Thermal shock resistance of core reinforced all-ceramic crown systems

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The coefficient of thermal expansion of core and veneer porcelains for all ceramic crowns must be compatible to prevent formation of stresses during the firing cycles. The purpose of this study was to use a thermal shock test to evaluate the crazing resistance of six all-ceramic crown systems. The systems tested were: Vita In-Ceram®, Vita Hi-Ceram®, Dicor™ veneered with Vitadur® N, magnesia core veneered with Ceramco® II, magnesia core veneered with Silhouette™, and magnesia core veneered with Vita VMK® 68. A maxillary central incisor was prepared with 1.0 mm axial and 1.5 mm incisal reduction. Refractory dies were prepared and crowns were fabricated using the manufacturers' recommendations. Six specimens of each system were placed inside a beaker in a furnace at 90°C. After 15 min heat soak, ice water was poured into the beaker through a funnel. The samples were dried in air, reheated, and inspected for crazing using light microscopy. If crazing was observed, this would constitute a failure at a temperature difference (ΔT) of 90°C. If no failure occurred, the test was repeated at increasing temperature increments of 10°C until failure. The crazing resistance of each system, expressed as the mean ΔT, was: > 200 (Hi-Ceram®), 163 ± 14 (In-Ceram®), 152 ± 19 (Dicor™/Vitadur® N), 143 ± 5 (magnesia core/Vita VMK® 68), 122 ± 21 (magnesia core/Silhouette™), and 118 ± 10 (magnesia core/Ceramco® II) °C. All systems tested resisted crazing due to quenching in ice cold water from 100°C. Systems with lower coefficients of expansion showed significantly greater resistance to thermal shock using ANOVA. © 1994 John Wiley & Sons, Inc.

INTRODUCTION

The increased demand for esthetic dentistry in recent years has resulted in a variety of all-ceramic crown systems available for use by the dentist and dental technician. Some of these all-ceramic systems are actually a composite of two types of ceramic materials. Initially, a core layer consisting of a high strength ceramic material, either aluminous oxide, magnesium oxide, or glass, is fabricated which provides strength to the restoration. Secondly a feldspathic porcelain is fired directly onto the core to provide final contour and esthetics.

Several factors can influence the success of core reinforced all-ceramic crowns including, but not limited to, crown design, defects or flaws in the structure, processing techniques, and thermally induced residual stresses. These stresses are the result of differences in the coefficients of thermal expansion of the core and veneer porcelains, which must be similar to

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prevent formation of stresses during the firing cycles that may subsequently craze the porcelain.[1]

In an ideal system, the core and body porcelains would match over the entire temperature range that would be encountered during a firing cycle used by dental technicians. However, this is difficult to achieve due to phase changes that occur in dental ceramics which result in nonlinear thermal expansion and contraction. Differences in the thermal expansion and contraction between the core and veneer porcelains could produce transient or residual tensile stresses in the porcelains. Transient stresses are created as the core and veneer porcelains cool at different rates from the glass transition temperature to room temperature,[2] while residual stresses remain due to differences in the coefficients of thermal expansion (Fig. 1). Other terms used to describe the glass transition temperature (T_g) are the Littleton softening point,[3] the porcelain softening temperature,[4] the deformation temperature, or the sag point. Although a common definition of the softening point is the temperature which produces a viscosity of $10^{7.6}$ poise,[3,5,6]

different T_g values will be determined experimentally depending on the measurement technique used.[6] The glass transition temperature is not an exact temperature but a temperature range since the transition from liquid to glassy behavior occurs over a range of temperatures.[7]

Residual stresses may be high enough to result in cracking or delamination of the porcelain upon cooling to room temperature after a firing cycle. It is generally believed that some residual stresses, such as those that place the porcelain in slight compression and help to strengthen it, would be beneficial. However, if these stresses are high they may produce microcracks that could propagate at a later time to produce failure.

Additional transient stresses may be produced from thermal shock to form cracks where initial stresses were not sufficient to cause porcelain fracture. Occlusal forces during mastication or sudden temperature change in an oral environment could provide additional stresses that might cause failure.[8]

Data from dilatometric measurements may be used to predict thermal compatibility of core reinforced all-ceramic crown systems. In addition, a practical method of testing the compatibility of porcelain for crown shaped specimens fabricated according to manufacturers' recommendations is to use a thermal shock test described by Anusavice et al.[9] Thermal shock testing has shown a positive relationship with dilatometric data[10] and the compatibility index described by Fairhurst et al.[11] The purpose of this study was to use thermal shock testing to evaluate the crack resistance of six all-ceramic crown systems which have coefficients of thermal expansion ranging from 7–15.3 × 10⁻⁶/°C.

