The effect of resistance grooves on the fracture toughness of zirconia-based crowns from mono and cyclic loading

Tarek Q. Qasim[1], Billal M. El-Masoud[2], Ahmed M. Abu Laban[2]

Correspondence: Dr. Tarek Q. Qasim
Email: tqqasim@just.edu.jo

[1]Department of Industrial Engineering, Faculty of Engineering, Jordan University of Science and Technology, Irbid, Jordan,
[2]Department of Prosthodontics, Jordan University of Science and Technology, Irbid, Jordan

ABSTRACT

Objective: Prosthetic molar crowns in service are subjected to chewing loads, which cause a shift or dislodgment. The objective of this study is to investigate whether the addition of resistance grooves to the proximal surfaces of the abutment teeth would enhance the fracture resistance of the zirconia crowns and to compare between the patterns of cracks development on the zirconia crowns after the application of mono loading versus cyclic loading forces. **Materials and Methods:** Thirty-six all-ceramic zirconia cored crowns were prepared on the same abutment. Resistance grooves were added to the mesial and distal surfaces of 16 abutments. Before testing, all specimens subjected to thermal aging. Two groups of crowns were then subjected to cyclic axial and lateral forces for 1,250,000 cycles in aqueous conditions. Two groups of samples were also tested in monoloading fashion. **Results:** The crack pattern between mono and cyclic loading were compared. The crown fracture resistance was compared in the two types of abutments, with and without grooves. The results confirmed that the grooves addition had no effect on critical conditions to initiate failure in the case of mono loading. In cyclic loading, grooves addition increased the critical loads in the order of two. Failure patterns and location were obtained. **Conclusions:** The results showed that the location of retention grooves halted the failure in the surfaces where it was located in all loading mechanisms used in this study.

Key words: All ceramic crowns, chewing simulator, failure modes, thermal aging

INTRODUCTION

In dental prostheses, all ceramic crowns are replacing porcelain fused to metal crowns as a material of choice, zirconia as a tough inner layer and porcelain as top layer where biocompatibility and esthetics are critical issues.[1-3] Several researches used hard spherical indenters "point contact" to study the failure of all-ceramic crown systems. Point contact magnifies the contact pressure, which represents extreme service conditions. The crack patterns and locations observed and reported using hard spherical indenters were limited to the occlusal top surface of the crown due to the concentration of tensile stresses around the small contact area. The top surface cracks fail to explain the failure modes observed in service of dental crowns at the distal, lingual, mesial, and buccal surfaces of the crown such as "semi-lunar" fracture pattern.[4] Cracks locations and failure modes are also

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affected by the method of applied loads in testing; mono-loading and cyclic loading shows distinctive differences in cracks location and more interestingly in crack propagation to failure. The case of cyclic loading cracks was initiated at the side surfaces of the crowns and propagated rapidly upward as number of cycles increased near the occlusal surface.[5] The argument of using point contact from hard spherical indenters to represent in service extreme conditions is valid, yet testing in cyclic dual loading (axial and lateral) brings the findings closer to the actual crown in service.

To avoid the high incidence of failure of dental restorations, several ceramic brands and processing systems found their way to the dental industry.[6-8] Another proposed technique to resist crown failure in service is the addition of grooves on the proximal surfaces of the abutment tooth after preparation to receive a prosthetic crown. It has been suggested that when the force rotational arc moves away from one wall of the groove, it hits the other wall, so resistance is substantiated one way or the other.[9,10] It is recommended that grooves should be routinely used in molars and to be placed in proximal areas.[11,12]

The aims of this study were to investigate whether the addition of resistance grooves to the proximal surfaces of the abutment teeth would enhance fracture resistance of the zirconia crowns. In addition, it was aimed to compare between the patterns of cracks development on zirconia crowns after application of mono loading versus cyclic loading forces.

MATERIALS AND METHODS

Crown fabrication and materials used

The abutment tooth considered in this study was prepared with nonoptimal parameters where retentive measures as groove boxes and pins needed in such cases. The primary preparation was made on a plastic lower first molar having an axial reduction of 1.5 mm on all cusps. In addition, facial and lingual reductions of 1 mm were made. The final tooth measures were buccolingual/mesiodistal ratio of 7.5/8.5 and occluso cervical/buccolingual ratio of 4/7.5. Two grooves were added to the proximal surfaces of the abutment tooth; one on the mesial surface and one on the distal [Figure 1].

