



Experimental Investigation of CAD/CAM-Fabricated Lithium Disilicate Fixed Dental Crowns: Influence of Design Parameters and Ageing on Adaptation and Surface Integrity

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Abstract

Computer-aided design and computer-aided manufacturing (CAD/CAM) technologies have significantly transformed fixed dental prosthesis fabrication by improving precision, repeatability, and clinical efficiency. The present study experimentally investigates the influence of critical design parameters—finish line geometry, convergence angle, and cement layer thickness—on the marginal and internal adaptation of lithium disilicate glass-ceramic (LDGC) fixed dental crowns. A structured design of experiments based on the Taguchi method was employed to systematically evaluate the selected parameters while maintaining clinically relevant constraints. Monolithic LDGC crowns were fabricated using a standardized CAD/CAM workflow, ensuring uniformity across all specimens. Marginal discrepancy (MD), absolute marginal discrepancy (AMD), and internal discrepancy (ID) were quantified non-destructively using synchrotron radiation X-ray micro-computed tomography (SR- μ -CT). In addition, the long-term surface integrity of the crowns was assessed through surface roughness and micro-hardness measurements under simulated thermal-pH ageing cycles up to 40,000 cycles. The results revealed that geometric design parameters significantly affect crown adaptation, with finish line type and cement layer thickness playing dominant roles. Ageing cycles led to a progressive increase in surface roughness and a corresponding reduction in micro-hardness, attributed to thermochemical degradation of the glass-ceramic matrix. The study demonstrates that optimized CAD/CAM design control combined with appropriate parameter selection can enhance the clinical performance and longevity of LDGC fixed dental crowns.

Keywords: CAD/CAM dentistry; Fixed dental crowns; Lithium disilicate glass-ceramic; Marginal adaptation; SR- μ -CT; Taguchi design; Ageing behavior; Surface roughness; Micro-hardness

1. Introduction

Implementation of CAD/CAM has benefited the clinical dentistry by reducing the chair time, eliminating the provisional appointments and impression method, and improving technical communication between dentist and laboratory technician. In addition to clinical benefits, CAD/CAM dentistry has benefited patients by providing a variety of aesthetic metal-free dental materials, elements the long casting process, and improves implant techniques. Despite of above benefits, dental CAD/CAM systems have some limitations such as high initial investment cost of restoration, need of skilled dental practitioners, and challenges in intra oral digital scanning process due presence of soft tissues and moistures [1-3].

Although CAD/CAM is being successfully implemented in medical prostheses for last few years, therefore, recent advancements in this technology can be further implemented not only to produce high quality prostheses but for clinical research and development also.

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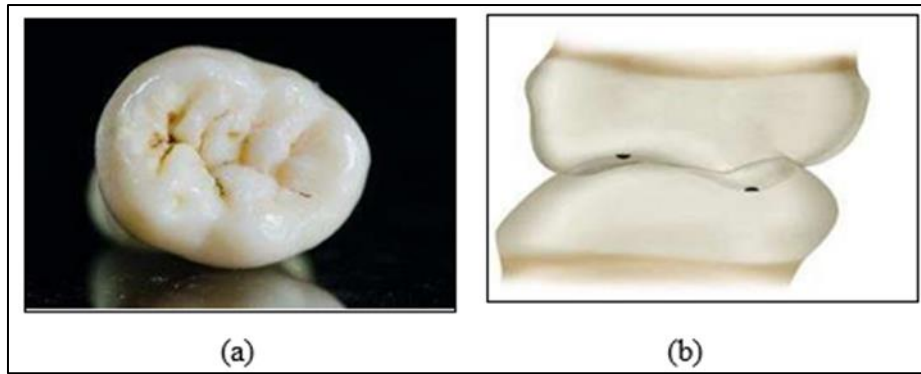


Figure 1 (a) Occlusal surface (b) Occlusal contact of opposite teeth



Figure 2 Classification of Removable Dental Prostheses (a) Partial unit (inlays & onlays restorations) prostheses (b) Single unit (Crown restoration) prosthesis

Dental Prosthesis is an area concerned with the assessment, recovery preparation, rehabilitation and preservation of functional ability, convenience, appearance and fitness of patients with pathological problems associated with damaged or defective teeth and/or maxillofacial tissues using biocompatible replacements. The main purpose of dental prosthesis is to restore oral function, particularly masticatory features which depend on the how well occlusal surfaces (Figure 1a) of opposite teeth contacts. Hence, to create effective and suitable occlusal contacts (Figure 1b), the customized geometry of dental prostheses is required. Dental prostheses can be classified into two types based on the restoration process: (i) Removable Dental Prostheses, (ii) Fixed Dental Prostheses [4, 5].