MATERIALS AND METHODS

The all-ceramic crown systems used in this study were Vita In-Ceram® (Vident, Baldwin Park, CA), Vita Hi-Ceram® (Vident), Dicor™ (Dentsply International Inc., York, PA) veneered with Vitadur® N (Vident), and magnesia core material veneered with Vita VMK® 68 (Vident), Silhouette™ (Leach & Dillon, Mansfield, MA) or Ceramco® II porcelains (Ceramco Inc., Burlington, NJ).

An ivorine maxillary central incisor (Columbia Dentoform, New York, NY) was prepared with 1.0 mm axial and 1.5 mm incisal reduction. A 90° shoulder preparation with a rounded internal line angle was used as a master die for all samples. Thirty-six impressions of the master die were taken using a polyvinylsiloxane impression material (Reprosil® Light Body, L. D. Caulk Co., Milford, DE) which were then allowed to cure for 24 h before pouring in die stone or refractory die material.
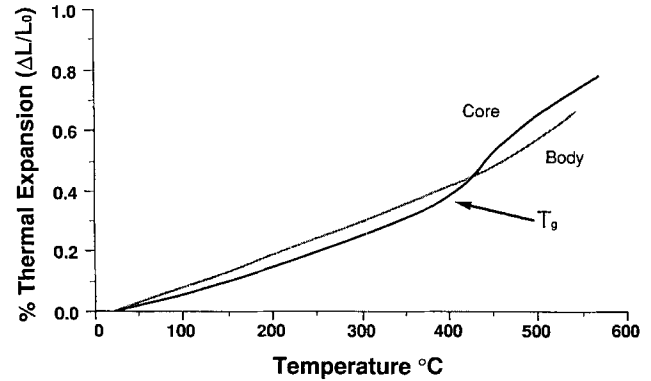

Figure 1. Typical thermal expansion curves for core and body porcelains in an all-ceramic crown system. Residual stresses are formed when the system is cooled below the measured glass transition temperature (T_g).

All refractory die materials used in this study were mixed and degassed according to the manufacturers' recommendations. The Vita Hi-Ceram® cores were fabricated using Hi-Ceram® refractory die material with Hi-Ceram® core porcelain fired directly on the refractory die. The Vita In-Ceram® cores were processed by a manufacturer's authorized commercial dental laboratory according to specifications. Both the In-Ceram® and Hi-Ceram® were veneered with a 1.0 mm layer of Vitadur® N dentine and enamel porcelains (see Table I for firing cycles).

Six impressions were poured in type IV stone (Die Keen®, Modern Materials, South Bend, IN) which provided dies to wax 1.0 mm thick copings to be cast in Dicor™ glass. After casting, the copings were cerammed, fitted to their respective master die, and dressed down to a thickness of 0.5 mm to allow room for application of Vitadur® N porcelain.

For the magnesia core crowns, 18 impressions were poured with Ceramco® refractory die material. Eighteen magnesia core crowns were fired to a thickness of 0.5 mm and fitted to their respective master dies. Three groups of six cores each were veneered with opaque and body porcelains using Silhouette™, Ceramco® II, or Vita VMK® 68 porcelains. The opaque layer was approximately 0.3 mm thick and the body layer about 1.0 mm. All crowns were fabricated to duplicate the size and shape of a maxillary central incisor to simulate the clinical application of these porcelains.

Six specimens of each system were placed inside a 100 mL beaker in an oven (Boekel Industries, Inc., Philadelphia, PA) preheated to 90°C. The temperature was monitored using a thermometer placed inside the beaker next to the samples. After a 15 min heat soak to allow the samples to reach temperature equilibrium, water at 0°C was poured into the beaker via a funnel placed through a hole in the ceiling of the oven.