The grooves measured 1 mm in depth and 1 mm in width, extending 0.5 mm above the finish line to the height of the tooth placed mesially and distally
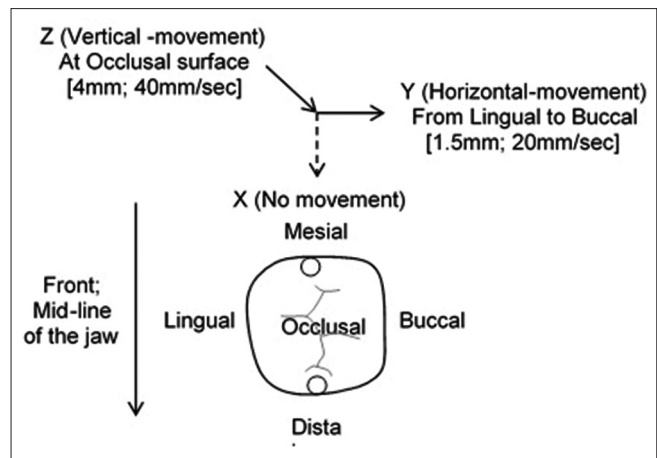

Figure 1: Schematic diagram showing top view of dental crown (the circles indicate the grooves locations) and the indenter movements (speed and distance) relative to the crown occlusal surface

[Figure 2]. The direction of the chewing was placed buccolingually, to mimic the chewing forces applied by the human jaws. Both stone dies were scanned using computer-aided design/computer-aided manufacturing CAD/CAM machine (NEO CAD 7.7). The Zirconia copings have overall thickness of 0.5 mm with the exception of the groove area. The CAD/CAM method is widely used in dental prostheses.[13] Two groups of eight zirconia copings where made for each abutment, zirconia compatible porcelain (Noritake–Japan) then veneered to all samples with 1 mm porcelain thickness. To hold the fabricated crowns in testing chamber, abutments for the crowns made from hybrid composite (Prime dent – USA). The composite built inside the crown and extended 8 mm below the crown edge, i.e., gum line. All specimens were subjected to thermal aging using a thermal cyclic machine for 6000 cycles (5°C–55°C); the duration of each cycle was 60 s to simulate 5 years in oral service. Before testing, the samples fixed in the specimens holder using dental acrylic (Metropair– England) and left to cure slowly for 24 h at room temperature. According to manufacturer specifications, materials properties used in this study are summarized in Table 1.

Testing

The specimens were divided into four groups, two groups (with and without grooves) of *n* = 8 each, tested in cyclic loading. The limitation of a number of samples tested in cyclic loading was the testing chambers number in the chewing simulator; it is recommended to fill all testing chambers with specimens during testing; in similar fashion, Kern *et al*. used eight specimens in his study to fill all chambers with specimens.[14] Another two groups (with

Table 1: Materials properties used in this study

	Material	Young's modulus, E (GPa)*
Indenter	Ni-Cr alloy steel	270
Crown top layer	Porcelain	70
Crown underlayer	Partially stabilized zirconia	205
Crown support (substrate)	Dental composite	15
Resin cement	Resin cement	15
Acrylic	Denture acrylic	3.5

*Manufacturer specifications

and without grooves) of $n = 10$ each tested under compressive mono-loading using universal testing. To mimic the action of human chewing conditions, all tests were done in wet conditions using distilled water in the test chamber at room temperature. The same stainless steel flat cylindrical indenter was used [Figure 3].[15] The indenter dimension area was large enough to cover the lateral movement of the samples during the cyclic testing.

Four testing chambers chewing simulator (CS 4.4 SD Mechatronik, Germany) utilized in this study. The simulator setting for one complete cycle, for vertical movement 4 mm with a speed of 40 mm/s and for horizontal movement 1.5 mm with a speed of 20 mm/sec [Figure 1]. Load was maintained at approximately at 60 ± 5 N and controlled using dead-weight.[14,16] The applied loads during testing were controlled from force-cell readings in Newton (N). The contact area was not uniform in the entire specimen as shown in Figure 3 from the marking on the indenter which shows the variability of contact area which might lead to variation in the load. To demonstrate 5 years in oral service, the samples were undergo 1,250,000 complete cycles; one cycle includes axial and lateral movements to simulate 5 years of in oral service.[9] Monoloading tests were performed under the same conditions as the cyclic testing. The specimens were loaded axially along the vertical axis of the specimen and monotonically at a crosshead speed of 0.1 mm/min (loading rate ~ 10 Nmin^{-1}).[17,18] Record of critical loads to initiate damage was established at intervals of 250,000 cycles during cyclic loading. During mono loading, samples continually monitored during testing and photographed at intervals of 100–200 N.

