ACTA BIOMATERIALIA
ODONTOLOGICA
SCANDINAVICA

http://informahealthcare.com/abo
ISSN: 2333-7931 (electronic)

Acta Biomater Odontol Scand, 2015; 1(1): 35–42

informa
healthcare

ORIGINAL ARTICLE

Fracture of porcelain-veneered gold-alloy and zirconia molar crowns using a modified test set-up

Christel Larsson, Marko Drazic, Eddie Nilsson, and Per Vult von Steyern

Department of Materials Science and Technology, Faculty of Odontology, Malmö University, Malmö, Sweden

Abstract

Objective: The main aim of this study was to compare fracture load and fracture mode of yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) and metal-ceramic (MC) molar crowns using a modified test set-up to produce fractures similar to those seen *in vivo*, i.e. fractures of the veneering material rather than complete fractures.
Materials and methods: 13 high-noble-alloy MC and 13 Y-TZP molar crowns veneered with porcelain were manufactured. The crowns were artificially aged before final load to fracture. Load was applied using a 7 mm diameter steel ball exerting force on the cusps with stresses directed toward the core-veneer interface. Fracture surface analysis was performed using light- and scanning electron microscopy.
Results: The test design produced fractures of the veneering material rather than complete fractures. MC crowns withstood significantly ($p > 0.001$) higher loads (mean 2155 N) than Y-TZP (mean 1505 N) crowns, yet both endure loads sufficient for predictable clinical use. Fracture mode differed between MC and Y-TZP. MC crowns exhibited fractures involving the core-veneer interface but without core exposure. One Y-TZP crown suffered a complete fracture, all others except one displayed fractures of the veneering material involving the core-veneer interface with core exposure.
Conclusions: The test set-up produces fractures similar to those found *in vivo* and may be useful to evaluate the core-veneer interface of different material systems, both metals and ceramics. The study confirms suggestions from previous studies of a weaker core-veneer bond for Y-TZP compared to MC crowns.

Keywords

Fracture analysis, metal-ceramic, surface mapping, Y-TZP

History

Received 1 April 2015
Revised 8 May 2015
Accepted 31 May 2015
Published online 14 July 2015

Introduction

Among all-ceramic materials available today, yttria-stabilized tetragonal zirconia polycrystals (Y-TZP)-based ceramics have shown the greatest fracture strength and have been suggested to be comparable to the gold standard of dental restorations – high-noble alloy metal-ceramic (MC) restorations.[1] The strength of the core material in Y-TZP restorations is excellent and complete fractures are rare.[2,3] Clinical trials, however, report a higher incidence of fractures of the veneering material for zirconia-ceramic crowns and fixed dental prostheses compared to metal-ceramic restorations but studies comparing the two material systems are few.[2,3]

There are difficulties in proving whether or not zirconia-based ceramics are more prone to fractures of the veneering material compared to metal-ceramic restorations as test methods vary and results are difficult to compare.

The core–veneer interface has been suggested to be a critical factor for the success of ceramic restorations.[4] The core-veneer bond strength for MC restorations has been claimed to be stronger than for Y-TZP restorations.[5,6], but other publications have failed to show significant differences.[7,8] To substantiate either claim is difficult as there are different standards for testing bond strength of the core-veneer interface for ceramic and metallic core materials, respectively.

The recommendation for metal-ceramic bond strength test is to use a three-point bend test of a thin metal plate with a centrally placed porcelain layer (ISO 9693-1:2012). The specimen is subjected to flexural forces that bend the metal plate, creating tension in the interface leading to porcelain delamination. To use the same method for bond strength tests of ceramic-ceramic combinations can be questioned as brittle materials react differently to bending forces compared to ductile materials like metals.

Bond strength may also be evaluated using shear bond and tensile bond strength tests, respectively. These tests are each influenced by a large number of factors.[9,10] Bond strength increases with smaller bonding areas and for materials with higher modulus of elasticity, and the concentration of stress at the interface is more severe in shear compared to tension.[10] Results obtained from one test method cannot be compared to another, making comparisons between results from different studies difficult.

Correspondence: Christel Larsson, Department of Materials Science and Technology, Faculty of Odontology, Malmö University, SE-205 06 Malmö, Sweden. Tel: +46 40-6658547. E-mail: christel.larsson@mah.se

DOI: 10.3109/23337931.2015.1057825

In addition, none of the tests mentioned include possibilities to identify more complex stress patterns, like those present in the clinical situation, as the specimens are not designed with a clinically relevant shape. Bond strength tests have produced mixed results, some showing adhesive delamination, while others show mainly cohesive fractures of the veneering material. Fracture testing of crown-like specimens often produce complete fractures through core and veneer, which is not clinically relevant as few fractures found *in-vivo* are complete fractures.[2,3] When analyzing the studies that evaluate clinical performance, the vast majority of fractures detected do not involve the core–veneer interface. Instead, the fractures are described as mainly limited cohesive fractures, often referred to as ''chip-off fractures''.[11–13] Hence, the validity of previously mentioned methods in predicting clinical performance is limited.[9]

