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Almarza, R., Ghassemieh, E., Shahrbaf, S. et al. (1 more author) (2020) The effect of crown fabrication process on the fatigue life of the tooth-crown structure. Materials Science and Engineering: C, 109. ISSN 0928-4931

https://doi.org/10.1016/j.msec.2019.110272

The effect of crown fabrication process on the fatigue life of the tooth-crown structure

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Keywords: Fatigue life, Tooth-crown structure, Manual press, 3D printing, Machining

Abstract

Objective:

To compare the fatigue strength of lithium disilicate ceramic crowns when cemented as a compound structure, as a function of the manufacturing process and the type of ceramic variation.

Method:

A typodont maxillary first premolar was prepared for an all-ceramic crown in accordance with the manufacturer's guidelines for monolithic ceramic crowns (IPS e.max®; Ivoclar-Vivadent, Liechtenstein). 60 dies were duplicated in a polymer with a Young's Modulus closely matched to dentine (Alpha die, Schütz GmbH). Three different crown fabrication techniques were used (n=20): (i) Manually applied wax spacer and pressed-crown; (ii) digitally scanned preparation, CAD-printed wax-pattern (D76PLUS, Solidscape Inc.) and pressed-crown; (iii) digitally scanned preparation and machined-crown (CEREC-inLab® v3.6 Sirona GmbH). Resin-based cement (Variolink-II®, Ivoclar-Vivadent, Liechtenstein) was employed with a standardised mechanised cementation technique to apply a controlled axial cementation pressure [Universal testing machine (Lloyd LRX®, Lloyd Materials Testing Inc)]. The samples were subjected to fatigue life testing with a cyclic impact load of 453N for 1.25×10^6cycles at 37C^0 and 1Hz frequency until the point of fracture.

Result:

There was a significant difference in the resistance to fatigue loading between the three groups. Weibull probability analysis and the α and β Weibull parameters indicate that the teeth restored with a 'Manually-applied wax spacer and pressed-crown' are best able to resist cyclic fatigue loading. They also have the most uniform interface geometry.

Conclusion:

Teeth restored with IPS e.max® crowns constructed by manually applied wax spacer and pressing have a more uniform interface and a greater structural integrity than wax CAD-printed patterns or CAD-CAM crowns.

Introduction

Dental ceramic have been used successfully to offer more esthetic crowns and fixed partial dentures restorations. However, dental ceramics are inherently brittle, with little or no plastic deformation. Dental ceramic is susceptible to tensile stress and as such is a category of materials that fail under time-dependent stress. Microscopic cracks act as local stress concentration sites that cause the ceramic to manifest fracture at a stress significantly lower than its theoretical strength under a repeated load [1, 2]. However, the ceramic crown should not be considered as a stand-alone entity but as part of a crown-tooth complex forming a multi-faceted compound structure. Both intrinsic and extrinsic factors play a role in determining the overall structural integrity of the complex crown-tooth structure. It should be noted that some aspects of the compound system would act synergistically to improve the structural integrity. Other factors, if not carefully designed and matched may actually precipitate failure. The marginal accuracy and internal fit of the ceramic crown is considered a key intrinsic factor affecting the longevity and ageing processes of the ceramic restoration[3, 4].

Lithium disilicate glass ceramic material was introduced by Ivoclar Vivadent® for use in all-ceramic dental restorations. It is available in two forms: (1) an ingot that can be press-fit (IPS e.max Press, Ivoclar Vivadent) and (2) a block that can be milled with computer-aided design/computer-aided manufacturing (CAD/CAM) technology (IPS e.max CAD, Ivoclar Vivadent)[5]. Lithium disilicate glass ceramic is recommended by the manufacturer to be used for veneers, inlays, onlays, anterior or posterior crowns and implant crowns. Both forms of the Lithium disilicate glass ceramic material were initially available as a substructure core material that afforded greater translucency than other high-strength ceramic core materials. Although they are initially offered for substructures of the restoration, both have been used for full-contour restorations of a single ceramic material (monolithic restorations) thus eliminating the challenge of managing two dissimilar materials. [5, 6].

The crystals of both the IPS e.max CAD and IPS e.max Press are the same in composition. They both have microstructures of 70% crystalline lithium disilicate. However the size and length of the crystals of IPS e.max CAD and IPS e.max Press are very different. IPS e.max Press has needle-like lithium disilicate crystals measure approximately 3 µm to 6 µm in length while the IPS e.max CAD has fine-grain crystals size approximate of 0.2 µm to 1.5 µm. Due to similarity of the microstructures composition the material properties such as modulus of elasticity, coefficient of thermal expansion and chemical solubility are the same for the both ceramics. However the IPS e.max Press shows a slightly higher flexural strength and fracture toughness comparing with IPS e.max CAD[5, 7] .

In-vitro tests have shown that the fatigue resistance in test of all-ceramic restorations is affected by several factors, such as the fabrication technique, microstructure of the ceramic material and the luting method. Whilst e.max CAD ceramic ingots are pressed under controlled industrial conditions, achieving a more homogenous microstructure, it is possible that the subsequent machining (grinding) process for the actual fabrication of the crown may create flaws from which fracture lines may propagate.. However, the effect of the machining process on the fracture behaviour of these restoration is yet to be determined [7, 8].

The cemented crown aims to restore the structural integrity of the tooth by achieving a complex compound system with the underlying tooth structure and the intermediate adhesive cement. Considering the role of the cement interface, the fit or accuracy of the marginal and internal adaptation are considered critical requirements for a successful fixed restoration [9-11].

There are various stages in the process of creating a ceramic crown restoration that vary according to the fabrication process. Following the preparation of the tooth, a pressed crown requires the preparation of a negative wax pattern that will be converted to ceramic through the 'lost-wax process'such as 3D image capturing, model designing process and pressing or milling process. However, during each stage there are several factors that might affect the final fit of the restoration. Consequently, the longevity of a restored tooth with an ill-fitted crown could be compromised by restoration, tooth fracture, dental caries or periodontal problems[12, 13]. However, the full effect of the cement interface geometry in terms of overall thickness and dimension on the fracture resistance of the all-ceramic restoration has not been well established. Also the effect of the manufacturing process on interface geometry and the resultant stress distribution within the tooth-crown structure under loading is greatly under researched area. Other researchers have used FEA in order to investigate the stress distribution within the crown/tooth structure to evaluate the use of different crown material [14] or to compare different implant design such as cemented-retained versus screw-retained implant [15] or to study the impact of the loading in various directions [16]. In order to examine further the effect of the manufacturing process and resultant interface geometry on the stress distribution and load transfer, we have performed finite element analysis (FEA) of the crown and tooth system in an independent study. The results of our FEA study are currently under review for publication.

In-vitro testing of the strength of the crown-tooth complex can be undertaken as a static progressive loading, test that determines the ultimate fracture strength of the system or as a dynamic, fatigue, test that reveals its behaviour under repeated loading. Fatigue test can be conducted in different load rate profiles such as static or dynamic fatigue profile. However, it is well documented that the behaviour of brittle structure under the cyclic loading is important and outperforms the static profiles [17].

