]

Dental Materials Journal Vol. 30 (2011) No. 3 P 281-285

(22) Mainjot AK, Schajer GS, Vanheusden AJ, Sadoun MJ. Residual
stress measurement in veneering ceramic by hole-drilling.
Dent Mater 2011;27(May (5)):439–44

(23) Rafferty BT, Janal MN, Zavanelli RA, Silva NR, Rekow ED, Thompson VP, et al. Design features of a three-dimensional molar crown and related maximum principal stress. A finite element model study. Dent Mater 2010;26(February(2)):156–63

(24) Bonfante EA, Rafferty B, Zavanelli RA, Silva NR, Rekow ED, Thompson VP, et al. Thermal/mechanical simulation and laboratory fatigue testing of an alternative yttria tetragonal zirconia polycrystal core–veneer all-ceramic layered crown design. Eur J Oral Sci 2010;118(April (2)):202–9

(25) ASTM. Determining residual stresses by the hole-drilling strain–gage method. Standard Test Method E837-08. West Conshohocken, PA, USA: American Society for Testing and Materials; 2008

(26) Choi, J.E., J.N. Waddell, and M.V. Swain, Pressed ceramics onto zirconia. Part 2: indentation fracture and influence of

cooling rate on residual stresses. Dent Mater, 2011. **27**(11): p. 1111-8.

Additional References :

[1] Schley JS, Heussen N, Reich S, Fischer J, Haselhuhn K, Wolfart S. Survival probability of zirconia-based fixed dental prostheses up to 5 years: a systematic review of the literature. Eur J Oral Sci 2010;118(October (5)):443–50.

[2] Heintze SD, Rousson V. Survival of zirconia- and metal-supported fixed dental prostheses: a systematic review. Int J Prosthodont 2010;23(November–December (6)):493–502.

[3] Gostemeyer G, Jendras M, Dittmer MP, Bach FW, Stiesch M, Kohorst P. Influence of cooling rate on zirconia/veneer interfacial adhesion. Acta Biomater 2010;6(December (12)):4532–8.

[4] Mainjot AK, Schajer GS, Vanheusden AJ, Sadoun MJ. Influence of cooling rate on residual stress profile in veneering ceramic: Measurement by hole-drilling. Dent Mater 2011;27(September (9)):906–14.

[5] Asaoka K, Tesk JA. Transient and residual stress in a

porcelain–metal strip. J Dent Res 1990;69(February (2)):
463–9.

[6] Taskonak B, Borges GA, Mecholsky Jr JJ, Anusavice KJ, Moore
BK, Yan J. The effects of viscoelastic parameters on residual
stress development in a zirconia/glass bilayer dental
ceramic. Dent Mater 2008;24(September (9)):1149–55.

[7] Swain MV. Unstable cracking (chipping) of veneering
porcelain on all-ceramic dental crowns and fixed partial
dentures. Acta Biomater 2009;5(June (5)):1668–77.

[8] DeHoff PH, Anusavice KJ, Vontivillu SB. Analysis of
tempering stresses in metal–ceramic disks. J Dent Res
1996;75(February (2)):743–51.

[9] Zarone F, Russo S, Sorrentino R. From porcelain-fused-tometal
to zirconia: clinical and experimental considerations.
Dent Mater 2010;20(November):20.

[10] Bonfante EA, Rafferty B, Zavanelli RA, Silva NR, Rekow ED,
Thompson VP, et al. Thermal/mechanical simulation and
laboratory fatigue testing of an alternative yttria tetragonal
zirconia polycrystal core-veneer all-ceramic layered crown

design. Eur J Oral Sci 2010;118(April (2)):202–9.

[11] Mainjot AK, Schajer GS, Vanheusden AJ, Sadoun MJ. Residual
stress measurement in veneering ceramic by hole-drilling.
Dent Mater 2011;27(May (5)):439–44.

[12] ASTM. Determining Residual Stresses by the Hole-Drilling Strain-Gage Method. Standard Test Method E837-08. West Conshohocken, PA, USA: American Society for Testing and Materials; 2008.

[13] Schajer GS, Prime MB. Use of inverse solutions for residual stress measurements. J Eng Mater Technol Trans ASME 2006;128(3):375–82.

[14] Tholey MJ, Swain MV, Thiel N. SEM observations of porcelain Y-TZP interface. Dent Mater 2009;25(July (7)): 857–62.

[15] Li JG, Zhang LM, Shen Q, Hashida T. Degradation of yttria stabilized zirconia at 370 K under a low applied stress. Mater Sci Eng A: Struct 2001;297(January (1–2)):
26–30.

[16] Chevalier J, Gremillard L, Virkar AV, Clarke DR. The tetragonal-monoclinic transformation in zirconia: lessons

learned and future trends. J Am Ceram Soc 2009;92(September (9)):1901–20.

[17] Tholey MJ, Berthold C, Swain MV, Thiel N. XRD2 micro-diffraction analysis of the interface between Y-TZP and veneering porcelain: role of application methods. Dent Mater 2010;26(June (6)):545–52