In summary, there is a lack of studies comparing Y-TZP and MC restorations under equal settings and many methods used so far are not designed to produce fractures representative of those found in a clinical setting. The objectives of the present study were therefore to investigate the fracture resistance of porcelain-veneered Y-TZP and MC crowns using a modified test set-up and analyze fracture mode. The aim of the test-set up was to direct stress toward cusp areas including all three material phases; core-supported veneer, core-veneer interface and un-supported veneer to possibly simulate fractures found in the clinical setting i.e. fractures of the veneering material rather than complete fractures.

The hypotheses were that the test set-up would direct stresses towards the core-veneer interface and produce fractures within the veneer, and that metal-ceramic crowns would sustain higher loads before fracture than zirconia-ceramic crowns.

Materials and methods

Production of specimens

A total of 26 single crowns were made, 13 Y-TZP (KaVo Everest BIO ZS-Blank, KaVo Dental GmbH, Biberach/Riß, Germany) with veneering porcelain (GC Initial Zr-FS, GC Europe) and 13 high-noble-alloy MC (M2, KarAna, Helsingborg, Sweden) with veneering porcelain (GC Initial MC, GC Europe, Leuven, Belgium). All crowns were produced by the same dental technician. A brass master model resembling a crown preparation of a mandibular first molar with a 120° chamfer and 15° angle of convergence was created by a laboratory (Wallins Mekaniska, Eslöv, Sweden). Twenty-four abutments were prepared from a polymer material (Delrin, E.I Dupont De Nemours & Co, Wilmington, DE) using a lathe-technique copying the brass master model. The modulus of elasticity of the polymer material was 2 GPa.

The master model was replicated using an impression material (Dublisil 15 speed, Dreve Dentamid GmbH, Unna, Germany). The impression was poured with die stone (GC Fujirock, GC Europe, Leuven, Belgium) creating a die upon which the dental technician waxed a pre-shape of a crown. The shape of the crown was simple to allow standardization, yet of a reasonably clinically relevant shape. A cutting template was used as a guide. The Y-TZP crowns were produced using a double-scanning technique where the waxed crown and die stone were scanned (D 700, 3Shape A/S, Copenhagen, Denmark). The core thickness was reduced evenly by 1 mm prior to milling to create space for an anatomical and even layer of porcelain. The CAD-file was exported to the milling machine (Kavo 3Shape export). The cores were milled from a pre-sintered Y-TZP blank (BIO ZS-Blank, KaVo, Dental GmbH, Biberach/Riß, Germany) and fully sintered in a calibrated furnace (KaVo Everest engine, KaVo, Dental GmbH, Biberach/Riß, Germany) according to manufacturer's instructions.

For standardization between the groups, the same computer file used for milling of the Y-TZP group was used to manufacture the metal copings for the crowns in the MC group. An acrylic coping was produced (C-cast, KaVo, Dental GmbH, Biberach/Riß, Germany), embedded (Fuji West, GC Europe, Leuven, Belgium) and cast. The cast MC copings were separated from the embedding material with 125 µm Al_2O_3 powder (Cobra, Renfert) using a fine blasting unit (Basic Quattro IS, Renfert, GmbH, Hilzingen, Germany).

All veneering was done using a standardized cutting template, ensuring a uniform 1 mm thickness of veneering material (Figure 1). The Y-TZP cores were veneered with porcelain adapted for zirconia (GC Initial Zr-FS, GC Europe, Leuven, Belgium). The firing of the ceramic was performed in a calibrated furnace (Programat P 500, IvoclarVivadent) according to manufacturer's recommendations. The metal cores were steamblasted and oxidized in a calibrated furnace (Programat P500, IvoclarVivadent) at 980 °C prior to porcelain application. The metal cores were veneered with porcelain adapted for metal (GC Initial MC, GC Europe). The firing of the porcelain was performed in a calibrated furnace (Programat P 500, Ivoclar, Vivadent, Liechtenstein) according to manufacturer's recommendations.

Prior to cementation the abutments were blasted with 50 µm Al_2O_3 from a distance of 10 cm under 2 bar pressure (Cobra, Renfert GmbH, Hilzingen, Germany) using a fine

Figure 1. Illustration of the cutting template used to ensure a uniform 1 mm thickness of veneering material.

blasting unit (Basic Quattro IS, Renfert GmbH, Hilzingen, Germany). The abutments were then cleaned with 70% alcohol. The inner surfaces of both MC and Y-TZP crowns were cleaned and coated with an alloy primer (ALLOY Primer, Panavia F 2.0, Kuraray Medical Inc, Okayama, Japan) prior to cementation using a methacryloyloxydecyl dihydrogen phosphate (MDP) containing resin cement (Panavia F 2.0, Kuraray Medical Inc, Okayama, Japan). Two of the 26 crowns were made as pilots to be sectioned to check the design of the core and veneer thickness and shape, respectively.