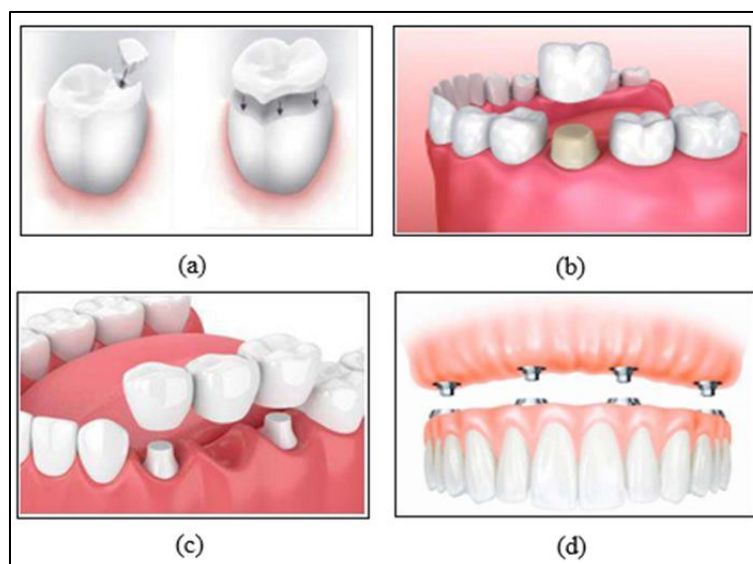


Figure 3 Classification of Fixed Dental Prostheses (a) Partial unit (inlays & onlays restorations) prostheses (b) Single unit (Crown restoration) prosthesis (c) Multi unit (Bridge restoration) prosthesis (d) Complete denture prosthesis

Removable Dental Prosthesis is all forms of dentures produced in the clinical laboratory at different levels of damaged teeth. These can be quickly separated from the patient's mouth for washing and reinserted without the use of cement. Most of the time, they are intended to replace multiple missing teeth rather than just one or two, as bridges do, or even more teeth in edentulous patients. Removable, partial and complete denture prostheses are common examples as shown in Figure 2 [6].

Fixed Dental Prosthesis is also produced in the laboratory for partial damaged and complete missing teeth, but these are cemented to the teeth prepared by the dentist and patients can not remove it for cleaning or other purpose. Generally, fixed prostheses are recommended for partial, single, and small unit (two or three) restoration such as inlays, onlays, veneers, crown, and bridge restoration as shown in Figure 3 [7].

2. Literature Review

Duret et al. [14], in the early seventies challenged the implementation of CAD applications in dental field. His research team designed an optical scanner that was capable of digitizing the tooth preparation. The digital information was then used to design the shaped crown using a specific program on the computer, and finally milled with a numerical control unit. Later, the same group further developed the *Sopha* concept that seems to have been advanced in the late 1970s.

In the 1980s, CAD/CAM reinvented the field of dentistry, making it more effective and accurate after the inception of the *CEREC* generation a dental CAD/CAM system, which was originated by Mörmann and Brandestini [8]. Using this system, they proposed making of inlays quickly even while the patient was inside the dental chair. A French software developer, Dr. Alain Ferru, was recruited to build the *CERE-1* the next generation dental CAD/CAM system. The CAD/CAM era then became "state-of-the-art" because of the invention of *CERE-1* that allowed the manufacturing of single and twin surface inlays. The first CAD/CAM generation allowed the clinician to restore inlays in a single visit: this reduced the chairside and lab time. Although, this generation was only capable of fabricating the inlays but failed to provide precise shapes similar to anatomical morphology. It was difficult to create an intra-oral optical upshot, so a higher level of CAD/CAM required an advanced scanner to digitize the stone model after taking an impression of the preparation, and milling the crown afterwards [9].

Later, three additional modern dental CAD/CAM systems were introduced to digitize the preparation as similar to other scanners such as laser beams and contact probes. The Siemens *CEREC* Team then created the advance follow-up program and developed the most popular CAD/CAM system of its generation *CEREC-2*. The inclusion of a cylindrical diamond tool allowed for milling inserts, inlays, veneers, and crowns. Therefore, second generation, dental CAD/CAM systems were capable of fabricating both metallic as well as ceramic restorations [10].