It should be noted that neither of these tests, static or dynamic, would be able to exactly simulate the real-life performance of crown-tooth structure. Moreover, the data obtained cannot be used to extrapolate real predicted survival of the restorations. However the tests will indicate the probability of early failure and assist with the optimisation of the intrinsic factors as detailed above. Nevertheless, in order to achieve an optimal simulation to the real life application, effort has been made to match as many of the extrinsic variables as possible. Some of the considerations are the stylus contact to the specimen, the perfect cementation of the restoration to the substrate, the load application in a dynamic profile, the presence of a periodontal ligament and performing the tests under a wet environment [18-20].

This study aimed to evaluate by means of mechanical fatigue testing using the stair case methodology (fatigue limit and fatigue life), the effect of the manufacturing process and the type of ceramic on the life of the restored tooth- ceramic crown complex. The effect of the manufacturing process on the interface size and quality is also analysed. The fatigue performance of the structures was explained in the light of the interface quality and geometry. The experimental fatigue tests performed in this research simulate a much more aggressive physical scenario for evaluating the fatigue life of the samples compared to the real life environment that the tooth-crown structure experience. Therefore the fatigue life of the tooth-crown structures are expected to be more extended compared to the results obtained through our tests. However the results of this study could indicate the differences between the 3 groups of tooth-crown structure fabricated through various fabrication processes.

The null hypothesis assumed that the pressed and milled ceramic crowns have a similar interface dimensions and show no difference in survivability under a thermo-mechanical fatigue loading.

Materials and method

Sample preparation

Since our objective has been to study the effect of the manufacturing process on the interface geometry and the resultant effect on fatigue life, we do need to exclude any other natural tooth variables from the study. These natural tooth variables are parameters such as tooth size, dimensions and dentine structure). Therefore throughout our study, we have considered a Frasaco tooth permanent upper right first premolar (Frasaco GmbH Oberhoferstrasse Tettnang, Germany) which was prepared according to Ivoclar/Vivadent instruction for the monolithic e.max® all-ceramic crown. The all-ceramic crown preparation was carried out with 1 mm rounded shoulder finish line, 1.5mm axial and occlusal reduction and 6 degrees of taper [21].

The prepared typodont tooth was used as a master die. It was duplicated to fabricate 60 tooth replicas from the dentine-like polyurethane-based resin material (AlphaDie® MF, Schütz Dental GmbH, Rosbach, Germany). The elastic modulus of this resin materials was (14800 MPa) which closely matched to the dentine elastic modulus [22, 23].

Dublisil 15 (Addition-vulcanising vinyl-polysiloxane, Dreve Dentamid GmbH, Germany) was employed for the fabrication of the master die mould.

Interface Geometry assessment

In order to characterise the thickness and geometries of the cement interface of the pressed and the machined ceramic crowns a novel digital and computerised technique has been used. Three teeth with cemented ceramic crown samples were scanned using a micro-CT with a resolution of 7.9 µm of the acquiring data. The stack of CT images was then imported into Mimics®14.1 software (Materialise Interactive Medical Image Control System). Mimics® [image modelling software] allow transferring the images into a 3-dimensional object. This allowed for more precise calculations in different directions. The measurement was done in three virtual reproducible planes; sagittal, coronal, and axial planes, which corresponded to the labio-lingual, mesio-distal, and horizontal planes respectively. Measurements were performed for the identical predefined nine points in the same cross sections for each sample.

To validate the novel measuring technique, a comparison of the common physical measurements and the new digital technique was carried out. A ceramic disk was scanned by the micro-CT and measured by the novel Mimics® measuring technique. The same ceramic disk was used for the actual measurement purpose. A custom build computer-controlled laser micrometer measuring device that has been validated in former studies was used for the actual measurement of the ceramic disc [24, 25]. A comparison of the 3D digital and the laser actual measurement for the disk's diameter demonstrated a perfect correlation between the two to an accuracy of 1µm[26, 27].

Interface measurements were performed for three samples per group for characterising different cement interface thickness that were generated using the three fabrication techniques. The three ceramic fabrication techniques used in this study were, (i) CEREC® [CAD/CAM] as machined group, (ii) 3D printer as a digital-designed and pressed groups and (iii) manual pressed as an entirely manual process with hand waxing and pressing. Detail of the manufacturing techniques are described in the following section.

60 samples were duplicated from the master prepared tooth and were divided into three equal groups according to the following crown fabrication techniques:

A. Conventional pressed technique:

I. Entirely manual pressing technique using hand-painted separator on a solid model (manual pressed group): using a lost-wax technique, an expert senior technician constructed the pressed crowns by following the manufacturer's guidelines. The lithium-disilicate glass ceramic crowns were constructed using IPS e.max® Press ingot. The physical properties of the IPS e.max® Press ingot is shown in [table 1]. A new brush was used [hand-painted separator] to apply an even layer of the die spacer (Surefit™ gold Die Spacers, Harvest Dental) on the coronal part of the master die. Two coat layers were applied; each coat created 6µm of space (according to product's leaflet information). A wax crown copy was build-up and through the conversional pressing technique using the IPS e max Press ingot the crowns were fabricated.

II. 3D wax printer and pressing technique (3D printed group): the 3D crown copy and its interface were digitally generated by the design software (3M ESPE Lava™ Scan ST scanner) through digitally scanning the preparation die. A 3D printer (Solidscape® 3Z lab) was used to produce a wax pattern for a full coverage crown. 20 wax patterns of full anatomical crown were printed using the same parameters of the milled crowns [interface was set to zero spacer]. The subsequent steps for pressing the ceramic using the IPS e.max® Press ingot were the same as the manual pressed technique (lost-wax technique).

B. Machining technique (CAD-CAM):

Crowns were milled from an IPS e.max® CAD block ceramic (e.max® CAD block, shade HT A3, Ivoclar Vivadent, Germany) via the CEREC® 3 inLab milling machine. In order to take an optical impression of the given tooth, the sample and its adjacent teeth were sprayed with an optical scanning powder (CEREC powder VITA Zahnfabric, Germany) before and after the preparation. The crown restorations were designed using the correlation mode option to create a crown with the same morphology as the original tooth (Frasaco® upper first premolar tooth). The thickness of the crowns (an overall thickness of 1.5mm and the finishing line of 1.0mm) was set as per the manufacturer's recommendations (Ivoclar/Vivadent, Germany) and the interface was set to zero spacer. , The selection criteria for each crown were: Perfect fit of the crown, single path of insertion, intact marginal integrity, and effective crown morphology. The selection criteria for each crown were examined by using the visual inspection and the dental probe. Any crown has not met the selection criteria were excluded from the study[28, 29].