The samples were removed from the furnace, dried in air, then reheated to 90°C for 15 min and allowed to

TABLE I
Firing Cycles for the Porcelains Tested

Porcelain System	Initial Temperature (°C)	Heat Rate (°C/min)	Vacuum Release (°C)	Maximum Temperature (°C)	Holding Time
Core porcelains/glass					
Hi-Ceram®	650	30	960	960	1 min
Magnesia®	590	10	1120	1120	5 min
Dicor™*					
In-Ceram®†					
Opaque porcelains					
Ceramco® II	650	38	930	1000	30 sec
Silhouette™	540	55	970	970	10 sec
Vita VMK® 68	800	32	960	960	10 sec
Body porcelains					
Ceramco® II	650	38	930	970	30 sec
Silhouette™	540	55	960	960	10 sec
Vita VMK® 68	750	32	960	960	10 sec
Vitadur® N	590	58	1170	1170	3 min

*See Dicor™ Laboratory Technique Manual, Dentsply International Inc., York, PA, 1984.
†See Vita In-Ceram® Instruction Manual, Vita Zahnfabrik, H. Rauter GmbH & Co. KG, D-7880 Bad Säckingen, Germany, 1990.

cool to room temperature. The crowns were inspected for crazing using light microscopy at 10× magnification (Stereomicroscope SV8, Carl Zeiss, Oberkocken, Germany) with fiber optic illumination.

If crazing was observed, this would constitute a failure at $\Delta T = 90°C$. If no failure was observed, the test was repeated at increasing temperature increments of 10°C until failure. A one-way analysis of variance was performed on the 36 samples to determine the effect of brand on thermal shock resistance, ΔT. Pairwise comparisons were run with simultaneous confidence intervals.

The samples for dilatometric measurement were compressed in a metal mold to provide rectangular bars 6 × 6 × 51 mm. The bars were fired according to the schedule recommended by the manufacturers of the various porcelains. The thermal dilatometric analyzer (Model TDA-H1–MP6, Harrop Laboratories, Columbus, OH) was calibrated on the cooling curve using an alumina standard. The coefficient of thermal expansion values were determined on the second heating-cooling cycle between 25°C and 500°C with a heating and cooling rate of 4°C/min.

RESULTS

For each ceramic system the mean ΔT value, standard deviation and ΔT range are shown in Table II. The data are based upon the results from the 36 samples tested, six for each system. The ΔT value represents the temperature difference required to produce a failure in the ceramic. Coefficients of thermal expansion are reported in Table III. A comparison of the types of fracture observed for the various ceramic systems is given in Table IV.

A one-way ANOVA showed there was a significant effect of ceramic systems on thermal shock resistance, ΔT ($P < .0001$). The magnesia core systems had ΔT values ranging from 90–150°C, with the magnesia core/Ceramco® II, magnesia core/Silhouette™, and magnesia core/Vita VMK® 68 systems having mean ΔT values of 118°C, 122°C, and 143°C, respectively. They were not statistically different from one another using the Scheffé F test at the 95% confidence level.

The Dicor™/Vitadur® N system had a mean ΔT value of 152°C with a failure range of 120–170°C. For the In-Ceram® system, the mean ΔT value was 163°C and cracking resulted in a ΔT range of 150–180°C. The Hi-Ceram® had the highest thermal shock resistance of the systems tested with no failures at temperatures up to 200°C.

The mean ΔT values for the Dicor™/Vitadur® N and In-Ceram® systems were statistically higher than the mean ΔT values for the magnesia core/Ceramco® II and magnesia core/Silhouette™ systems. The mean ΔT value for the magnesia core/Vita VMK® 68 system was not significantly different from the mean ΔT values of the other systems except for the mean ΔT value of the Hi-Ceram® system, which was significantly higher than the mean ΔT values of all other systems tested.

DISCUSSION

The thermal shock test can serve as a practical method for testing the thermal compatibility of all-ceramic crown systems. It can be used to identify systems where residual stresses are not of a sufficient magnitude to cause failure upon completion of the initial firing cycle, but which could cause failure at a

TABLE II
ΔT Values that Resulted in Failure

Porcelain	n	Mean ΔT ± SD (°C)	ΔT Range (°C)
Magnesia Core/Ceramco® II	6	118 ± 10	110–130
Magnesia Core/Silhouette™	6	122 ± 21	90–140
Magnesia Core/Vita VMK® 68	6	143 ± 5	140–150
Dicor™/Vitadur® N	6	152 ± 19	120–170
In-Ceram®	6	163 ± 14	150–180
Hi-Ceram®	6	> 200	> 200

Groups joined by vertical lines are not significantly different using Scheffé F test at the 95% confidence level.

later time when crowns are in service.[12] However, it only measures the effect of thermal change on stresses, but not the effect of cyclic mechanical stresses. It should be noted that the thermal shock test does not correlate well with clinical failure because of the many factors involved in this complex system.