While third generation dental CAD/CAM systems refined the process of scanning of tooth preparation in order to model a crown and providing networked distribution for milling the crown, *CEREC-3* was evolved in the year 2000. It had a two-bur based mechanism and its CAD-CAM system was focused mainly on windows.

In 2006, another improvement of the *CEREC-3* was developed to boost precision and sturdiness. It has made a name for itself in dentistry because it is the first to do a full crown job for a dentist on a maiden visit [11]. The D4D technology united many multi-specialty engineering groups to plan and construct one of the revolutionary and licensed techniques for the efficiently functioning healthcare field. They developed *D3D* and *D4D* dental CAD/CAM systems in collaboration with other partners in the year 2003. Later, they commercialized their extended version of dental CAD/CAM system namely *E4D* in the year 2013 [12].

Third generation dental CAD/CAM systems are capable to construct the complete orthodontic braces that enables the dentist to rebuild old denture prostheses using special tools such as a reliner and a clinical remount. This can be achieved with the assistance of intra-oral computed tomography that generates an x-ray image of the teeth. It is now feasible to mill a detachable partial denture construction as well as 3-D print dental restorations, due to advancements in dental CAD/CAM technology.

3. Methodology

3.1. Design parameters in FDC prosthesis restoration process

Distinct input parameters affecting the clinical success of FDC restoration can be classified into material parameters, geometrical parameters, and process parameters. Because of the numerous process impediments, material parameters

(mechanical and chemical properties of crown and cement) and process parameters (machining parameters) are rarely redesigned. On the other hand, clinicians and lab technicians have the option to alter the geometry of tooth preparation (Finish Line, Convergence Angle, Tooth Height etc.) and crown (Cement Layer Thickness, Crown Thickness etc.) respectively.

3.2. Selection of the levels of input design parameters

In the design of an experiment, selection of levels of input parameters is an important part. In the current study, input parameter levels have been determined from the previous literature. Levels of all design input parameters have been selected rationally, taking clinical and design process feasibility into account. All the input design parameters have been varied at three levels as shown in Table 1. Besides these determined input design parameters, other dental restoration design parameters remained constant (shown in Table 2).

Table 1 Parameters with the different level

Symbol	Control Parameters	Unit	Levels		
			1	2	3
FL	Finish Line Type	-	Chamfer	Round Shoulder	Shoulder
CA	Convergence Angle	Degree	8	12	20
CLT	Cement Layer Thickness	μm	20	40	60

Table 2 Fixed input parameters

Prosthesis material	Lithium disilicate glass-ceramic (LDGC)
Tooth preparation height	4 mm
Crown thickness	1 mm
Occlusal depth	2 mm

3.3. Design of Experiment

In order to retrieve information and address the research questions for relevant and objective conclusions, appropriate experimental study planning is needed. There are often certain experimental errors in the record data during experiment study, which can be reduced using statistical technique. As a result, proper DOE and data interpretation are two key facets of the experimental challenge.

The DOE frameworks in the area of statistics are intimately associated with the data analysis methods. The DOE may be utilized for a number of purposes, such as:

- To limit the number of research experiments used to investigate parameter outcomes.
- To determine the process aspects and characteristics of the process during investigation.
- To achieve the best possible set of input parameters.
- To estimate the errors that will be created throughout the experiment.
- To define the pattern of the impact of input parameters on the process's responses.

In current research work, Grey Based TM has been executed to plan the DOE analysis of the data collected from experimental tests.

3.4. Taguchi experimental design and analysis

Genichi Taguchi, regarded as the "Father of Quality Engineering," developed the Taguchi system, which effectively incorporated effective applied statistical methods into engineering systems to achieve greater stability and capabilities. His methodology was pragmatic, focusing on calculation, interpretation, estimation, and mitigation, and it emphasized designing consistency into products and systems rather than inspecting them [13]. This approach puts a heavy focus on consumer loyalty and responsiveness. Taguchi understood and respected the importance of reaching a deadline, and he came to the realization that undue variance in results was the root cause of low production and was detrimental to society as a whole. He went on to claim that these differences in output or deviations from aim will result in unforeseen

social losses due to early wear out, difficulties incorporating or interfacing with other parts, maintenance, the need to have safety margins, and other considerations that, if overlooked, will result in consumer frustration and a lack of company credibility. To put it another way, Taguchi stressed the importance of reducing process uncertainty around a target value and then getting the process on track. Only by rendering processes immune to different sources of noise can this be achieved, and the approach is known as Robust Parameter Design [14].