Periodontal Ligament (PDL) simulation and sample mounting

The alignment of all samples were achieved by placing the tooth in an inverted vertical direction (upside down) according to the long axis of the tooth by using the dental surveyor [Figure 1 (A)]. The prepared typodont tooth was painted evenly with a thin layer of die separator and embedded upside down till 2 mm above the CEJ in a square container filled with Dublisil® 15 A and B (Addition-vulcanising vinyl-polysiloxane, Dreve Dentamid GmbH, Germany) [Figure 1 (B)]. Thereafter, a cylindrical copper specimen holder was used for the root of the tooth located in the centre of the cylinder base [Figure 1 (C)]. The two bases were surrounded by a large square base container and then filled with Dublisil® 15 A and B [Figure 1 (D)]. Accordingly, each sample was put in the first mould and inserted in the second mould with the cylinder base to be filled with polyurethane-based resin material (AlphaDie® MF, Schütz Dental GmbH, Rosbach/Germany). After the recommended setting time of AlphaDie® MF, the tooth was gently removed from the cylindrical base in order to leave a space to be occupied later by PDL simulator impression material [Figure 1 (E)].

According to the study by Brosh et al.,[30] the light body silicone impression material, President Plus® light body [Coltène, Altstätten, Switzerland] proved as the most effective PDL simulation material due to its matched resilience to natural PDL. The pre-created socket was injected with President Plus ® light body and the tooth was immediately re-inserted into the socket. In this experiment, a space of 200µm thickness of the light body impression material was replicated to allow for 50µm movement in order to approximate the normal physiological tooth movement of Grade Zero tooth mobility [figure 2]. Subsequently, after the recommended setting time, the excess light body material over the socket was cut off with a surgical scalpel blade [30, 31].

Cementation

The ceramic crowns were etched with IPS ceramic etching gel [hydrofluoric acid] for 20 seconds and subsequently rinsed with water, in accordance with the manufacturer's guidance. The tooth was treated with phosphoric acid [37%] for 20 seconds and subsequently rinsed with water, to remove any biofilm and grease residue from the surface. The crowns were subsequently cemented with Variolink II [Variolink II, intro pack, Liechtenstein, Ivoclar/Vivadent, LOT R72873, Exp. 2014-08]. In order to standardise the cementation procedure, the tensometer (Lloyds Instrument Model LRX, Lloyds Instruments, USA) was used. This provided a constant pressure and time throughout the cementation of the crowns. A special jig was attached to the tensometer, which was filled with a heavy-bodied impression material (Aquasil Putty, blue colour, Dentsply Detrey). An impression of the coronal 1/3 of the ceramic crown was obtained. An even and uniform occlusal cementation pressure analogous to that of finger pressure of the dentist was applied during the cementation [Figure 3]. The device applied a 40N pressure in a compression mode for 3 minutes for cementing each crown [Figure 3]. Then the crown margins were exposed to the blue LED light of a light cure device (coltolux75) for 20 seconds as recommended; then any excess material was removed.

Mounting the specimen in the fatigue testing machine

The fatigue testing machine simply works by applying an axially aligned load onto the crown-tooth specimen. The load is generated from the weighted metal discs from one side and transferred through a leverage arm to the indenter at the opposite end of the arm [Figure 4]. The following parameters can be adjusted on the machine: The magnitude of the load (between 4Kg to 80Kg), the size and point of application of the load, the directional vector of the load, the frequency of the load and can be undertaken in a dry or temperature controlled wet environment. The machine has an automatic cut-off so that it will cease to apply the load upon fracture of the specimen, thus enabling observation of the fracture specimens relating to the moment of fracture.

The fatigue machine tester has 5 separated stations that enable testing 5 spaceman independently and simultaneously. The design of the mounting base was modified to allow for the movement of the specimen in the directions in order to adjust the contact point of the indenter to the occlusal surface. A customised stainless-steel indenter with a spherical tip a profile of 4.25 mm diameter [Figure 5] was used to create it to equidistant occlusal contact on the cusp inclines of the occlusal surface. This implements an axial compressive load on the occlusal surface of the tooth. A disc cushion or light-body silicone was placed between the indenter point and the load transfer arm (which is simulating the opposing teeth in the mouth) in order to uniformly apply the load on the specimen (the ceramic tooth sample), in a manner analogous to the PDL of the tooth in the mouth [Figure 5].

Each station's arm is connected to an independent cycle counter that can stop counting automatically when the sample fractures. The cycle frequency was set at 60 cycles/minute. Throughout the experiment, the specimens were permanently immersed in recirculating heated water at 37C˚ [Figure 4].

The contact points of the indenter on the tooth were confirmed with occlusal indicator paper for all specimens as per the diagrammatic representation shown [Figure 6]. The indenter contacted the occlusal surface of the tooth in the lingual inclination of the buccal cusp and buccal inclination of the lingual cusp.

Load cell calibration

A highly sensitive force sensor device was used to calibrate the load [LOAD CELL model TR150, version V1.10, UK]. The load cell was centred in the mounting base of one station where the actual specimen should be placed. To calibrate the load, discs of 0.5Kg were placed in a sequential and incremental manner and the force in Newton was recorded. The load/force calibration was taken over two measurements for each load.

Fatigue limit experiment

The evaluation of the fatigue limit was carried out by implementing the staircase method. In this technique, the sample was subjected to a certain stress for a predetermined number of cycles. If the sample survived the cycled stress, the load would be increased for the next fresh sample by a fixed incremental load. The procedure would be repeated with the fixed incremented load until the sample showed failure. Thereafter, the load would be decreased for the next sample to the last load (endurance load) that was used before failure [32-34]. 21 teeth were restored with full-coverage [CEREC] machined crowns that were adhesively cemented, as previously described. However, a hypothesis has been considered that the crowns fabricated by the two processing methods of lithium disilicate ceramic [machined and pressed] would be quite similar regarding the endurance limit if they cycled for short period.

According to the currently accepted testing variables of the staircase methodology, the samples were cycled with an assigned load for 5000 cycles in a water bath at 37C˚ at a rate of 60cycles/minute. The experiment conducted by applying cyclic load of 3 Kg (390N) to the first sample and then incrementally adding 0.5Kg (30N) loads for a fresh specimen every time. The fatigue behaviour of the samples during the fatigue limit test is shown in [Figure 7].

Fatigue life experiment

When the fatigue limit has been evaluated, a load value for performing fatigue life experiment can be defined. Generally, the load for testing the fatigue life would be close to the fatigue limit load. In the fatigue limit experiment the maximum load that the sample had survived for 5000 cycles was 5kg (522 N). Theoretically, a substance will withstand an infinite number of cycles if loaded below its fatigue limit (Yoshida, Morimoto et al. 2004). Therefore, the load of the fatigue life test was reduced by 1Kg. Thus, the samples underwent the cyclic load of 4Kg. This load is equivalent to 453N according to the load calibration test at a frequency of one Hertz (one impact/second).