Artificial aging procedures

The crowns underwent 5000 cycles of thermocycling between two water baths, 5 °C and 55 °C. Each cycle lasted 60 s; 20 s in each bath and 10 s to transfer between baths. The crowns then underwent cyclic mechanical preload; 10,000 cycles at loads between 30 N and 300 N with a load profile in the form of a sine wave at 1 Hz in a specially constructed pre-load device (MTI Engineering AB/Pamako AB, Malmö, Sweden). Force was applied with a 7 mm Ø stainless steel ball placed on the occlusal surface of the crowns mounted at a 10° angle relative to the vertical plane. During mechanical preload a 0.2-mm thick plastic foil (PE-Baufolie, Probau, Bauhaus, Zug, Switzerland) was placed between the crowns and the steel ball to ensure an evenly distributed load. The test was performed with the specimens submerged in room temperature water. Between rounds of thermocycling, cyclic mechanical preload and final load to fracture the crowns were stored in an incubator (Memmert Incubator, Memmert, GmbH, Schwabach, Germany) in a moist environment at a temperature of 37 °C.

Load until failure

The crowns were finally loaded to fracture in a universal testing machine (Instron, Instron Co, Norwood, MA). The force was applied at a crosshead speed of 0.255 mm/min using a stainless steel ball with a 7 mm Ø placed occlusally on to the cuspal planes without contact with the fossa. The force was thus placed at the core-veneer interface level, tangentially to the highest point of the curvature between the buccal and the occlusal core cusp facets (Figure 2). The occlusal surface of each crown was checked visually, as well as placement of the steel ball, before applying the load. A 0.2-mm thick plastic foil (PE-Baufolie, Probau, Bauhaus, Zug, Switzerland) was again placed between the steel ball and the crown. Fracture was defined as occurrence of visible cracks, load drops of 15 N or cracking sounds at which the test was terminated.

Surface analyses

Visual inspection as well as microscopic analyses was performed. The fractured surfaces were first analyzed under a light microscope (Wild M3, Wild Heerbrugg, Heerbrugg, Switzerland). Photographs were taken at 8 × magnification. A preliminary classification of the surfaces as adhesive, cohesive or a combination was done at this stage. Three representative surfaces from each group were then selected for further analysis in high resolution scanning electron microscopy (FEI Quanta 200 FEG, FEI Company, Hillsboro, OR) operating between 5 and 10 kV at 44–45 × magnification. The selection was made by two investigators independently and consensus was reached through comparison and discussion. Before analysis, a photograph of the crown placed in the holding device was taken to facilitate orientation to focus analysis on areas where light microscopy had suggested possible core exposure. Surface mapping with analysis of atomic composition was performed (Oxford Instruments X-MAX 80, Abingdon, UK) at selected areas as described above.

Statistical analyses

The loads at fracture were registered and any differences between the materials were calculated. Choice of statistical methods was done in collaboration with a statistician who performed the calculations. The IBM SPSS statistics 20 software program was used for calculations (IBM Corporation, Armonk, NY) and Student's t-test was used to analyze the data. Results were considered statistically significant at a p-value of <0.05.

Results

The load values for the MC-group ranged from 1887 N to 2342 N with a mean load at fracture of 2155 N. In the Y-TZP-group, the values ranged from 1243 N to 1862 N with a mean load at fracture of 1505 N. Load at fracture differed significantly between the two groups ($p < 0.001$) (Table 1).

All MC crowns exhibited fractures of the veneering material of one cusp. The fractures involved the core-veneer interface but visual inspection and light microscopy suggested

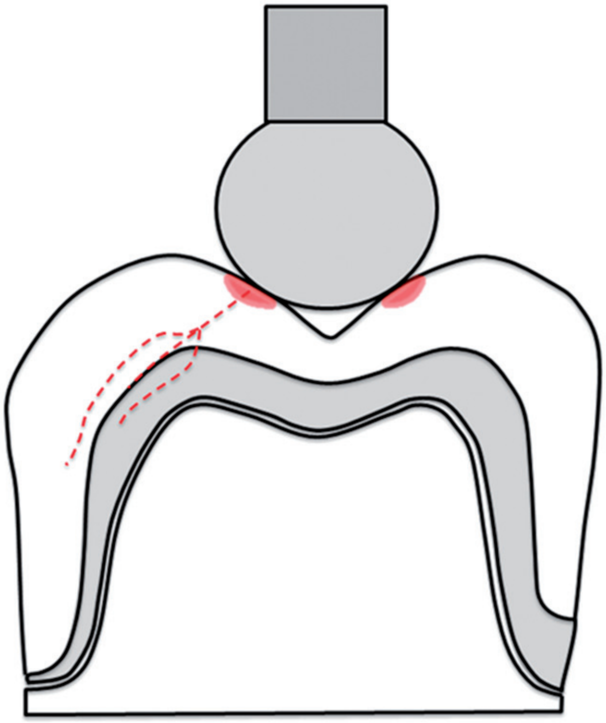

Figure 2. Application of the load aligned with the core-veneer interface, tangentially to the highest point of curvature between the buccal and the occlusal cusps. The dotted line shows three different crack pathways in the interface region; cohesive in the unsupported porcelain, cohesive in the core material or adhesive in the interface.