Rather than defining stricter tolerances for individual parts, Taguchi tackles the problem by carefully choosing design parameters known as parameters, resulting in a more robust design that can tolerate deviations from unintended sources. He suggested an accurate and efficient approach for deciding the feasible combination of design parameters that eliminates uncertainty in product responses in order to do this. As a result, the Taguchi method of experimental design is an effective method for improving design performance, quality, and cost.

3.5. CAD/CAM Manufacturing of Fixed Dental Crowns

The fabrication of lithium disilicate glass-ceramic (LDGC) fixed dental crowns in the present study was carried out using a Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) workflow to ensure high dimensional accuracy, repeatability, and consistency across all experimental trials. The CAD/CAM manufacturing process consisted of three major stages: digital data acquisition, virtual crown design, and computer-controlled milling.

Initially, standardized tooth preparation models corresponding to the selected design parameters finish line geometry, convergence angle, and cement layer thickness were generated. These prepared tooth geometries were digitized using a high-resolution optical scanner to obtain accurate three-dimensional digital models. The digitized data served as the basis for subsequent virtual crown design, eliminating errors associated with conventional impression techniques.

In the CAD stage, the scanned tooth preparation models were imported into dedicated dental CAD software. Virtual crown designs were generated by defining the external morphology, occlusal anatomy, and internal cement space according to the experimental design matrix derived from the Taguchi design of experiments. Cement layer thickness values were precisely controlled within the software to maintain uniform internal spacing across all specimens. Other design parameters such as crown thickness, occlusal depth, and preparation height were kept constant to isolate the effects of the selected variables.

Following the design stage, the finalized crown models were transferred to the CAM module for fabrication. LDGC blocks in a partially crystallized state were used as the raw material for milling. The crowns were fabricated using a multi-axis CNC milling unit under controlled machining conditions to ensure dimensional fidelity. The milling process was performed using diamond-coated burs suitable for glass-ceramic materials, minimizing surface damage and tool wear.

After milling, the crowns underwent a crystallization firing cycle in a ceramic furnace as per manufacturer recommendations to achieve full crystallization of lithium disilicate. This process transformed the partially crystallized structure into a fully crystallized glass-ceramic with improved mechanical strength and optical properties. No additional veneering was applied, as the study focused on monolithic LDGC crowns.

The CAD/CAM-based manufacturing approach ensured uniformity in crown fabrication, minimized operator-dependent variability, and enabled precise control over critical design parameters. This standardized manufacturing route was essential for accurate evaluation of marginal and internal adaptation, surface roughness, and micro-hardness, thereby supporting reliable experimental comparisons and statistical analysis.

3.6. Experimentation and data collection

This research study performs the experimental work in two stages. The tests are run against each combination of parameters (trial) designed by the inner array in the first step. Every trial is run with basic repetitions (if the outer array is avoided) or repetitions according to the outer array are stored for each experimental trial, and the S/N ratio for replicated values of each run is calculated. The inner array was added to the process variables in this sample with basic repetitions to avoid forcing noise into the experiment. Further, the second stage was performed after data analysis of first stage experiment work.