20 samples per group were assigned. Simultaneously, five samples of the same group were placed in the five stations of the machine and underwent cyclic load to failure under the assigned load. Following the fracture failure of a specimen the counter would stop and the number of cycles was recorded. A fresh specimen would be placed, the counter reset to zero and the experiment re-commenced.

Fatigue life estimation with Use of Weibull statistics for probability distribution

Prediction of the tooth-crown fatigue life could be achieved by adopting the probability distribution, which can be considered as the best way for effectively describing the variation in the life expectancy. Although several ways have been adopted for the probability distributions analysis, Weibull analysis has been shown by the literature as the preferred [35, 36].

The fatigue life experiment translates the survivability of the sample based on the number of cycles to failure. In order to apply Weibull analysis, special analysis software [Reliability and Maintenance Analyst, version 4.5.9, Novell, USA] was used. Using this software, the two Weibull parameters [α, β] could be obtained. The mean number of the survived cycles would be indicated by the α parameter. The failure interval in relation to the mean could be indicated by the β parameter [scale parameter] or Weibull modulus [Figure 8]. The β parameter value has some significance explained below:

- $\beta < 1$ indicates an early failure in relation to the mean
- $\beta = 1$ indicates a regular intervals of failure throughout the experiment time
- $\beta > 1$ indicates a late failure interval

The higher β value means the more reliable the sample as it indicated the higher ratio of late to early failure [Figure 9].

Fracture mode

In order to investigate the differences in the fracture mode of the specimens under the fatigue load, the mode of the fracture was recorded for each fractured samples [37]. The fractured sample was dried and the fracture parts were visually inspected and recorded. Burke's classification for the mode of fracture was followed in order to classify the mode of failure in the fractured samples [Table 2]. ''One-way ANOVA on ranks'' for non-parametric data analysis ''Kruskal-Wallis'' was applied to determine if there are statistically significant differences among groups' samples regarding the fracture mode recorded.

Results

Interface assessment

On the basis of our interface measurements results on the crown-tooth complex we can identify the following categories.

(i) Thick and non-uniform interface created by a machined crown (CEREC®) (mean 157µm ±36); (ii) thin thickness and most uniform interface (least discrepancy from the mean) created by a conventional pressed crown (mean 114µm ±19) and; (iii) thinnest and uniform interface (less discrepancy from the mean)created by the 3D printer-pressed crown (mean 81µm ±26) [Figure 9].

Fatigue strength

Fatigue limit

Through the application of the staircase methodology, the fatigue limit load value was defined when the samples showed a constant rate of survivability. The samples in the fatigue limit experiment have shown a failure at the load of 5.5Kg (553N). While, at a level of 5Kg (522N) the samples survived the load for the 5000 cycle [Figure 7]. Thus, a 5Kg load could be defined as a fatigue limit load as several samples have shown a constant success (survival) rate. Accordingly, the samples would be expected to survive more cycles if they are subjected to a load close or slightly lower to the fatigue limit load value. Thus, the fatigue life experiment was setup at the load of 4kg [453N] the number of cycles were set to 1,250,000[Figure 7].

Use of Weibull statistics for probability distribution

Prediction of the tooth-crown fatigue life could be achieved by adopting the probability distribution, which can be considered as the best way for effectively describing the variation in the life expectancy. Although several ways have been adopted for the probability distributions analysis, Weibull analysis has been shown by the literature as the preferred [35, 36].

Fatigue life

The fatigue life experiment results are analysed using the Weibull analysis to represent the survivability of the sample based on the number of cycles to failure [figure 12].

The Weibull plots for the three sets of samples are shown in figure 10. The Maximum Likelihood Estimation plots [MLE] which depends on the given data of the Weibull parameters are shown in [figure 11] for the three groups of the samples.

In order to investigate the level of the significance between the mean values of the survived cycles between the three groups [Table 3] and [Figure 13], at an alpha level of 0.05, a one-way ANOVA (Analysis of variance) test was carried out using (IBM SPSS statistics version 20) [Table 4].

Fracture mode analysis

Each fractured sample has been examined [Figure 14, 15 and 16] and the mode of the fracture is recorded according to the Burke's classification for mode of fracture [Table 5].

‘’One-way ANOVA on ranks’’ for non-parametric data analysis ‘’Kruskal-Wallis’’ was applied to determine if there are statistically significant differences among groups’ samples regarding the fracture mode recorded. The statistical analysis of the code data has demonstrated a significant difference between the three groups [p<0.05] [Table 6 and 7].

Discussion

This investigation evaluated and compared the fatigue life of three types of all ceramic crowns fabricated by three different fabrication techniques . Machined [CAD/CAM], manual pressed and 3D printed/ manual pressed techniques were used in order to fabricate the crown-tooth structure. Fracture and fatigue behaviour of all ceramic crown-tooth complex could be affected by several variables. Thus, to obtain a high reliability of predicting the long term success of dental restoration, simulation of the oral environment was designed by utilizing the chewing simulator [7, 38, 39].

In order to minimise the variables involved in using natural tooth, it was decided to construct the abutment from the polyurethane-based resin (AlphaDie® MF, Schütz Dental GmbH, Rosbach, Germany) which has a Young's Modulus closely matched to dentine[22, 23].

Since three ceramic fabrication techniques were used, it was necessary to measure and characterise the interface that would be generated by each fabrication technique. As a result of using different fabrication techniques the tested crowns have shown different interface thickness and geometries[26, 27] . A new measurement technique has been developed to characterise the interfaces obtained from each fabrication technique.

It is well documented from the retrieved clinical data that the initiation and propagation of the crack due to the fatigue effect of the masticatory force is supposed to be the common case for the clinical failure of the all-ceramic restoration [34]. In this study, the cyclic fatigue loading with very close oral environmental factors has been considered in order to evaluate and compare the fatigue strength of the samples.

300N is a commonly used load value for the average mastication force subjected to maxillary premolar in some studies [18, 40-43]. However the literature is inconclusive regarding the stress generated from biting forces. Therefore stress or the load values for simulating the natural biting force on the dental restoration were obtained through fatigue load experiment.

The estimated fatigue life load was assessed to be 453N. This is higher than the average load on the premolar area that has been recorded in other studies. Therefore we expect the results obtained through our current study to be very conservative. Yet they are valid for the purpose of comparison of the crown-tooth system manufactured through different methods.