If a porcelain has a low coefficient of thermal expansion, the contraction upon cooling is small and the resulting residual stresses are low. This is indicated by the following equation[3]:

$$\Delta T_f = \frac{\sigma_f(1 - \mu)}{\alpha E} S$$

where ΔT_f is temperature difference when fracture occurs, σ_f is the fracture stress, μ is Poisson's ratio, E is modulus of elasticity, α is linear coefficient of thermal expansion, and S is a shape factor. This relationship applies when the quench is so rapid that the surface temperature reaches its final value before the average temperature changes. By this criterion of failure, a material with high fracture stress, low modulus of elasticity, and low thermal expansion coefficient will likely be resistant to thermal stress failure.[3] Therefore, porcelains with a low coefficient of thermal expansion tend to have high thermal shock resistance. The results in this study demonstrated this principle. The Hi-Ceram® and In-Ceram® systems had the highest shock resistance. Both are alumina-based systems, and therefore have low coefficients of thermal expansion. The Dicor™/Vitadur® N system had a lower thermal shock resistance than the Hi-Ceram® or In-Ceram® systems. Again this could be due to the relatively low coefficients of thermal expansion of the Dicor™ cast glass and the Vitadur® N porcelain (Table III). The magnesia core material has a higher coefficient of thermal expansion than do the three feldspathic porcelains tested (Cermaco® II, Vita VMK® 68, and Silhouette™). However, these systems showed adequate thermal shock resistance since thermal shocks of 100°C and above would not be likely in vivo.

The stresses which arise from thermal shock are transient but can initiate failure if they place the surface in tension as would be the case for rapid cooling. If these surface stresses are sufficiently large

(ΔT is large in the above equation) cracks can be initiated on the surfaces of brittle materials. For the system investigated here, these surface cracks would be expected to occur in the body porcelain because this material is weaker than the core material and because the thermal shock to the outer surface of a crown would be greater than for the inner surface where the external surface of the core material is located. These surface cracks will propagate into the bulk of the material and interact with internal residual stresses. The nature of these residual stresses will determine the path followed by the thermal shock induced surface crack as it propagates inward.

While a crown is a complicated system, some general comments can be made about residual stresses. When the coefficient of thermal expansion of the core is greater than that of the opaque/body porcelain, then the body porcelain will be in radial tension while the hoop stresses will be compressive following cooling after firing. These residual stresses will be greatest at the opaque/core interface. As a surface crack propagates inward, it will be deflected in the direction of higher tensile stress, which in this case would be along a surface tangential to the opaque/core interface. This type of crack can often be seen to deflect, running parallel to the core due to the tensile stresses present. This type of fracture usually appears as a curved line or a half-moon shape that runs in a mesial/distal direction (Fig. 2). For complete

TABLE III
Typical Values of Coefficient of Thermal Expansion for Various Ceramics

Material	CE × 10⁻⁶ (per °C)
Dicor™*	7
In-Ceram®	6.2
Hi-Ceram®	8.0
Magnesia Core Frit #101691	15.3
Vitadur® N†	6.7
Ceramco® II	13.4
Silhouette™	14.0
Vita VMK® 68†	12.7

*Reference 14.
†Vident, Baldwin Park, CA.

TABLE IV
Description of Fractures for Core Reinforced All-Ceramic Crowns

System	Type of Fracture		
	Horizontal/Tangential	Vertical/Radial	Branched
Magnesia Core/Vita VMK® 68	6	0	0
Magnesia Core/Ceramco®II	4	2	0
Magnesia Core/Silhouette™	0	5	1
Dicor™/Vitadur® N	0	2	4
In-Ceram®/Vitadur® N	3	0	3
Hi-Ceram®/Vitadur® N			No failures observed at $\Delta T = 200°C$

failure chips of porcelain and opaque would break off from the core material.

When the coefficient of thermal expansion of the core is less than that of the opaque/body porcelain, the hoop stresses in the opaque/body porcelain will be tensile while the radial stress will be compressive. In this case the thermal shock induced surface crack will be driven radially inward by the residual tensile hoop stresses. The fractures appeared as a vertical line running in the occlusal/gingival direction (Fig. 3). These fractures would likely be arrested in the stronger core material where the hoop stresses would be compressive.