RESULTS

Figure 4 shows the means and standard deviations of critical loads when radial cracks observed at the
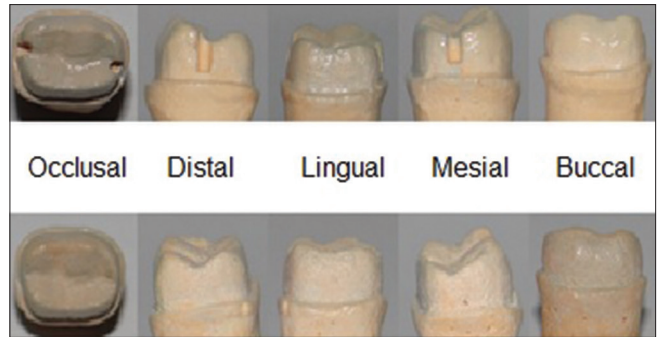

Figure 2: Different views of the abutments used in this study after duplication and the addition of grooves in one of the abutments to insure standardization of the abutment and to minimize the variables to only the grooves addition
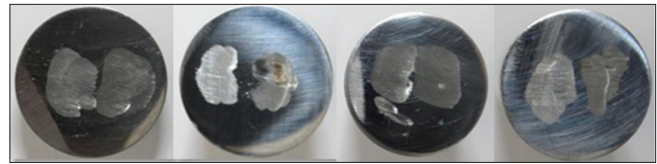

Figure 3: The wear on the stainless steel indenters of four samples after 1,250,000 cycles in the chewing simulator facing the veneering layer of the crown occlusal surfaces
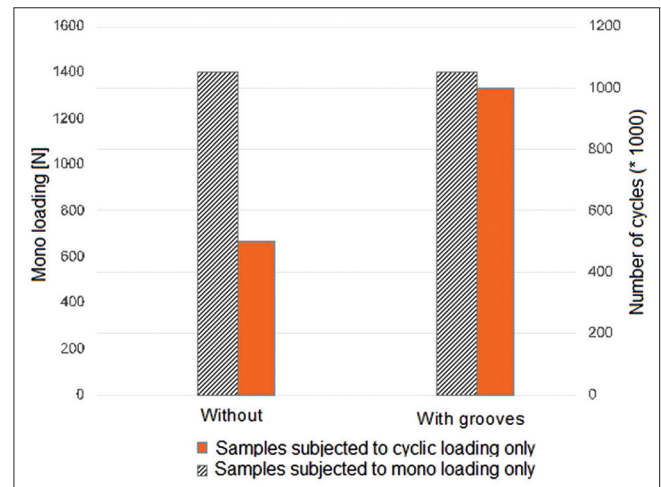

Figure 4: Critical conditions to initiate radial cracks for samples with and without resistance grooves. The error bars approximate the interval at which data taken

end of each interval (250,000 cycles) for both grooved and ungrooved samples. The error bars give an approximate value of the intervals between loading and unloading when the cracks were not monitored during cyclic loading for both grooved and ungrooved samples. The two modes of loading are presented in Figure 4 for samples subjected to mono loading only; the grooves had no effect on critical loads. These samples were not subjected to cyclic loading which leads to smaller contact areas at the cusps of the crown. The cusps reside next to side surfaces of the crown where damage occurs, no cone cracks were

observed in any of the specimens tested. The critical loads in this were relatively high (1400 N) followed by a complete lunar crack failure (chipping of veneering layer) at 2000N. The critical loads to initiate radial cracks in the case of cyclic loading for samples with grooves were twice the amount of cyclic loading for zirconia core without grooves [Figure 4]. In this case, the cracks propagated upward but remain within the vicinity of the crown extremities.

Representative photographs of failure morphology for samples underwent monoloading are presented in Figure 5. The photographs showed that the damage in the samples from a mono loading at higher critical loads resulted in a larger damage area seen as fully developed cracks leading to dislodgment of veneering in the form of semi-lunar cracks as loading increased to 2000 N.