The statistical analysis by ANOVA one-way test of the result [Table 4] showed significant difference between the three groups. Since, the test and the sample parameters were fixed for all the groups, the possible explanation of this clear difference between groups could be related to the differences in the cement interface geometry and to the different crystalline structure for the pressed and the milled ceramic material. However, the two pressed ceramic groups (the manual pressed and the 3D printed group) have shown a great variation in terms of the number of the survived load cycle [figure 12]. This is despite the fact that the crowns for these two cases have the same crystalline structures. Thus, the influence of the crystalline structure on fatigue life could be a secondary parameter. Whilst the interface geometries of the samples could have had the primary role in different fatigue life obtained for three groups. The interface

geometries are closely resulted from the manufacturing techniques following the manufacturers' instructions.
Considering the **α** and **β** parameters of the Weibull analysis [Figure 9], samples of the medium interface thickness were found to be more reliable than the other two groups. The scale [β] parameter of the medium interface thickness group [manual pressed] shows more upright line slope and further to the right side than the others [Figure 10]. Although, the group of the high interface thickness [CAD/CAM] shows less reliability than the medium interface thickness group [manual pressed], but still more reliable than the low interface thickness group [3D printer] [Figure 10].
The study conducted by Prakki et al. has suggested that the higher film thickness of the uniform cement interface could increase the fracture resistance of ceramic disc when the ceramic thickness below 2mm. [9]. The maximum thickness of the ceramic crowns used in this experiment was fixed to be 1.5mm. Therefore, the low fatigue life of the low thickness interface samples in our tests confirms the results of the Prakki et al study.
Moreover, the low fatigue life of the low interface thickness group could be related to the resin cement physical properties. The high polymerizing shrinkage stress even over a very small area of the cement interface could contribute to creating cement crack. The cement cracks act as stress concentration loci leading to failure of the restoration under occlusal force. A reasonable standard film thickness (50-100µm) may have favoured greater absorption of the stress produced by the resin cement polymerization shrinkage that contributes to a substantial stress relief at the resin cement interface [44-46].
The medium interface thickness (mean 114µm ±19) group samples [manual pressed] have manifested a higher fatigue resistance by surviving a maximum of 974,286 cycles with an average was 639,857 cycles. The high interface thickness (mean 157µm ±36) group samples [CAD/CAM] showed less reliability compared to the medium interface thickness group samples [manual pressed] by surviving a maximum of 678,660 cycles with an average of 343,864 cycles [Table 3].
A possible explanation for the difference in the survival rate of the medium interface thickness group samples [manual pressed] and the high interface thickness group samples [CAD/CAM] could be related to the uneven stress distribution within the ceramic structure. According to our finding in the previous study[26, 27] , regarding the cement interface thickness, the machined sample (the high interface thickness group) shows higher discrepancy and thickness above the accepted standard compared with the manual pressed sample (the medium and uniform interface thickness). It has been suggested that the stress distribution in a non-uniform cement interface can result in high concentration in some areas. This could be the cause of pre-mature failure in the structure. The stress distribution in the non-uniform interface could affect the bonding surface by increasing the maximum shear stress to values exceeding the bond strength of the cement layer to the restoration and tooth walls [47, 48]
It is well established through the examination of the clinically failed all-ceramic crowns that the failure is initiated from the inner surface of the crown where the micro flaws exists [18, 49]. It has been shown that the CAD/CAM fabrication technique could induce subsurface defects. Process dependent micro-defects that could be induced by the bur's grinding action of the CAD/CAM machine contributes to the reduced performance of the ceramic structure. [50].

Moreover, the improved fatigue life achieved by the manual pressed (the medium interface thickness) samples could be related to the cement interface nature. According to our finding of the previous study[26, 27] , the manual pressed samples showed an ideal standard uniform cement interface thickness (mean 114µm ±19). The uniform interface geometry could be an explanation of the benign or an even stress distribution within the restored tooth.

Moreover, the manufacturer's data shows the IPS e max press has a flexural strength of 400 MPa which is slightly higher than 360 MPa for the IPS e max CAD and fracture toughness of 2.75 and 2.25[MPa $m^{0.5}$] respectively. Therefore, manual pressed crown could perform better especially it is combined with a most homogenous interface (less interface thickness discrepancies) comparing with the machined crown group.

Another parameter contributed to the high fracture resistance of the manual pressed crowns could be the technical lab steps involved. The single professional technician skill could contribute effectively in reducing the process-dependent defects in the ceramic structure during the pressed technique. The spacer that has been used for generating the interface space (Pi-Ku-Plast HP 36, Bredent medical GmbH & Co.KG /Senden/ Germany) has reported to have a low [less than 0.036%] polymerising shrinkage[51]. The low polymerising shrinkage of the spacer could contribute effectively in keeping the generated interface space as a uniform and that in turn increase the performance of the ceramic crown.

Yildiz et al have reported that the Onlays fabricated by pressed technique shows higher fracture resistance than Onlays fabricated by CAD CAM technology [7]. This is in accordance with the result of our current study.

The Maximum Likelihood Estimation [MLE], which depends on the given data of the Weibull parameters has indicated that the samples with the medium interface and uniform thickness [Manual pressed] could survive even more cycles compared with the other [Figure 11].

Taking the result of the survived cycles one step further, [Figure 12] showed a considerable variation in the survived cycles between samples within each group and across the groups. The most likely cause of this observed variation could be related to the variability of the flaws distribution within the ceramic structure.

It has to be considered that no sample has survived the proposed cycles 1,250,000. This could be due to adopting the load of 453N which is higher than the clinically recorded bite load [300N in premolar segment].

Conclusions

Within the limitations of this study the following conclusions were drawn:

1. There is a relationship between interface thickness and structural integrity.
2. The crowns with the medium cement interface thickness and most uniform cement interface exhibited large Weibull modulus compared with low and high cement interface thickness of the other tested groups and that implies greater clinical reliability for the crown with this cement interface features.
3. The non-uniform interface dimension and the proposed production of strength-limiting surface flaws of the CAD/CAM fabrication technique increased the failure rate of the crowns under the cyclic loading.

4. The lowest Weibull modulus and high failure rate were recorded with the thinnest and uniform cement interface crowns [the 3D wax printed and pressed crown group]. Therefore, to optimize structural reliability of this type of cement interface profile, more attention should be paid to setup the thickness of the interface within the reasonable standard (50-100µm).

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Table 1 Physical properties of IPS e.max® Press and CAD ceramic [the data collected from Ivoclar/Vivadent websites]

physical properties	IPS e.max® Press	IPS e.max® CAD
Flexural strength (biaxial) [MPa]	400	360
Fracture toughness [MPa $m^{0.5}$]	2.75	2.25
Modulus of elasticity [GPa]	95	95
Vickers Hardness [MPa]	5800	5800
Chemical solubility [µg/cm^2]	40	40

Table 2 Burke's classification of modes of fracture

The Mode	Characterization
Mode 1	Minimal fracture or crack in crown
Mode 2	Less than half of crown lost
Mode 3	Crown fracture through midline: half of crown displaced or lost
Mode 4	More than half of crown lost
Mode 5	Severe fracture of tooth and or crown

Table 3 The maximum and average of the survived cycles for all the groups

Groups	Maximum	Average
High interface thickness[CAD/CAM]	678660	343864
Medium interface thickness [Manual pressed]	974286	639857
Low interface thickness[3D printer]	378945	132882