4. Results and Discussion

4.1. Measurement of Discrepancies using SR- μ -CT

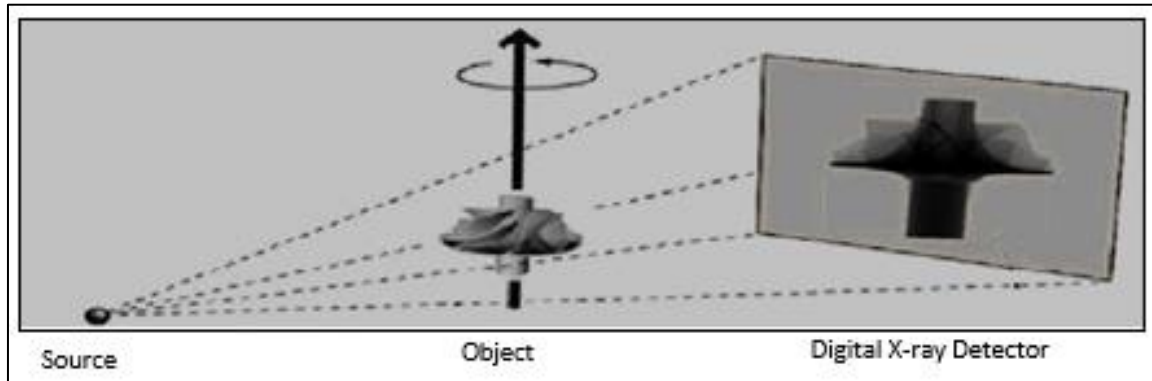


Figure 4 SR- μ -CT working principle

Synchrotron Radiation X-ray Micro Computed Tomography (SR- μ -CT) is the advanced and modified version of micro-computed tomography, or " μ -CT," which produces high resolution three-dimensional x-ray images using the same approach as hospital CT scans. It resembles 3D microscopy, in which the internal configuration of structures at a very fine scale is imaged non-destructively. The working principle of μ -CT is schematically described in Figure 4.

In this work, SR- μ -CT experimental set-up available at Raja Raman Centre for Advanced Technology (RRCAT), Indore, India, (Figure 4.3), has been used to obtain high quality images of all the assembled specimens. This experimental set-up is visualized in Figure 3 whereas its specifications are represented in Table 4.

In order to account for the varying curvature and wall height of each region, complete curve is divided into 5 segments i.e. 02 Shoulder Area (SA), 02 Axial Space (AS), and 1 Occlusal Space (OS) as shown in Figure 5(a). For each vertical section, sixteen measurement points are chosen (2 each for MD, AMD, and SA; 6 for AS; and 4 for OS) as shown in Figure 5 (a). All the prescribed sites have been measured by using image viewer software (ImageJ, NIH). Final measurement values have been considered after averaging their all respective measurements. This process has been repeated for each specimen.

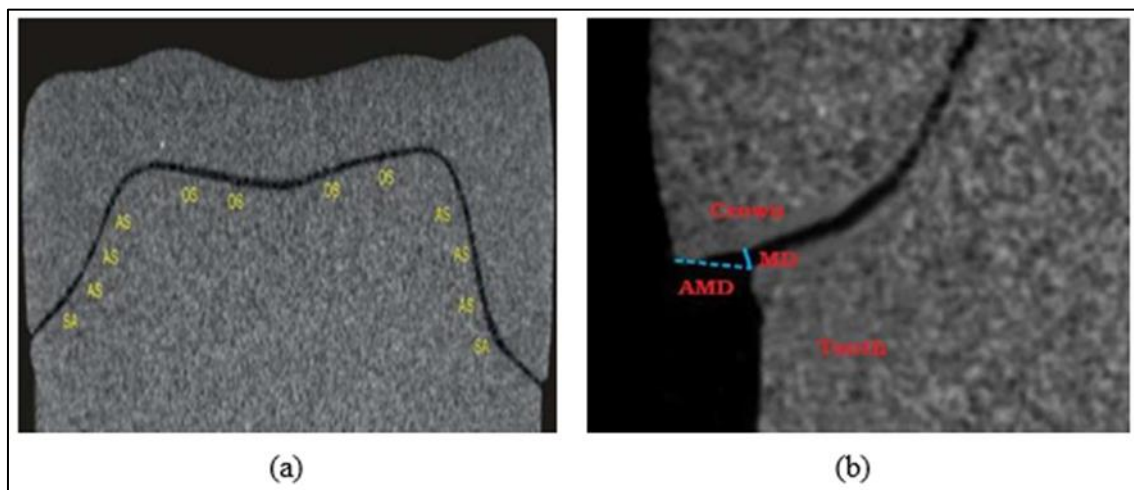


Figure 5 Vertical sections of 3D reconstruction used for discrepancies measurements (a) ID (b) MD and AMD

Experimental test results for Marginal Adaptation have been classified into Marginal Discrepancy (MD) and Absolute Marginal discrepancy (AMD). The results of MD and AMD have been shown in Table 3 and Table 4, while, results for Internal Discrepancy (ID) have been given in Table 4.

