The Fracture Resistance of Zirconia Based Dental Crowns from Cyclic Loading: A Function of Relative Wear Depth

T. Qasim, B. El Masoud, D. Ailabouni

Abstract**—**This *in vitro* study focused on investigating the fatigue resistance of veneered zirconia molar crowns with different veneering ceramic thicknesses, simulating the relative wear depths under simulated cyclic loading. A mandibular first molar was prepared and then scanned using computer-aided design/computer-aided manufacturing (CAD/CAM) technology to fabricate 32 zirconia copings of uniform 0.5 mm thickness. The manufactured copings then veneered with 1.5 mm, 1.0 mm, 0.5 mm, and 0.0 mm representing 0%, 33%, 66%, and 100% relative wear of a normal ceramic thickness of 1.5 mm. All samples were thermally aged to 6000 thermo-cycles for 2 minutes with distilled water between 5 ˚C and 55 ˚C. The samples subjected to cyclic fatigue and fracture testing using SD Mechatronik chewing simulator. These samples are loaded up to $1.25x10^6$ cycles or until they fail. During fatigue, testing, extensive cracks were observed in samples with 0.5 mm veneering layer thickness. Veneering layer thickness 1.5-mm group and 1.0-mm group were not different in terms of resisting loads necessary to cause an initial crack or final failure. All ceramic zirconia-based crown restorations with varying occlusal veneering layer thicknesses appeared to be fatigue resistant. Fracture load measurement for all tested groups before and after fatigue loading exceeded the clinical chewing forces in the posterior region. In general, the fracture loads increased after fatigue loading and with the increase in the thickness of the occlusal layering ceramic.

Keywords**—**All ceramic, dental crowns, relative wear, chewing simulator, cyclic loading, thermally ageing.

I. Introduction

OVER the last decades, porcelain fused to metal (PFM) restorations have been considered to be the “Gold standard”, due to their good mechanical properties, satisfactory esthetic outcome, and acceptable adaptation. In addition, it has predictable clinical outcome validated by several scientific evidences [1]. According to a systematic review on the survival and complication rates of PFM crowns after an observation period of 3 years, the short-term survival rate of PFM crowns was about 95.6%. The mean complication incidence of PFM crowns over 6 years was 11% [2]. On the other hand, its fabrication is considered technique-sensitive owing to the considerable number of operative steps involved in the fabrication process. Moreover, it lacks translucency because of the presence of grayish metal infrastructure [1]. An increasing trend toward metal –free dentistry has led to the development of different all-ceramic systems [3]. Ceramic restorations have gained popularity because of their several advantages: esthetics, color stability, biocompatibility, low plaque retention, high hardness, wear resistance, low thermal conductivity and chemical inertness. On the other hand, their brittleness, ease of crack propagation, poor marginal fit, repair difficulty and low tensile strength and fracture toughness were considered some important drawbacks of the material [1]. Their clinical performance proved to show some failure by fracture. Fatigue fracture has been reported to occur when it is subjected to deformation strain of more than 0.1%-0.3% [4]. High strength ceramics such as zirconia have been introduced to the market as a core material in veneered restorations for fixed dental prosthesis in high load-bearing areas [4]. Because of its biocompatibility, high flexural strength [5]-[7], high fracture toughness [8], and esthetics, monolithic zirconia restorations have been used widely for single crowns and full-mouth rehabilitation cases especially for patients with para-functional habits [3].

All ceramic restorations could be used in two forms; monolithic and bilayer. It should be pointed out that there is an inverse relationship between favorable optical properties and strength [1]. A reinforced ceramic substructure is used in conjunction with a veneering ceramic to achieve better esthetic outcome or be entirely made of the reinforced ceramic for increased strength. For high load bearing areas such as the posterior segment, the use of high strength ceramic cores with veneering ceramic is widely used especially for establishing aesthetics [9]. However, the major drawbacks were related to failure of the veneering layer [3]. In fact, veneer chipping is more likely to occur in zirconia-based restorations than in metal based restorations.

In the extremely worn dentition, some practitioners tend to increase the vertical dimension of occlusion. However, this might not be feasible in all circumstances [10], [11]. According to the minimum occlusogingival height, the modular tooth is prepared with a crown of a height of 4 mm in order to have a retentive preparation design [12].

Monolithic zirconia restorations have been introduced to the market because they show higher strength and easier fabrication than their veneered counterpart. In an *in vitro* study comparing monolithic CAD/CAM lithium disilicate crowns versus veneered Y-TZP crowns, it was found that monolithic crowns resulted in fatigue-resistant structures, whereas veneered zirconia crowns revealed a higher susceptibility to

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early veneer failure under cyclic loading [13].