Table 4 ANOVA test for all the groups comparing the survival cycles

ANOVA					
Cycles					
	Sum of Squares	**df**	**Mean Square**	**F**	**Sig.**
Between Groups	2.594E+12	2	1.297E+12	56.898	0.000
Within Groups	1 .299E+1 2	57	22797978312		
Total	3.894E+1 2	59			

Table 5 Mode of fracture in the group samples

The Mode	Medium interface thickness [Manual pressed] Average survived cycles (639857)	Low interface thickness[3D printer] Average survived cycles (132882)	High interface thickness[CAD/CAM] Average survived cycles (343864)
Mode 1	0	1	0
Mode 2	9	3	2
Mode 3	7	2	5
Mode 4	4	10	8
Mode 5	0	4	5

Table 6 Kruskal-Wallis Test showing the mean rank of fracture mode for each group

Ranks		
Technique	N	Mean Rank
Medium interface thickness model[Manual pressed]	20	19.80
Low interface thickness model [3D printer]	20	35.03
High interface thickness model [CAD/CAM]	20	36.68
Total	60	

Table 7 Kruskal Wallis test for the fracture mode for each group of samples

Test Statistics	
	Code
Chi-Square	12.309
df	2
Asymp. Sig. [P-value]	0.002

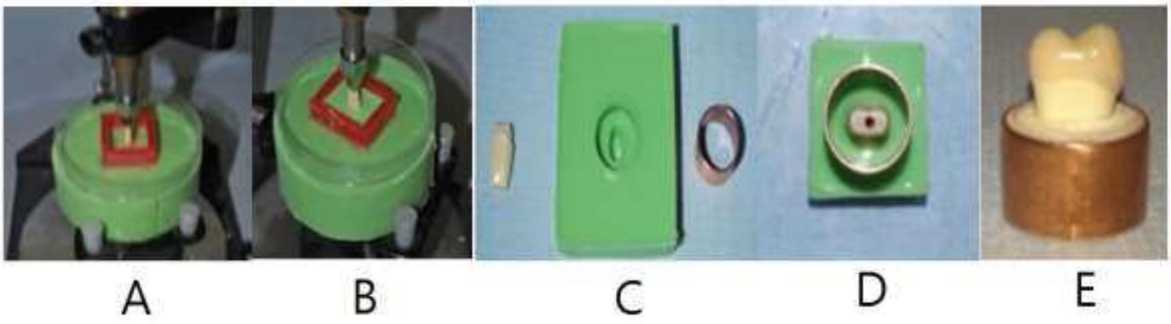

Figure 1 (A) Alignment of the tooth in the dental surveyor, (B) Covering the sample by the Dublisil 15 A and B material, (C) The Alignment mould, (D) The metal base, (E) Actual sample in the base

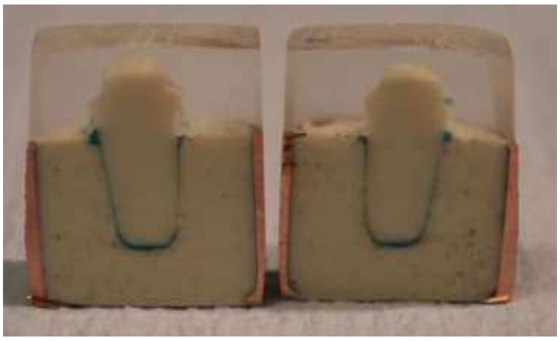

Figure 2 PDL simulation (tooth crown embedded in acrylic for this specimen to facilitate sectioning that enables visualisation of the tooth and PDL in cross-section)

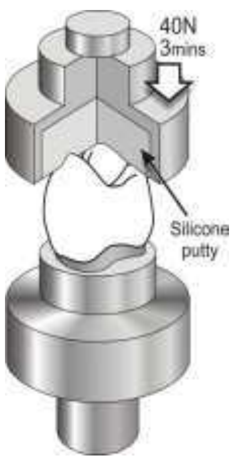

Figure 3 Cementation technique by universal testing machine

Figure 4 Fatigue machine tester

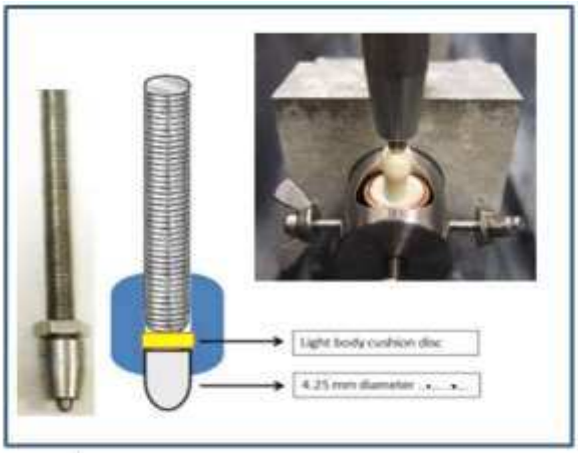

Figure 5 Indenter

Figure 6 Diagrammatic representation of the occlusal contact points of the indenter on the tooth surface.