By rotating the crown under illumination the direction of the cracks can be seen and also if the crack penetrates the core or turns to run tangentially to the core. This will help to identify if the cracks are the result of radial tensile (vertical crack) or radial compressive (horizontal crack) stresses. Identifying the type of crack will also help to determine what type of thermal expansion mismatches may exist between the core and body porcelains.
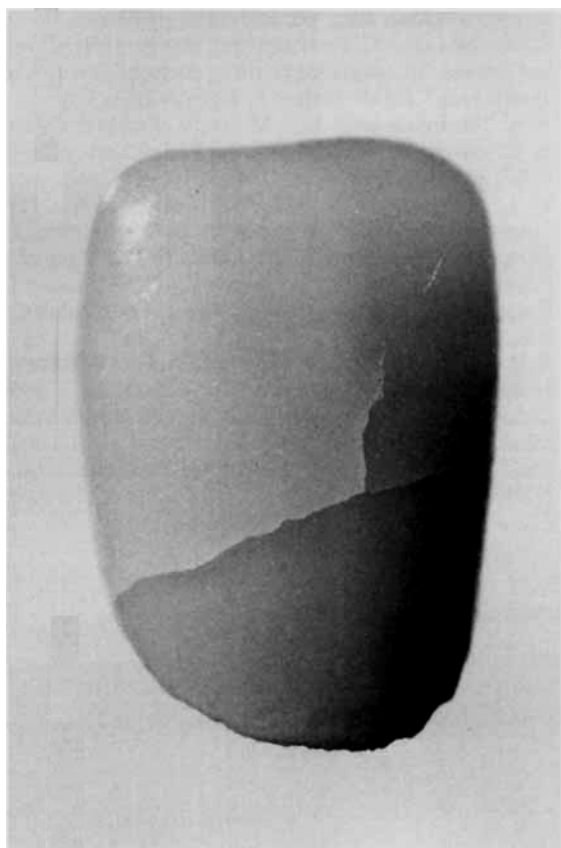

Figure 2. A core reinforced all-ceramic crown with cracks visible after thermal shock testing. This type of fracture is an example of cracks resulting from tangential stresses. The temperature difference when fracture occurred was 110°C.
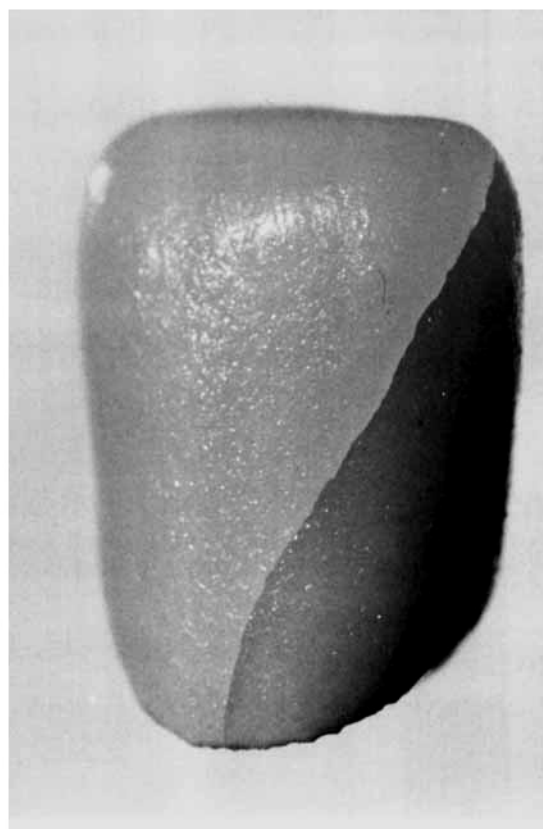

Figure 3. A core reinforced all-ceramic crown with cracks visible after thermal shock testing. This type of fracture is an example of cracks resulting from radial stresses and will usually penetrate into the core. The temperature difference when fracture occurred was 100°C.

Several factors can influence the thermal shock resistance of all-ceramic systems. Obviously, a significant difference in thermal expansion between the two porcelains would produce residual stresses. The thermal conductivity and interfacial bond strength between the layers of porcelain also affect thermal shock resistance. As the thermal conductivity increases, the shock resistance will decrease.[13]

The elastic moduli of the porcelains as well as the dimensions of the restoration also play a role. As the thickness of the porcelain varies from one layer to another, the stiffness changes and the residual stresses are altered. For this reason, the incisor crown shape was used for all samples in this study to insure consistent geometry.

CONCLUSIONS

A thermal shock test was used to evaluate the crack resistance of six composite all-ceramic crown systems. The test results agree with anticipated results that alumina core and body porcelain systems with lower coefficients of thermal expansion had higher thermal shock resistances than magnesia-based systems with body porcelains having higher coefficients of thermal expansion. All the systems tested had adequate thermal shock resistance for clinical use.

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