Veneering porcelain addition onto a ceramic core material diminishes the biaxial flexural strength of the restoration. Nevertheless, zirconia-veneered ceramics exhibited greater strength than monolithic leucite reinforced and lithium desilicated ceramics [14]. In an *in vitro* study on the performance of full-contour zirconia single crowns, crowns with conventional veneering showed lower –load bearing capacity than polished and glazed full contour zirconia restorations [15].

This study aimed to evaluate the mouth-motion fatigue behavior and failure of zirconia crowns with variable veneering layer thicknesses, in addition to investigating the effect of ageing (thermal cycling and cyclic loading) of various crown thicknesses on the fracture load of the zirconia crown. The effects of various loading conditions on crown failures are measured as a function of wear depth relative to a normal 1.5-mm thickness of porcelain layer. The types of loading considered in this study is cyclic loading to investigate the survival of samples in conditions simulating five years of function.

II. Methods

A total of 32 molar zirconia based cores KATANA Zirconia (Kuraray Noritake Dental Inc, Japan) were fabricated with 0.5-mm thickness. All cores were veneered with a compatible zirconia layering ceramic Cerabian ZR zirconia (Kuraray Noritake Dental Inc., Japan) to establish a molar crown with standard dimensions. The occluso-gingival dimensions of the crowns were adjusted to establish four groups having variable occlusal layering ceramic thicknesses of 1.5 mm, 1.0 mm, 0.5 mm, and 0.0 mm. Composite cores were fabricated to the depth of at least 8 mm below the crown level to replicate the remaining of the natural tooth structure after preparation as shown in Fig. 1. The specimens were fitted in a specimen holder using an acrylic base covering the extension of the composite core below the crown level.

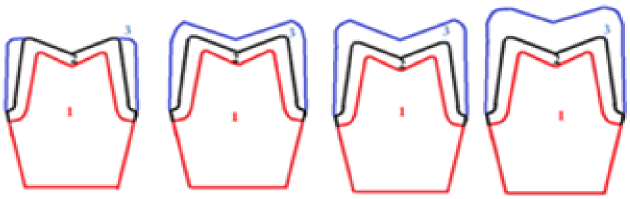

Fig. 1 Cross-sectional representation of samples prepared with different porcelain veneering layer thicknesses: 1. composite cores; 2. zirconia cores (0.5 mm); 3. porcelain veneering layer of thickness 0.0 mm (a), 0.5 mm (b), 1.0 mm (c) and 1.5 mm (d)

In this study, the prepared tooth was scanned using Dental wings 3 series delivered with DWOS dental scanner (Dental Wings, Montreal, Canada). As the ideal coping thickness for molar is at least 0.5 mm (Noritake Katana, Japan), 32 copings of 0.5 mm thickness were made using Noritake KATANA discs (98.5 mm x10 mm thickness) of a shade KT 10 (bleaching shade). Y-TZP Noritake KATANA blocks are partially stabilized with 5% yttrium oxide. Table I lists some of the physical and chemical properties of Katana Noritake zirconia. Computer software was used to transmit the data from 3D laser scanner to the CAM machine. The pre-sintered ZrO_2 (Katana Zirconia, Noritake Dental Supply Co., Ltd., Japan) was milled with Katana H-18 (Noritake Dental Supply Co., Ltd., Japan) and sintered to full density in a furnace (Katana F-1, Noritake Dental Supply Co., Ltd., Japan) at 1400 °C for 90 minutes according to the manufacturer's instructions.

TABLE I
PROPERTIES OF NORITAKE KATANA ZIRCONIA (KURARY NORITAKE)

	Item	Data
	Flexural strength	1,200 MPa
Physical Properties	Fracture toughness (K_{1C})	≧5 MPa m$^{1/2}$
	CTE	10.4×10^{-6}/°C
Chemical composition	ZrO_2 / Y_2O_3	95/5

A. Preparing Specimens for Testing

Light cured hybrid resin-based composite material "prime-dent" (Prime Dental, Chicago, USA) was used to fabricate abutments to simulate actual dental restorations because its modulus of elasticity is similar to that of dentine [16].