4.2. Measurement of Surface Roughness

The vertical deviation of the real surface of the product from the ideal shape is measured as surface roughness. Large deviations from the ideal surface profile result in rough surfaces. The average roughness (R_a) value, an international roughness measuring parameter and the arithmetic mean of the profile deviation describes the integral of the height of surface irregularities

4.2.1. Surface Roughness test results

Surface Roughness test results are recorded for eight LDGC dental crown prosthesis specimens at various stages of the ageing process are given in Table 3. Tukey's HSD test is used in one-way ANOVA ($\alpha = 0.05$) for statistical analysis of the results. In this part of work, MiniTab statistical software is utilized to perform experimental design and result analyses.

Table 3 Results of average roughness

No. of Ageing	Surface roughness (R_a)								
	R1	R2	R3	R4	R5	R6	R7	R8	Mean
0	0.374	0.233	0.429	0.268	0.342	0.432	0.354	0.197	0.3286
10000	0.453	0.312	0.512	0.268	0.421	0.51	0.422	0.314	0.4139
20000	1.024	0.826	0.834	1.026	0.867	0.984	0.753	0.854	0.8960
30000	1.752	1.66	1.346	2.083	1.87	1.526	1.631	1.492	1.6700
40000	2.376	2.593	1.94	2.824	2.601	2.447	2.75	2.154	2.4606

4.2.2. Analysis and discussion of results for surface roughness

The influence of thermal and pH fluctuations on surface roughness has been studied in this section. The mean values of surface roughness of all LDGC dental crown prosthesis specimens at prescribed ageing stages have been determined from raw data of experiments. Additionally, analysis of variance (ANOVA) of calculated values is performed to assess the significance of the effect of thermal-pH cycles on surface roughness (R_a).

4.2.3. Influence of ageing process on surface roughness

It has been observed from the response curve that surface roughness increases with the increase in thermal-pH cycles due to the fact that the surface corrosion of ceramics due to temperature and pH of the surrounding while cyclic pH accelerates the rate of corrosion. Surface roughness of specimens remains almost consistent in the first phase of the ageing process, but in later phases, it has been raised with higher rate. It could be drawn by the fact that glazed specimens are used in this experiment. The glazing process improves the surface quality of glass-ceramics and also protects them from aqueous environments. In the remaining phases, the parent material (LDGC) of specimens might be exposed to thermal and pH fluctuations.

The corrosion premise for glass-ceramics in acidic and basic mediums better explains the surface degradation of LDGC dental restoration prostheses. Bases strike the silica legitimately while acids strike the alkalis of the glass matrix. Glass surface dissolution in the presence of alkali results consistent erosion as long as the alkali is adequately supplied to solution. Therefore, a porous surface which is comprised of silica matrix with depression is restructured. After that attack of acids on this porous surface eliminates the alkalis from the glass matrix. Further erosion begins with acid infiltration deep within the glass-ceramic through the porous surface.

Moreover, the degradation of LDGC in this work substantiates some previous investigations state that disintegration of glass by synthetic concoctions can be assigned by the amalgamation of three concurrent fractional essential cycles, ion exchange, hydration, and hydrolysis [15]. Also, the rise in surface roughness might be due to the fact that surface erosion is a function of time, temperature, and pH [16]. The rate of surface erosion of ceramics remains higher in thermal fluctuations and cyclic pH ageing process rather than at room temperature and immersed in constant pH.