remaining veneering porcelain on the fracture surfaces of all MC crowns and they were tentatively defined as cohesive fractures (Figure 3). SEM analysis and atomic composition analysis confirmed these findings (Figure 4).

One of the Y-TZP crowns suffered a complete fracture through veneer and core, all others exhibited fractures of the veneering porcelain involving the core-veneer interface. One crown showed fracture of the veneering porcelain through both cusps, all others showed fractures of the veneering porcelain of only one of the cusps. Light microscopy suggested one fracture to be without core exposure, all others seemed to involve areas of core exposure and the fractures were tentatively defined as a combination of cohesive and adhesive fractures (Figure 5) SEM analysis and atomic composition analysis confirmed areas of core exposure in all samples except one (nr 12) (Figure 6).

Table 1. Load at fracture.

Material	Crown nr	Load (*N*)
Y-TZP	1*	1599
	2	1243
	3	1479
	4	1862
	5**	1720
	6	1636
	7	1449
	8	1391
	9	1293
	10	1628
	11	1306
	12	1456
Mean load at fracture (*N*)		1505
Standard deviation		188
MC	14	2103
	15	2239
	16	2172
	17	2266
	18	2342
	19	2052
	20	1887
	21	2241
	22	2048
	23	2329
	24	1956
	25	2231
Mean load at fracture (*N*)		2155
Standard deviation		146

*Fracture trough both cusps.
**Complete fracture.

Discussion

The hypothesis that the test set-up would manage to produce fractures found in the clinical setting was confirmed as well as the hypothesis that there would be a difference in fracture resistance between crowns of the two material groups.

Simple bilayer core-veneer bond tests of discs seldom subject the interfaces between different material layers to the complex stresses that occur during clinical function. In the traditional norm-crown test set-up, the load is applied by a small indenter in the occlusal fossa. The porcelain under load is then supported by the stiff core, creating a situation where the porcelain is compressed between the loading point and the solid support. The stiff support may lead to an overestimation of the strength of the supported material and the resulting fractures are often described as Hertzian cone cracks which are seldom seen in crowns fractured *in vivo*.[14–16] It has been suggested that using an indenter with a larger diameter would create more clinically relevant results.[16] Simply increasing the size of the indenter may not *per se* lead to more clinically relevant fractures. However, if the size of the indenter is adapted to the size and shape of an anatomical crown specimen, so that the load applied is directed towards both supported and unsupported veneer, the clinical situation might be better replicated. In this way, the load reaches all three material phases: core-supported veneer, core-veneer interface and un-supported veneer. One way to achieve this is to slide the indenter over a cusp-plane of the specimen as in, e.g. a mouth-motion-step stress fatigue test. This test does produce failures within the veneer rather than complete fractures but it is more time-consuming and hence expensive to perform.[17]

The test method used in the present study is simpler and less time-consuming. By applying the load on the cusps of an anatomically shaped crown specimen at the core-veneer interface level, it is possible to direct the load towards the