To reduce shrinkage stress and cuspal deflection, the crown-fitting surface was filled with resin-based composites using the incremental layering technique buildup, and consequently, optimal adaptation to the crown can be achieved [17]. Each layer (about 2 mm thickness) was light cured for 40 seconds according to manufacturer's instructions using light curing device at 450 nm. The dies had a length not less than 8 mm below the gingival line to be able to embed them in the acrylic resin, and were checked visually to determine whether voids and defects are present, as shown in Fig. 2.

Fig. 2 Lateral view of fabricated abutments

B. Fatigue Testing

Specimens were subjected to cyclic fatigue and fracture testing using CS-4.2 SD Mechatronik chewing simulator (SD Mechatronik, Germany) as shown in Fig 3. The chewing simulator contains four test chambers, each chamber having an individual weight with a loading bar. A transverse bar that is mechanically driven by a stepping motor controls the horizontal and vertical movement links all bars. All chambers were filled with room temperature distilled water. To simulate the excursive movement of the human jaw, the sample's buccal surface was mounted facing forward with the direction of the lateral. The simulator's movement is normally based on four biaxial movements: downward movement of the antagonist, lateral movement of the X-axis, upward movement and then movement of the X axis back to the starting point.

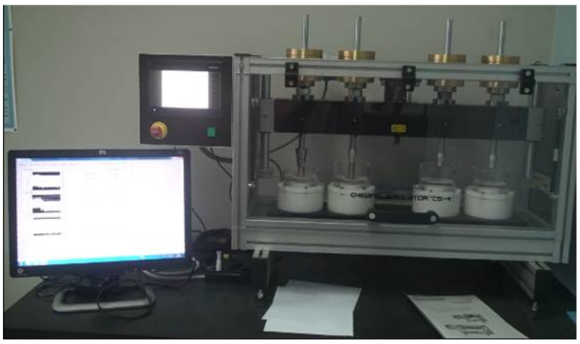

Fig. 3 Chewing simulator with the testing system's computer monitoring software

The simulator was set to have vertical movement of 4 mm with speed of 40 mm/sec, horizontal movement of 1.5 mm with a speed of 20 mm/sec as depicted in Fig. 4. The indenters contact surface with the specimens was grinded and polished before each set of testing, to reduce friction and heat generation during the testing. The test was started without an impulse-low impact- to settle the samples before a load of 50±5 N (~4 kg dead weight) was applied. During testing, force measurements were observed by monitoring the data from the force sensor cell and not from dead weight applied onto the samples. The tested samples were inspected for cracks at intervals of $250x10^3$ cycles. Then, the surviving crowns were subjected to load to failure test.

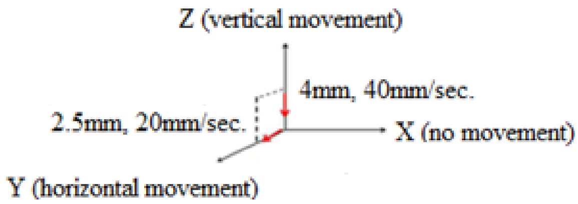

Fig. 4 Velocity and distance travelled by the antagonist at the vertical and horizontal directions

III. Results and Discussion

Results obtained from cyclic loading for 16 samples, with various veneering layer thicknesses. 16 crowns were exposed to cyclic fatigue testing for $1.25x10^6$ cycles at 50 N. The groups were divided according to the veneering layer thickness, and each group of four samples was tested separately in the four chambered chewing simulators.

In the samples having veneering layer thickness of 0.0mm, no cracks were observed in all the tested samples for loading up to $1.25x10^6$ cycles which represents five years of chewing function. A white spot was observed in–sample no.1 prior to testing, and this white spot's physical appearance was not changed for the entire loading cycles which indicate that this white spot is not a crack.

In the samples with 0.5-mm occlusal veneering layer thickness, all samples had occlusal damage related to the indenters' friction throughout the experiment. It is noteworthy that this sample as can be presented in this figure had a well-established crack on its lingual surface that was detected early at the $250x10^3$ cycle interval, indicating that this crack may have appeared beforehand. For the 1.0-mm veneering layer thickness, there were no signs of well-developed cracks or any visible fracture in any of the samples tested. Moreover, all samples showed signs of wear at their occlusal surface. All the samples from the group comprising the 1.5 mm porcelain veneering layer thickness showed no indication of cracks, chipping or fractures. The four samples had occlusal damage attributable to indenter surface friction.

None of the 0.0, 0.5, and 1.5 mm thickness groups showed any failures during the mouth-motion fatigue testing ($1.25x10^6$ cycles at 50 N), with a survival rate of 100%. While 1 sample of 0.5 mm thickness group showed extensive crack formation detected early during the experimental procedure. Table II summarizes the results obtained after mouth-motion fatigue testing.