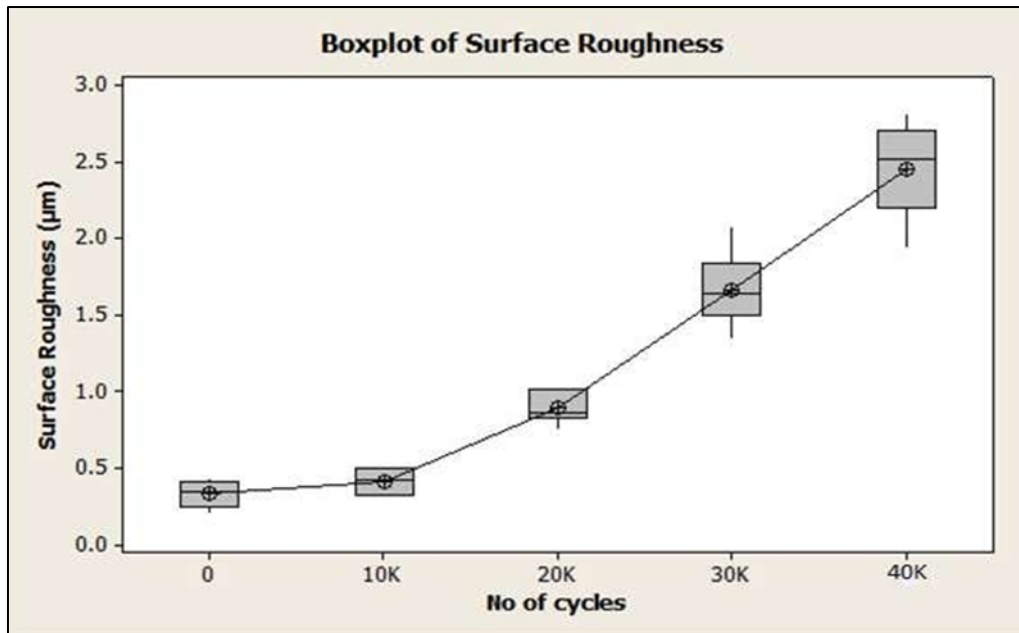


Figure 6 Influence of ageing process on Surface Roughness

4.3. Micro-Hardness

For glass-ceramics, wear behavior is complex and is determined by a variety of factors, including ceramic hardness which is critical because it affects the material's ability to withstand surface penetration caused by a combination of brittle fracture and plastic flow. Further, in certain wear conditions which include the erosive wear behavior of oxide ceramics (glass-ceramic), the ratio of fracture toughness to hardness of ceramics is found to be the most important factor in determining wear quality. Therefore, to know the surface behavior of glass-ceramics such as LDGC, micro-hardness plays a vital role.

4.3.1. Micro-hardness Test Results

Micro-hardness test results are recorded for same eight LDGC dental crown specimens which have been tested for surface roughness, at various stages of ageing process have been given in table 4.

Table 4 Results of micro-hardness

No. of Ageing cycles	Micro-hardness (Vicker's hardness)								
	R1	R2	R3	R4	R5	R6	R7	R8	Mean
0	537.3	531.2	556.7	529.9	533.6	543.1	547.0	534.4	539.15
10000	533.4	523.6	547.1	521.8	526.8	531.7	538.6	527.6	531.33
20000	521.2	508.6	529.3	506.8	513.9	524.2	525.8	515.3	518.14
30000	502.3	499.7	508.8	494.7	501.2	508.9	509.6	496.6	502.73
40000	486.0	479.1	488.3	477.9	481.4	483.8	484.6	480.7	482.72

Tukey's HSD test is executed in one-way ANOVA ($\alpha = 0.05$) for statistical analysis of the results. In this part of work, MiniTab statistical software is utilized to perform statistical result analyses.

4.3.2. Analysis and discussion of results for micro-hardness

The influence of thermal and pH fluctuations on micro-hardness of LDGC dental crown specimens has been studied in this section. The mean values of micro-hardness of all LDGC dental crown prosthesis specimens at prescribed ageing stages have been determined from raw data of experiments. For raw data, mean box plot diagram (response curve) is

used to illustrate the effect of ageing process on micro-hardness. Additionally, analysis of variance (ANOVA) of calculated values is performed to assess the significance of the effect of thermal-pH cycles on micro- hardness.

5. Conclusions

- A standardized CAD/CAM manufacturing workflow enabled precise control over crown geometry, ensuring repeatable fabrication of LDGC fixed dental crowns across all experimental trials.
- Finish line geometry, convergence angle, and cement layer thickness significantly influenced marginal and internal adaptation, with finish line type emerging as a critical determinant of marginal accuracy.
- Synchrotron radiation X-ray micro-computed tomography (SR- μ -CT) proved to be an effective non-destructive technique for high-resolution, three-dimensional evaluation of marginal and internal discrepancies.
- Thermal-pH ageing resulted in a consistent increase in surface roughness and a gradual reduction in micro-hardness, indicating progressive surface degradation of lithium disilicate glass-ceramics under simulated oral conditions.
- The observed degradation mechanisms are attributed to combined ion exchange, hydration, and hydrolytic processes within the glass-ceramic matrix during cyclic thermal and chemical exposure.
- Optimized selection of CAD/CAM design parameters can significantly enhance the adaptation quality and long-term surface integrity of fixed dental crowns, thereby improving clinical performance and service life.
- The findings support the use of CAD/CAM-fabricated monolithic LDGC crowns as reliable restorative solutions when design parameters are carefully controlled.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed

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