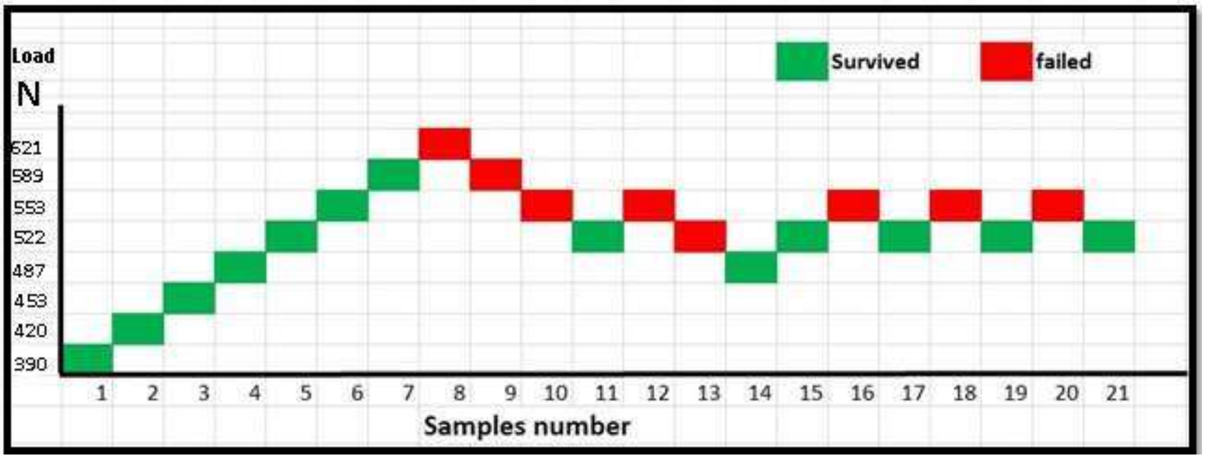

Figure 7 Staircase for fatigue limit of CAD/CAM specimens

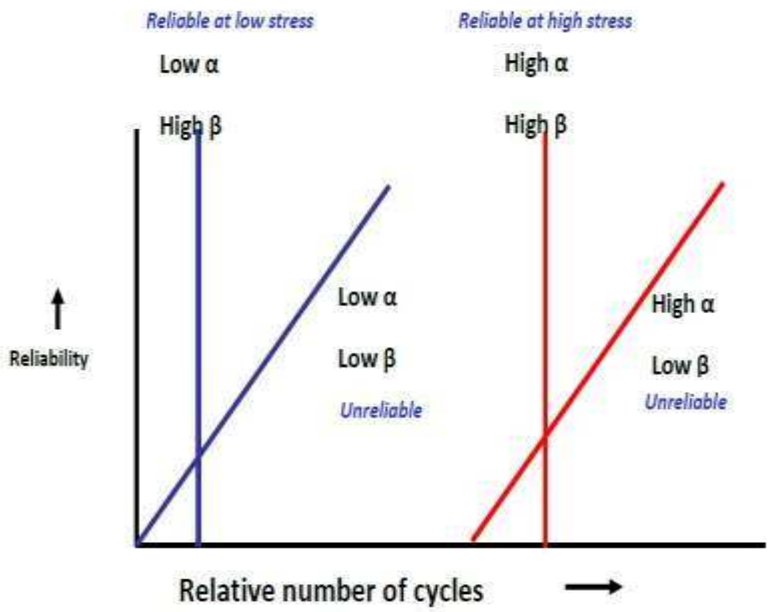

Figure 8 The relation of β to α parameter in Weibull analysis

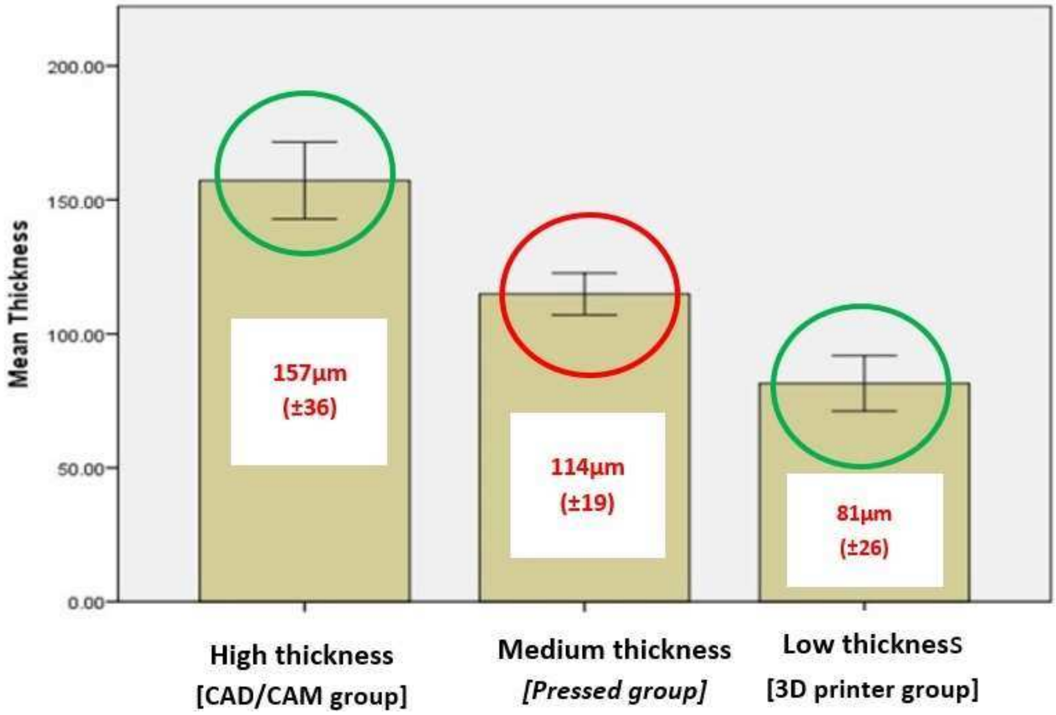

Figure 9: Mean (3D) and SD of the cement thickness of the three test groups

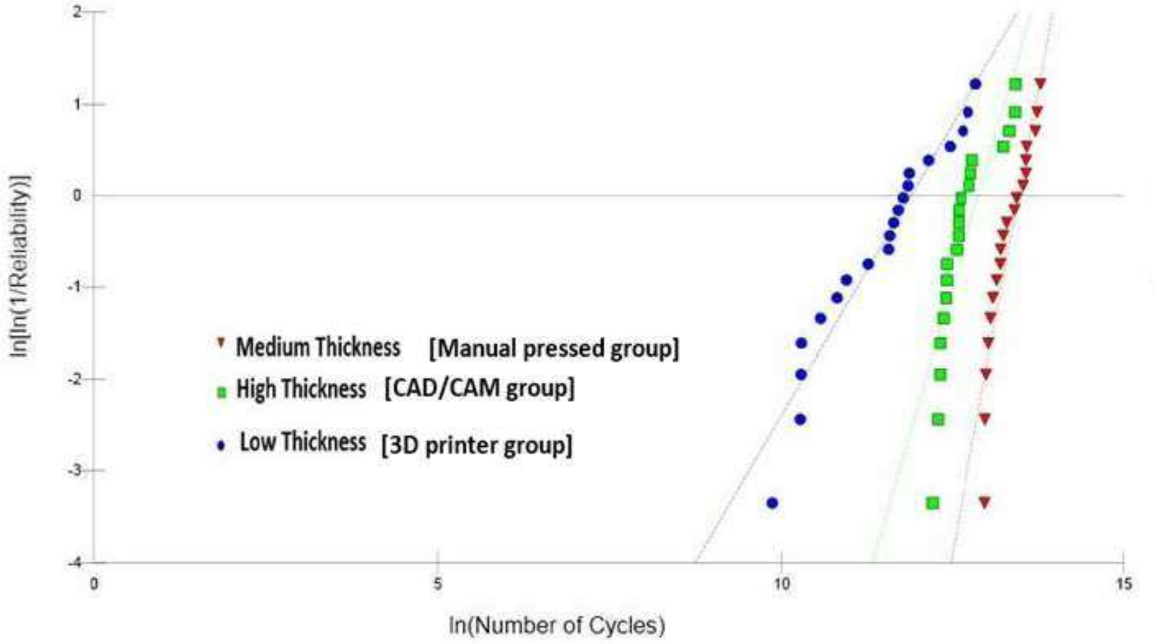

Figure 10 Weibull probability of failure for all the groups at 453N load