TABLE II
SURVIAVAL RATE AND FAILURE MODES AFTER (1.25 MILLION CYCLES)

Group	0.0 mm thickness	0.5 mm thickness	1.0 mm thickness	1.5 mm thickness
Number of crowns	4	4	4	4
No failure	4	4	4	4
Minor chip fracture	0	0	0	0
Extensive chip fracture	0	0	0	0
Minor cracks	0	0	0	0
Extensive cracks	0	1	0	0
First damage seen	–	$250x10^3$ cycles	–	–
Survival rate	100%	75%	100%	100%
Failure rate	0%	0%	0%	0%

Extensive as well as minor chipping fractures were not observed in any of the experimental crowns tested for samples having veneering of 1.0 and 1.5 mm. Clear extensive wear in the contact sliding area was observed in all the samples tested (Fig. 5 (b)) without any evidence of crack formation, as shown in Fig. 5 (a).

Fig. 5 (a) Occlusal surface before mouth-motion fatigue testing. (b) Wear and damage related to the top (occlusal) surface after mouth-motion fatigue testing

Extensive crack was observed in one sample in the 0.5-mm veneering layer thickness group. This crack was observed first at $250x10^3$ cycles with one cracking behavior. This crack occurred on the crown's lingual surface starting at the surface's margin and extended occlusally indicating the presence of a radial crack, shown in Fig. 6 with arrow pointing to radial cracks.

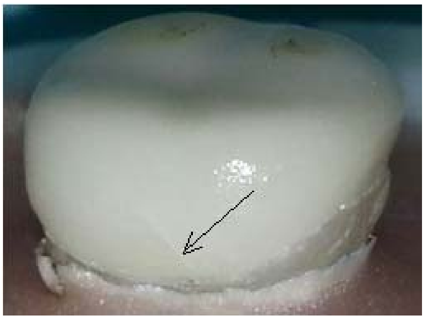

Fig. 6 Lingual surface of sample no.1 of 0.5 mm group after mouth-motion fatigue testing indicating its crack pattern

An increasing trend toward metal–free dentistry has led to the development of different all-ceramic systems to replace metal and metal-ceramic restorations [3]. High strength ceramics such as zirconia have been introduced to the market as a potential restorative material for fixed dental prosthesis in high load-bearing areas [4]. All ceramic restorations could be used in two forms; monolithic and bilayer. It should be pointed out that there is an inverse relationship between favorable optical properties and strength [1]. For high load bearing areas such as the posterior segment, the use of high strength ceramic cores with veneering ceramic is widely used especially for establishing esthetics [9]. However, the veneering layer is considered the weakest part of zirconia restorations and is associated with most of the clinical failures [18]. This may be attributed to either weakness in the zirconia-veneer bond or inferior strength of the veneering porcelain. Most of the failures are cohesive in nature suggesting weakness in the veneering layer itself rather than the bond with the zirconia [5]. This cohesive failure, manifested as chipping of the veneering layer, is the primary concern in zirconia based restorations [3], [18], [19].

Several factors influence the fracture resistance of ceramic restorations. It has been stated that the fracture resistance of the ceramic material increases as the core/veneer thickness ratio increases [20], [21], while on the other hand, another study found that the thickness of the veneering material (2 mm vs. 4 mm) did not affect the failure load of all ceramic crowns [22].

In the extremely worn dentition, some practitioners tend to increase the vertical dimension of occlusion. However, this might not be feasible in all circumstances [10], [11]. In clinical settings, the dental practitioner sometimes faces the dilemma when the surgical intervention by crown lengthening to lengthen the tooth is not feasible due to financial, physical, medical or psychological reasons, and the patient is not willing to go through the process of raising the vertical dimension of occlusion. Therefore, sacrificing part of the restorative material instead of the tooth might be the only feasible option.

IV. Conclusions

Within the limitations of this *in vitro* study, the following conclusions were drawn:

A. All ceramic zirconia crown restorations with varying occlusal veneering layer thicknesses appear to be fatigue resistant.
B. It was found that the initial fracture resistance increased statistically significantly after 5 years of chewing function for zirconia restorations of the 0.0, 0.5, and 1.5 mm veneering layer thicknesses.
C. The final fracture resistance increased statistically significantly after five years of chewing function for the un veneered zirconia restorations.
D. Even worn down zirconia crowns can survive which would be clinically worth for five years of loading.
E. Long-term clinical studies are needed to verify the observed *in vitro* results.

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