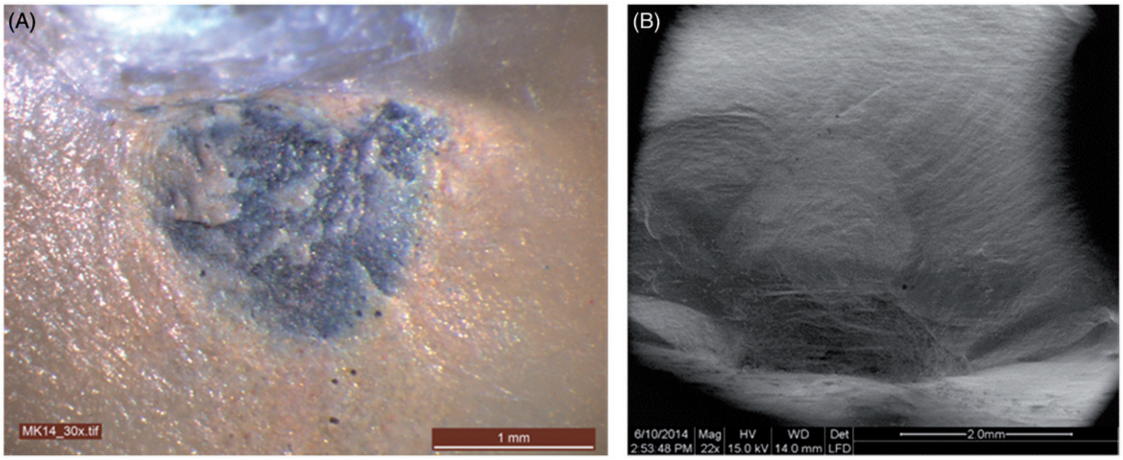

Figure 3. (A) Fracture surface of MC crown (nr 14) at 30 × magnification (light microscopy); (B) Fracture surface of MC crown (nr 14) at 44 × magnification (SEM).

core-veneer interface and the three material phases; core-supported veneer, core-veneer interface and un-supported veneer. By loading both cusps simultaneously, the most critical flaw on either side will determine fracture. The fact that the fractures predominantly involved only one cusp suggests that the test set up manages to identify the critical flaw instead of being a ''crunch the crown test''.

The chosen shape of the specimens was anatomical but standardized by using a specially made knife, so that all crowns had the same dimensions. This produces specimens with a clinically relevant shape, while at the same time allowing for comparisons between the two materials. This anatomical shape is proven to provide support for the veneer and simultaneously controlling the thickness of the veneer to provide conditions for optimal fracture resistance.[18–20] The abutments were made from a polymer material with a modulus of elasticity (2 GPa) better resembling that of a natural tooth (approx 15 GPa) than e.g. metal abutments

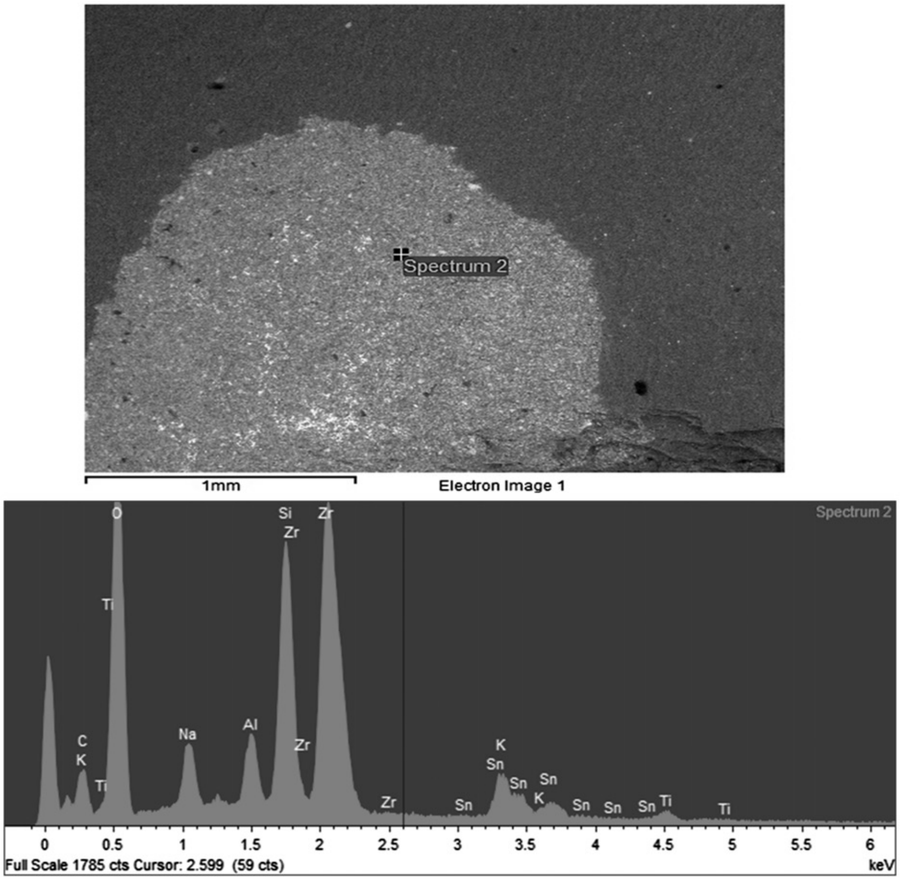

Figure 4. Surface mapping of MC crown (nr 14).