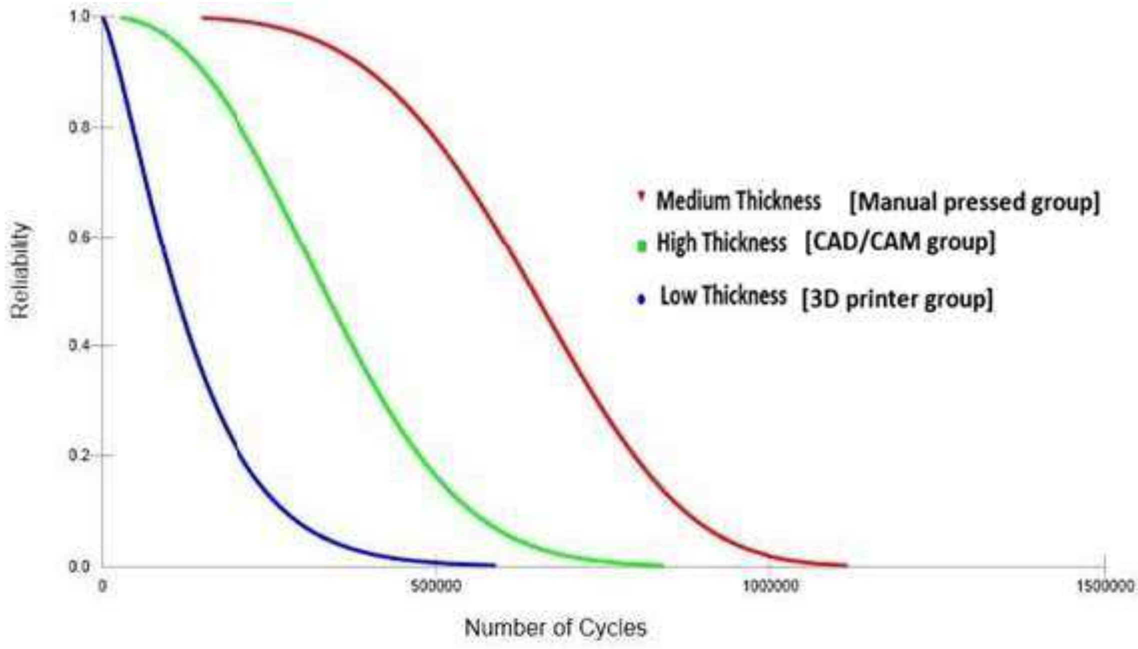

Figure 11 Weibull maximum likelihood comparison of the all the groups

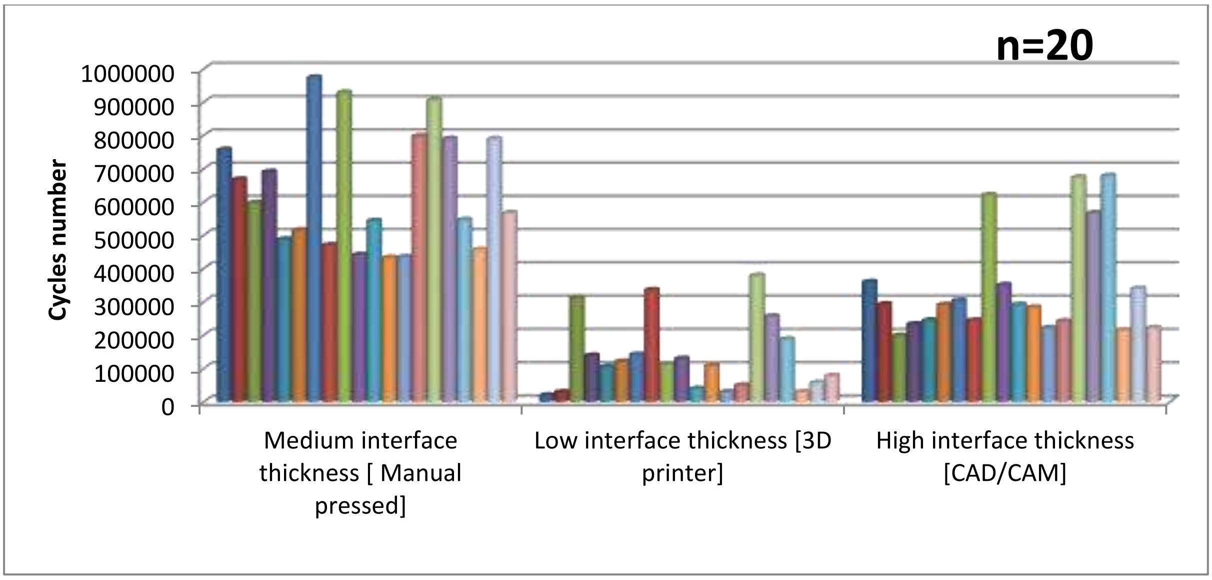

Figure 12 Number of cycles at failure (columns refer to different specimen)

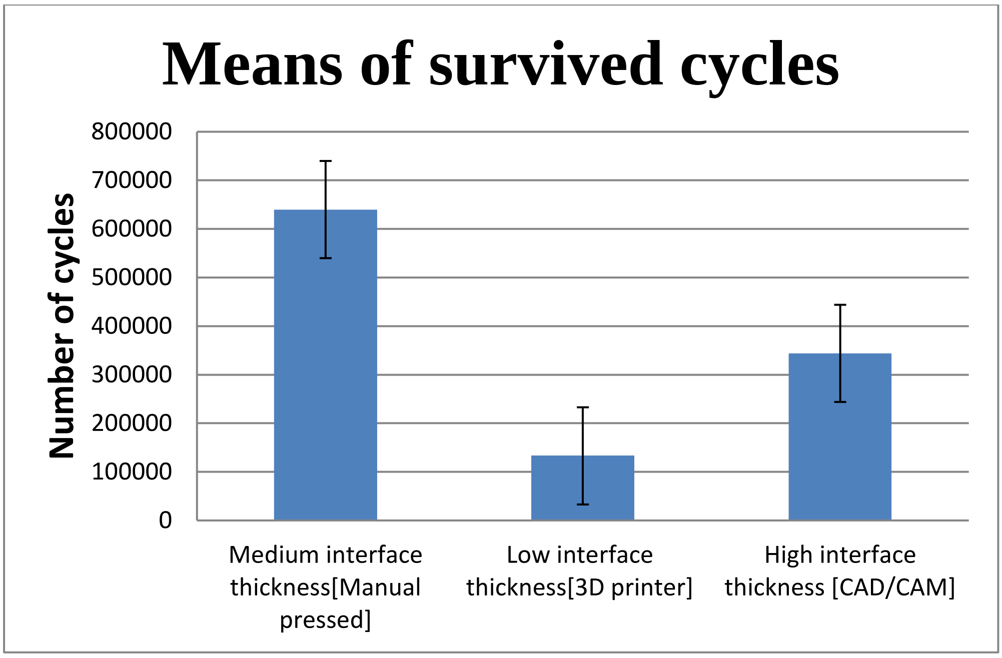

Figure 13 The mean values and SD of the survived cycles for all the groups

Figure 14 Fracture mode 2

Figure 15 Fracture mode 3

Figure 16 fracture mode 4