Figure 6 shows comparison between samples with and without resistance grooves for both cyclic and monoloading. Samples with resistance grooves showed extensive damage in comparison with samples without resistance grooves at the buccal surfaces. More interesting, the extent of damage of mono-loaded samples was more deleterious in all samples examined in this study.

DISCUSSION

Due to the use of the flat indenter, the contact areas in all samples had a border area of contact in comparison with a traditional spherical indenter used by several researchers.[19,20] This wider contact area kept the occlusal surface under compression stresses during testing shifting the tensile stress regions to the side surfaces of the crown (distal, lingual, mesial, and buccal surfaces). As a result of this stress distribution, no cone cracks were observed on the top surface of all specimens tested, which was consistent with Whitton *et al*.[21]
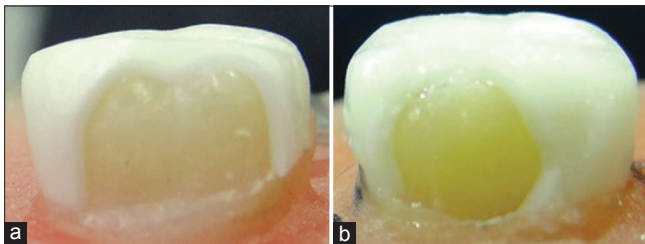
In samples subjected to 1,250,000 cycles (cyclic loading only), the addition of grooves showed a remarkable difference in critical loads. There was a doubling increase in the number of cycles for samples with grooves, which could be attributed to the fact that the young modulus of the zirconia core was three times higher than the veneering porcelain. It is well documented that the tensile stress responsible for radial cracks initiation at the cervical surface increases with stiffer core material.[22-24] The addition of grooves in the distal and mesial surfaces of the crown gave these surfaces extra core thickness resulted in an increase in the tensile stress at the cervical surfaces for samples without grooves. In addition, the location of grooves shifted the tensile stress concentration to the buccal surface where most of the observed cracks first appeared. The question that remains unanswered is that the samples have resistance grooves showed extensive damage at buccal surface. This can be attributed to the fact that the energy produced during loading shifted to the surface with thinner zirconia thickness.

The resistance effect of friction force on the horizontal sliding force was not considered significant since all tested specimens were completely immersed in water during testing. The readings of vertical forces during sliding represented the friction force, and the height of the curve for force in Z-direction was increased slightly as number of cycles increased, this could be attributed to the increase in contact area, and hence, the increase of friction force as number of cycles increased.
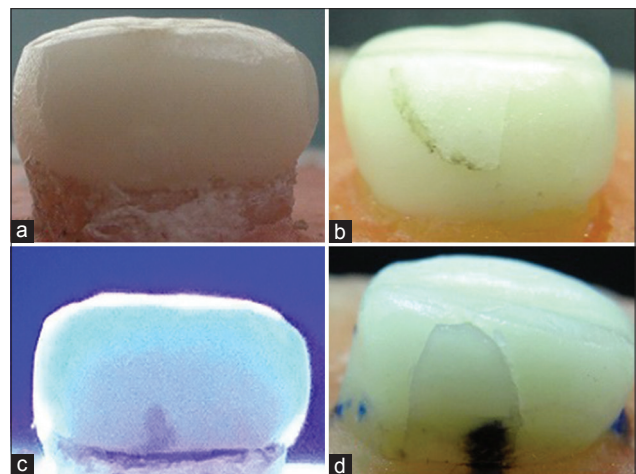

Figure 6: (a) Contact fracture at buccal surface in all ceramic crowns, sample without resistance, 500,000 cycles cyclic loading, (b) sample without resistance grooves, 1400 N mono loading, (c) sample with resistance grooves, 1,000,000 cycles cyclic loading, (d) sample with resistance grooves, 1400 N monoloading

Figure 5: (a) Failure of samples indented mono loading with flat steel indenter load 2000 N, showing damage in buccal surfaces sample without resistance grooves, (b) sample with resistance grooves

CONCLUSIONS

The results showed that the location of retention grooves halted the failure in the surfaces where it was located in all loading mechanisms used in this study. The grooves had no effect on the critical loads in the case of a mono loading; in contrast, the samples with grooves doubled the critical number of cycles to initiate radial cracks. As number of cycles increase, the contact area increases, which shifted the tensile, stress region to the side surfaces of the crowns and resulted in fracture at the side surfaces.

Conflicts of interest

There are no conflicts of interest.

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