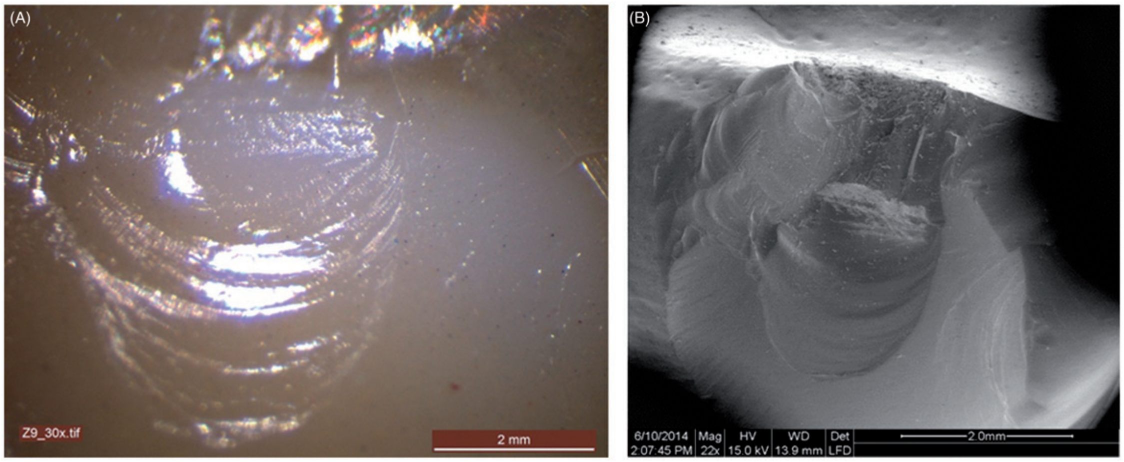

Figure 5. (A) Fracture surface of Y-TZP crown (nr 9) at 30 × magnification (light microscopy); (B) Fracture surface of Y-TZP crown (nr 9) at 45 × magnification (SEM).

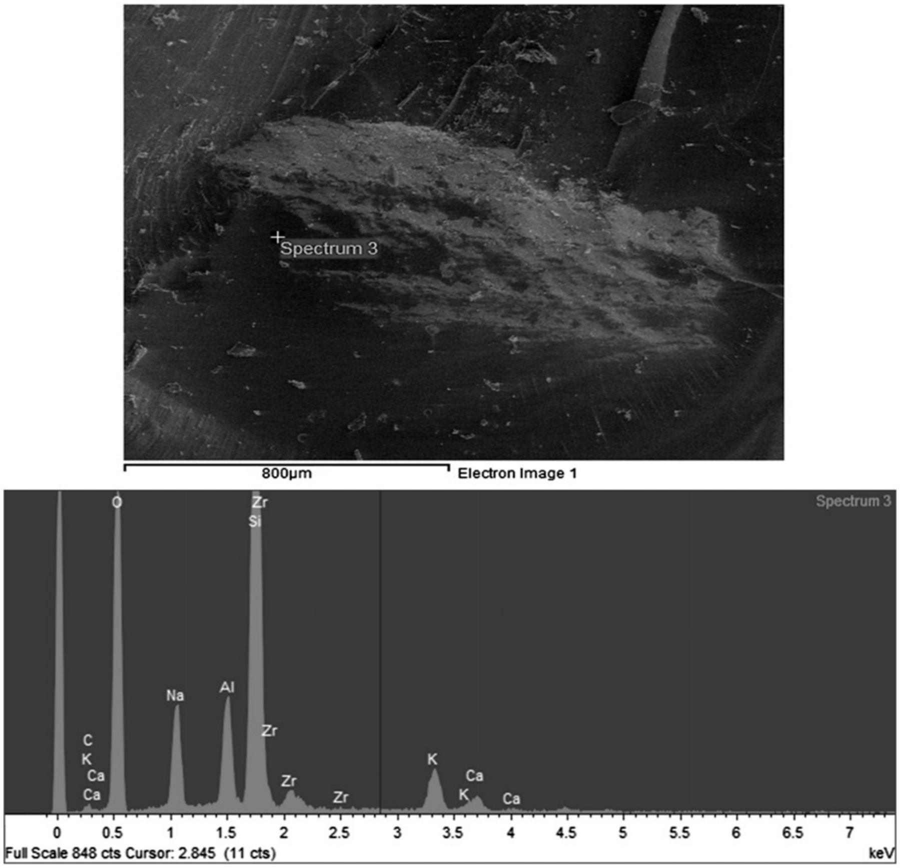

Figure 6. Surface mapping of Y-TZP crown (nr 9).

(70–225 GPa). Using a more rigid material has been shown to produce unrealistically high loads at fracture and an overestimation of the strength of the restorations that is not clinically relevant.[14,15]

Dental restorations are to function in a moist environment under different temperatures as well as load variations over time. This leads to damage accumulation and degradation that significantly reduces the strength of materials over time.[1,21] The specimens were therefore subjected to artificial aging in the form of thermocycling and mechanical preload in water as this is proven to influence values of loads at fracture.[21] Final load was done using a cross head speed of 0.255 mm/min, which was chosen as this seems sufficient to allow for crack build-up and propagation.[22]

The load at fracture differed significantly between the two groups, with the MC crown sustaining higher values. Even so, the loads at fracture for both groups are well within requirements for sufficient strength for clinical use and clinical trials have proved that both crowns types show predictable results.[3,12].

The fracture mode noted, chip-off fractures, suggests broadly distributed shear forces. No Hertzian cone cracks were noted. The presence of a foil may have helped distribute the loads and reduce the risk of contact damage and the use of an intermediate sheet is recommended.[16] The absence of Hertzian cone cracks and crushing of the surface is however probably more dependent on the large indenter and its application on the crown. With stresses concentrated over the interface of supported and unsupported veneer, the unsupported veneer was sheared off instead of a crushing damage of the supported veneer.

The surface mapping of the MC crowns showed failures close to the core/veneer interface but with residual ceramic material, from the porcelain and the ceramic primer, covering the core. The fracture surfaces of the Y-TZP crowns appeared similar when inspected visually but light microscopy suggested areas of core exposure and surface mapping revealed areas with a high content of zirconium in the surface. By comparing the analysis of areas with suspected core exposure with areas with porcelain coverage, such as non-fractured sites, it was possible to exclude remaining porcelain and confirm exposed core as zirconium is not a component of the porcelain used to veneer the Y-TZP crowns.

The results from other laboratory studies comparing zirconia and metal-ceramic restorations vary.[5,6,23,24] These studies have made comparisons with high-noble gold alloys.[5,6,23,24] Although high-noble gold alloys are less common today due to the high cost, it is still considered the gold standard and much research is based on these alloys. Equal resistance to chipping has been found by one group.[23] Some find predominantly cohesive fractures in MC specimens[6], others confirm core-veneer involvement and exposed core material when veneer fractures occur in MC crowns.[24] One group identified the test method as being decisive as significant differences in fracture behavior could only be found in shear and not in flexure tests.[5]

The failures in the Y-TZP group are not consistent with the fractures reported in clinical trials, i.e. predominantly cohesive fractures with remaining veneering material covering the core.[11–13] These restorations have, however, not undergone light- or scanning electron microscopy, so it has not been established whether minute areas of the core have been exposed as in the present study.

A lower incidence of fractures of the veneering material has been reported from clinical evaluations of MC crowns.[25] These reports, however, only mention whether fractures are present or not and seldom declare their severity or mention core exposure. It is therefore not possible to state whether the results from the present study are representative of the clinical performance of MC crowns. From the patients' point of view, it is perhaps irrelevant whether the fracture is defined as cohesive or adhesive, i.e. involving exposure of areas of the core material. If the core is visually exposed there is a greater risk of aesthetic complications irrespective of whether minute porcelain remnants are present or not. Simultaneously, if the fractured area appears to be completely covered by veneering porcelain, the restoration could very well be adjusted and kept in function irrespective of minute areas of exposed core material. Only a few Y-TZP restorations have been necessary to remove due to veneer fractures, instead they have been polished and kept in function.[2,3] When fractures of the veneering material occur in MC crowns, and run close to the core-veneer interface, it is less likely that the restoration can be kept in function as the dark underlying core is more likely to affect aesthetics compared to the Y-TZP core that is white or tooth-colored.

Many different terms have been used to describe veneer fractures; minor, major, extensive, cohesive, adhesive, acceptable and unacceptable.[26] Some have attempted to classify them by their size and/or how they affect function and what kind of intervention is needed, if any. The perception of how a chip-off affects function and the decision on whether an intervention is needed or not rests on the patient as well as the treatment provider. For example, the perception of a chip may vary greatly whether it is placed buccally or lingually. It would be a welcome addition to future clinical trials if an attempt at classification was made with the opinions of both patient and treatment provider included.

Conclusions

The test set-up used in this *in vitro* study generates fractures of the veneering material rather than complete fractures. It might thus be useful for evaluating differences in bond strength and comparing fracture modes of different material combinations, both metals and ceramics.

MC crowns sustain significantly higher loads before fracture than Y-TZP crowns but both material systems tolerate loads well above those encountered during function in the oral cavity. The study confirms suggestions from previous studies of a weaker core-veneer bond for Y-TZP crowns compared to MC crowns.

Declaration of interest

The project has not been commercially funded in any way. The authors declare no conflicts of interest.

References

1. Rekow ED, Silva NRFA, Coelho PG, Zhang Y, Guess P, Thompson VP. Performance of dental ceramics: challenges for improvement. J Dent Res. 2011;90:937–952.
2. Heintze SD, Rousson V. Survival of zirconia- and metal-supported fixed dental prostheses: a systematic review. Int J Prosthodont. 2010;23:493–502.
3. Takeichi T, Katsoulis J, Blatz MB. Clinical outcome of single porcelain-fused-to-zirconium dioxide crowns: a systematic review. J Prosthodont Dent. 2013;110:455–461.
4. Kelly JR, Tesk JA, Sorensen JA. Failure of all-ceramic fixed partial dentures in vitro and in vivo: analysis and modeling. J Dent Res. 1995;74:1253–1258.
5. Ashkanani HM, Raigrodski AJ, Flinn BD, Heindl H, Mancl LA. Flexural and shear strengths of ZrO_2 and a high-noble alloy bonded to their corresponding porcelains. J Prosthet Dent. 2008;100: 274–284.
6. Guess PC, Kulis A, Witkowski S, Wolkewitz M, Zhang Y, Strub JR. Shear bond strengths between different zirconia cores and veneering ceramics and their susceptibility to thermocycling. Dent Mater. 2008;24:1556–1567.
7. Al-Dohan HM, Yaman P, Dennison JB, Razzoog ME, Lang BR. Shear strength of core-veneer interface in bi-layered ceramics. J Prosthet Dent. 2004;91:349–355.
8. Ishibe M, Raigrodski AJ, Flinn BD, Chung KH, Spiekerman C, Winter RR. Shear bond strengths of pressed and layered veneering ceramics to high-noble alloy and zirconia cores. J Prosthet Dent. 2011;106:29–37.
9. Kelly JR, Benetti P, Rungruanganunt P, Della Bona A. The slippery slope – critical perspectives on in vitro research methodologies. Dent Mater. 2012;28:41–51.
10. Braga RR, Meira JB, Boaro LC, Xavier TA. Adhesion to tooth structure: a critical review of ''macro'' test methods. Dent Mater. 2010;26:38–49.
11. Sailer I, Gottner J, Känel S, Hämmerle CHF. Randomized controlled clinical trial of zirconia-ceramic and metal-ceramic posterior fixed dental prostheses. Int J Prosthodont. 2009;22:553–560.
12. Rinke A, Schäfer S, Roediger M. Complication rate of molar crowns: a practice-based clinical evaluation. Int J Comput Dent. 2011;14:203–218.
13. Pelaez J, Cogolludo PG, Serrano B, Lozano JFL, Suarez MJ. A four-year prospective clinical evaluation of zirconia and metal-ceramic posterior fixed dental prostheses. Int J Prosthodont. 2012; 25:451–458.
14. Rosentritt M, Behr M, Gebhard R, Handel G. Influence of stress simulation parameters on the fracture strength of all-ceramic fixed-partial dentures. Dent Mater. 2006;22:176–182.
15. Mahmood DJ, Linderoth EH, Vult von Steyern P. The influence of support properties and complexity on fracture strength and fracture mode of all-ceramic fixed dental prostheses. Acta Odontol Scand. 2011;69:229–237.
16. Kelly JR. Clinically relevant approach to failure testing of all-ceramic restorations. J Prosthet Dent. 1999;81:652–661.
17. Coelho PG, Silva NR, Bonfante EA, Guess PC, Rekow ED, Thompson VP. Fatigue testing of two porcelain-zirconia all-ceramic crown systems. Dent Mater. 2009;25:1122–1127.
18. Rosentritt M, Steiger D, Behr M, Handel G, Kolbeck C. Influence of substructure design and spacer settings on the in vitro performance of molar zirconia crowns. J Dent. 2009;37:978–983.
19. Larsson C, El Madhoun S, Wennerberg A, Vult von Steyern P. Fracture strength of yttria-stabilized tetragonal zirconia polycrystals crowns with different design: an in vitro study. Clin Oral Implants Res. 2012;23:820–826.
20. Swain MV. Unstable cracking (chipping) of veneering porcelain on all-ceramic dental crowns and fixed partial dentures. Acta Biomater. 2009;5:1668–1677.
21. Kohorst P, Dittmer MP, Borchers L, Stiesch-Scholz M. Influence of cyclic fatigue in water on the load-bearing capacity of dental bridges made of zirconia. Acta Biomater. 2008;4:1440–1447.
22. Yoshinari M, Dérand T. Fracture strength of all-ceramic crowns. Int J Prosthodont. 1994;7:329–338.
23. Quinn JB, Sundar V, Parry EE, Quinn GD. Comparison of edge-chipping resistance of PFM and veneered zirconia specimens. Dent Mater. 2010;26:13–20.

24. Suleiman SH, Vult von Steyern P. Fracture strength of porcelain fused to metal crowns made of cast, milled or laser sintered cobalt-chromium. Acta Odontol Scand. 2013;71: 1280–1289.
25. Pjetursson BE, Sailer I, Zwahlen M, Hämmerle CH. A systematic review of the survival and complication rates of all-ceramic and metal-ceramic reconstructions after an observation period of at least 3 years. Part I: single crowns. Clin Oral Implants Res. 2007;18 Suppl 3:73–85.
26. Anusavice K. Standardizing failure, success, and survival decisions in clinical studies of ceramic and metal–ceramic fixed dental prostheses. Dent Mater. 2012;28:102–111.